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A special issue devoted to

Building Resilience through Advanced Digital Safety and Technology

Guest Editor

Mohammad Shakir Nasif

PERTANIKA

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About the Journal

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What happens to a manuscript once it is submitted to *Pertanika*? Typically, there are seven steps to the editorial review process:

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2. The CEE sends the article-identifying information having been removed, to 2 or 3 reviewers who are specialists in the subject matter represented by the article. The CEE requests them to complete the review within 3 weeks.

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3. The Editor-in-Chief (EiC) examines the review reports and decides whether to accept or reject the manuscript, invites the author(s) to revise and resubmit the manuscript, or seek additional review reports. Final acceptance or rejection rests with the CEE and EiC, who reserve the right to refuse any material for publication. In rare instances, the manuscript is accepted with almost no revision. Almost without exception, reviewers' comments (to the author) are forwarded to the author. If a revision is indicated, the editor provides guidelines to the authors for attending to the reviewers' suggestions and perhaps additional advice about revising the manuscript.

4. The authors decide whether and how to address the reviewers' comments and criticisms and the editor's concerns. The authors return a revised version of the paper to the CEE along with specific information describing how they have answered' the concerns of the reviewers and the editor, usually in a tabular form. The author(s) may also submit a rebuttal if there is a need especially when the authors disagree with certain comments provided by reviewer(s).

5. The CEE sends the revised paper out for re-review. Typically, at least 1 of the original reviewers will be asked to examine the article.

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Guest Editor

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AN INTERNATIONAL PEER-REVIEWED JOURNAL

ABSTRACTING AND INDEXING OF PERTANIKA JOURNALS

Pertanika has reached 40 years old; this accumulated knowledge has resulted in the journals being abstracted and indexed in SCOPUS (Elsevier), Clarivate-Emerging Sources Citation Index [ESCI (Web of Science)], BIOSIS, National Agricultural Science (NAL), Google Scholar, MyCite and ISC.

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Building Resilience through Advanced Digital Safety and Technology

Preface

We are glad to present this Special Issue of Pertanika Journal of Science and Technology. Major accidents in process plant cause significant hazards which may result in substantial loss of lives as well as significant financial loss. Developing technologies as well performing research which lead to reducing the effect or preventing the occurrence of these accidents always receive much interest from governments, regulatory agencies, stakeholders, as well as practicing engineers. In this regard, the Centre of Advanced Process Safety (CAPS), Universiti Teknologi PETRONAS (UTP) in collaboration with the Department of Occupational Safety and Health (DOSH)-Malaysia, IChemE Safety Centre (ISC) and Centre of Risk, Integrity and Safety Engineering (C-RISE) - Canada, had organized the International Conference and Exhibition on Loss Prevention Asia 2019 (LPA 2019). More than 200 participants from different countries around the world had attended this event which was organized on 25-26 November 2019 at Hotel Istana – Kuala Lumpur. Participants from academia, industries, regulatory agencies had discussed the latest advancement, research findings, and implementation of new regulations in process safety in the advent of the Fourth Industrial Revolution.

LPA 2019 hosted various panel discussions, and keynote presentations by internationally renowned speakers. The technical session covered 10 topics: safety culture, environmental protection, human factors, corrosion, offshore safety, risk management, integrity management, data analytics, emergency response, fire and explosion.

This special issue of LPA 2019 includes thirteen selected reviewed manuscripts which were presented in LPA 2019. It is hoped to be a good reference and great use for process safety researchers and practitioners.

We would like to take this opportunity to thank the contributors as well as the reviewers for the effort and expertise that they have invested in making this Special Issue a success. We would also like to thank Pertanika's Editor-in-Chief, the Chief Executive Editor, and their dedicated publication team for their advice and dedication with respect to maximising the quality of this issue. It is hoped that this publication will benefit all relevant stakeholders and further enhance the quality of future research in the areas mentioned.

Guest Editor

Mohammad Shakir Nasif *(Assoc. Prof. Dr.)*

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Review Article

Conceptual Framework - Hazard Assessment of Nanomaterıals Using Bayesian Network

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ABSTRACT

The development and application of advanced materials i.e. nanomaterials are important for the technology revolution and economic progress of the country. However, the potential health risk arising from nanomaterials become a major concern. Given the fact that both particulate and molecular identity of nanomaterials is responsible for the biological effects, the effects of nanomaterial exposure cannot be predicted based on the current understanding of their bulk properties. The lack of nanomaterials data for safety assessment become a major challenge to implement safe work practice at nanomaterials related industries. To resolve the aforementioned problem, a conceptual framework for hazard assessment of nanomaterials is presented in this study. Bayesian Network (BN) is used to support hazard assessment according to the guideline issued by the Department of Occupational Safety and Health (DOSH) Malaysia. The understanding of the hazard is crucial to encourage the development of an action plan to ensure the safety aspect while processing and handling nanomaterials.

Keywords: Bayesian Network, big data, data-driven, nanomaterials risk, prediction

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INTRODUCTION

The development and application of advanced materials which are nanomaterials are important for the technology revolution and economic growth around the world. At the scale of 1 to 100 nanometers, nanomaterials pose unique physical, chemical, and biological properties. The surface and quantum effect of nanoscale

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materials give a significant influence on the behaviours. The quantum effects will affect the optical, electrical, thermal, mechanical and magnetic properties while surface effects will affect the reactivity (Azoulay et al., 2013). These properties can improve the performance and characteristics of the final products. Therefore, they have been widely used in different sectors such as construction, energy storage, electric and electronic, paint and coating, and food agricultural. The database from STATNANO indicates the vast usage of nanomaterials around the world involving 2237 companies from 60 countries.

Market Overview and Consumers Perception

Due to the vast industrial application, the nanomaterials market is booming in recent years with a promising market value worldwide. According to the report by Inkwood Research, the market was valued $14,741.6 million in 2015 and is expected to reach $55,016 million by 2022, supported by a compound annual growth rate (CAGR) of 20.7% (Inkwood Research, 2017). In Malaysia, the government plays a prominent role in the advancement of nanomaterials technologies by supporting research and development, pre-commercialization, scale-up, and commercialization process, providing the fund valued at MYR176.3 million in 9^{th},10^{th} and 11^{th} Malaysia Plan until June 2016. Further, RM 75 million and MYR10.9 million funds were allocated for Graphene Commercialization and Nanosafety Risk Level Determination project respectively (Masrom, 2016). National Nanotechnology Centre (NNC) was established in 2010 under the Ministry of Science, Technology, and Innovation (MOSTI) as a national focal point to manage all activities related to nanomaterials in Malaysia. Under the National Policy on Industry 4.0, the nanomaterials-related activities are anticipated to become one of the new economic drivers for Malaysian industries (MITI, 2018). According to the report by MIMOS Berhad, the advancement in nanotechnology in the electric and electronic sector is expected to raise the sector by 20% to 30% in 2020 (MIMOS Berhad, 2015). The activation of graphene projects by NanoMalaysia in March 2018 was expected to generate a future revenue of RM1.35 billion and could potentially achieve RM20 billion in gross national income (GNI) impact (Ong, 2018).

While a great advancement of nanomaterials in the industry can be observed, public perceptions and their acceptances play important roles and become key in determining the future of nanotechnology. A survey done in Malaysia involving 512 tertiary students shows that 14.06% of the respondents know about nanomaterials and 75.97% of them have heard the word ‘nanotechnology’. Overall, the respondents have a positive impression of nanotechnology (Karim et al., 2017). A survey conducted in South Korea involving 1007 consumers indicated low awareness about nanotechnology among them in which 80.3% of respondents did not know about nanotechnology. Although they were concern about safety status, they had a positive impression of nanotechnology. According to the study, the respondents who come from low household income have low awareness about nanotechnology (Lee et al., 2005). Another study conducted in the same region showed that the experts had a higher level of awareness about nanotechnology than consumers. The experts had a concern about the safety issue and they perceived the nanotechnology negatively (Kim et al., 2014b). A survey done in Singapore involving 1,080 consumers indicated a high level of awareness among the younger generation and educated people and they had a concern about the safeness of nanomaterials in food and medicine (George et al., 2014). A study conducted in the United State of America (USA) also showed a similar finding whereby younger and educated people were aware of nanotechnology. By contrast, the European people are less optimistic compared to USA respondents in which they have a concern about the impact of technology on the environment and lack of confidence towards the regulatory body. Different perceptions in these two regions were influenced by media coverage, where the potential benefits of nanotechnology were highlighted more in the USA than in the United Kingdom (UK) (Gaskell et al., 2004). The fact that the younger and educated respondents react negatively towards nanotechnology shows that they are aware of the potential risk that comes from nanomaterials products. However, the uncertainty in risk information will instil unnecessary fear that may lead to rejection. Therefore, the clarity and the right information are very crucial in shaping the perception of risks versus benefits of nanotechnology and general attitudes toward nanotechnology.

Safety Issue

Nanomaterials Safety Issue and Previous Developed Tools. The rapid growth of the nanomaterials industry gives a good prospect for employment whereby in 2020, around 6 million workforces will be employed worldwide (Roco, 2011). However, the lack of information regarding nanomaterials leads to the lack of understanding related to the occupational, health and safety aspects. This issue will contribute to the negligence towards safe work practice in which workers will exposed the to the danger. The previous studies reported that most of the nanomaterials were produced mainly by small businesses (Azoulay et al., 2013). For the manufacturing process, the business with sales turnover between RM300,000 to RM15,000,000 or the number of employees between 5 to 75 are classified as a small business (SME Corporation Malaysia, 2013). Comparing with the major hazard installation such as oil and gas industries that are bound to comply with safety regulations such as Process Safety Management (PSM) or Control of Major Accident Hazards (COMAH), the occupational safety level for small businesses are relatively poor.

According to the previous studies, the exposure of nanoparticles, especially through inhalation, may give a negative impact on human health. Previously reported cases due to the exposure of nanoparticles are summarized in Table 1. Among the challenges to ensure the safety aspect for the process involving nanomaterials is the lack of nanomaterials data for safety assessment. Given the fact that both particulate and molecular identity of nanomaterials are responsible for the biological effects, the effects of nanomaterials exposure cannot be predicted based on the current understanding of their bulk properties. Therefore, different groups of researchers highlighted the need of identifying the risk of nanomaterials towards humans and environments to develop the precautionary approach for nanomaterials risk (Azoulay et al., 2013; Karim et al., 2017; Kim et al., 2014a; Yokel & MacPhail, 2011). However, with the conventional way to collect the data through lab testing, the industries facing a great challenge to keep pace with the high speed of the development that results in an ever-increasing diversity of nanomaterials in industry. Further, the conventional lab testing methods are time-consuming, involving the high cost of experimental equipment, breach the ethical and suffer from inaccuracy on the results.

Table 1
Previous reported cases on nanomaterials exposure

Source	Activity / process	Syndrome	Consequence	Evidence
Phillips et al. (2010); Rendall et al. (1995)	Spraying nickel in a metal arc process	Respiratory distress syndrome	One fatality	• High level of nickel found in urine and kidney • Nanoparticles with the size less than 25 nm found in alveolar macrophages
Hull and Abraham (2002)	Aluminum welding	Pneumoconiosis	Two fatalities	• Aluminum concentration from 8.5 to 11.2 billion particles per cm3 of lung tissue. Most of the particles have 10 nm in size
Song et al. (2011, 2009)	Polyacrylate spray painting	Shortness of breath, pleural effusion, progressive pulmonary fibrosis	Seven injuries	• Silica nanoparticles in alveolar macrophages, epithelial cells, and chest fluid
Cheng et al. (2012)	Polyester powder painting	Bronchiolitis obliterans organizing pneumonia	One fatality	• Titanium dioxide nanoparticles in pulmonary sample

Table 1 *(Continued)*

Source	Activity / process	Syndrome	Consequence	Evidence
Theegarten et al. (2010)	Toner from the laser printing process	Abdominal pain, weight loss, and diarrhea	One injury	• Submesothelial aggregates of carbon nanoparticle (CNP) with a diameter of 31-67 nm were found in tissue specimens
Kim and Yu (2016)	340 workplaces handling or manufacturing nanomaterials	Suspected respiratory occupational disease	Nine injuries	• Not specify
		Recommended for regular follow-up health monitoring	Seven injuries	

To resolve this issue, several research groups developed the computerized tools for risk assessment as summarized in Table 2. Although the proposed tools are useful, these tools should be used with care. A comparison study done by Jiménez et al. (2016) shows that the assessment done using the tools as in Table 2 gave different outcomes, which were contributed by several factors; limitation on the activities covered by the tools, the dependency on expert judgment due to the lack of data, high sensitivity towards the changes in exposure input data but lack of sensitivity to the changes of hazard (Jiménez et al., 2016).

Table 2

Computerized tools for nanomaterials risk assessment (Jiménez et al., 2016)

Tools	Developer	Description
NanoSafer	National Research Centre for the Working Environment (NRCWE), Denmark	• Assess exposure and hazard when handling powders in the case of spills. • The tool provides a risk evaluation in the near and far-field for short (15min) and long-term (8hrs) exposure. • Estimates whether the material is nano-relevant from the input parameters (i.e. particles less than or equal to 200 nm and or products with a specific surface area more than or equal to $30 m^2 g^{-1}$

Table 2 *(Continued)*

Tools	Developer	Description
CB Nano Tool	Lawrence Livermore National Laboratory in the United States	The tool estimates an emission probability (without considering exposure controls) and severity band and provides advice on engineering controls to use. Includes nine domains covering the handling of liquids, powders, and abrasion of solids. The tool does not make any assessment of whether the substances are nano-relevant based on the substance's input parameters.
Stoffenmanager-Nano	The consortium led by TNO, Netherlands	Estimating an exposure and hazard band, providing a risk prioritization and recommending a series of control measures Four domains are considered: synthesis, powder handling, spray and dispersions of ready to use nanoproducts, fracturing, and abrasion of nanomaterials embedded in products The substance of nano-relevant (defined as particle size less than 100nm and/or products with a specific surface area more than or equal to $60m^2g^{-1}$ No reference is made to the substance's input parameters
The Precautionary Matrix	TEMAS Switzerland	Provide advice about whether a precautionary approach is required under normal working conditions, worst scenario and for the environment. Assesses the nano-relevance of the substance as a function of the particle diameter and the solubility in the lung
Nanotoolkit	California Nanosafety Consortium of Higher Education	Provide practical guidance as to how nanomaterials should be handled safely in the research laboratory setting

In the process safety area, the causal relationships between parameters can be used to enhance the understanding of the process. Among the common technique used in process safety is fault tree analysis (FTA). FTA is a technique for identifying and analyzing factors that can contribute to a specified undesired event (called the "top event") based on the causal factors e.g. component hardware failures and human errors. FTA can be used to identify potential causes and pathways to failure (the top event) or to calculate the probability of the top event, given knowledge of the probabilities of causal events. The FTA has been used in ARAMIS Project for MIMAH and MIRAS methodology by Delvosalle (Delvosalle et al., 2006). Although it has been used extensively in process safety, FTA is not suitable for analyzing large systems, especially for the system with redundant failures, common cause failures, or mutually exclusive primary events. Further, the assumption used in FTA where the events are assumed independent is invalid (Khakzad et al., 2011). In recent years, a Bayesian network (BN) methodology has begun to be used in engineering applications. A BN is a graphical inference technique used to express the causal relationships among variables. BNs are used either to predict or to update the probability of known variables given the certain state of other variables (evidence) through the process of probability propagation or reasoning. The reasoning is based on Bayes' theorem. BN is ideal for taking an event that occurred and predicting the likelihood of several possible known causes was the contributing factor. The capability of BN to perform three inference tasks; inferring unobserved variables, parameter learning, and structure learning make BN become a promising technique for process safety (Khakzad et al., 2011).

Due to the advantages offered by BN, BN was used in this work for the prediction of hazard potential due to nanomaterials exposure. A new framework is proposed in this study by integrating the BN output with the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018). The strength of the framework:

- The graphical model from BN is very important to enhance the understanding of the interdependency between exposure routes, potential biological effects and physicochemical properties of nanomaterials.
- The data-driven technique in BN is used for hazard prediction whereby the machine learning algorithm will be used to resolve the lack of nanomaterials data for safety assessment. This is a very important feature that can contribute to the time efficiency, reduction of manpower, and cost-effectiveness.
- Further, the integration of BN to support the hazard assessment process based on the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018) is valuable as a widely accepted guideline is used for the Malaysian process industries.

Conceptual Framework and Expected Results

Figure 1 summarizes the flowchart of the proposed framework followed by brief explanations of each activity.

Understand the Process and Identification of the Group of Hazard. The first step in this work is to understand the process and identification of the group of hazards. To complete the step, the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018) is used as guidance. The nature of the process needs to be understood; the process/task and work activities involving nanomaterials, the degree of release, the exposure duration, and the hazard group. The process/task and work activities divided into production of nanomaterials, downstream processing, product packaging, and maintenance. From the process/task and work activities, the potential nanomaterials exposure can be identified. Subsequently, the degree of release needs to be identified based on the state:

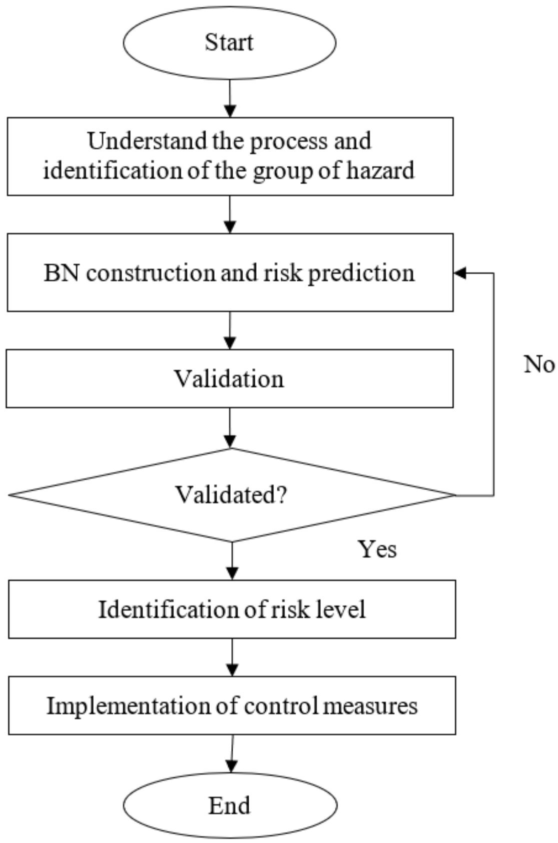

Figure 1. Conceptual framework of nanomaterial risk assessment

bound, potential and free/unbound. The exposure duration needs to be categorized based on three categories; short (4hours/day or 2days/week), medium (4 to 6 hours/day or 3 to 5 days/week) and long (6 to >8hours/day or 3 to 5 days/week). The hazard group needs to be identified from Group A (known to be inert), Group B (understand reactivity and function) and Group C (unknown properties). Based on the above criteria, the rating of the process involving nanomaterials will be given based on guidance from the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018) in Table 3. In the next step, the BN model will be developed to further understand the risk of nanomaterials.

Table 3
Risk level of nanomaterial exposure

Degree of Release Exposure duration	Bound material	Potential release	Free/unbound
Hazard Group A (known to be inert)			
Short	1	1	2

Table 3 *(Continued)*

Degree of Release Exposure duration	Bound material	Potential release	Free/unbound
Hazard Group A (known to be inert)			
Medium	1	1	2
Long	1	2	2
Hazard Group B (understand reactivity/function)			
Short	1	2	2
Medium	1	2	3
Long	1	3	3
Hazard Group C (unknown properties)			
Short	2	2	3
Medium	2	3	4
Long	2	4	4

BN Construction and Risk Prediction. In this work, GeNIe Modeler from BayesFusion (2019) is used to re-construct the BN model using the data from previous research work by Marvin et al. (2017). The data has been classified in the group as presented in Table 4. The main purpose of model development in this work is to capture the interdependency between exposure routes, potential biological effects, and physicochemical properties. The initial BN graphical structure is constructed manually. Subsequently 467 nanomaterials data are used for parameter learning for each node to produce an optimal configuration. The optimal configuration is produced via the interaction between nodes and with sufficient data, the machine learning algorithm (expectation-maximization algorithm) embedded in this software can estimate the conditional probability table (CPT).

Table 4

Classification of nanomaterials

Exposure routes	Physicochemical properties	Potential biological effects
Inhalation	Shape	Cytotoxicity
Oral	Purity of nanomaterials	Neurological effects
Dermal	Dissolution	Pulmonary effects
Intravenous	Surface area	Fibrosis
	Surface charge	RCNS effects
	Surface coatings	Immunological effects
	Surface reactivity	Genotoxicity
	Aggregation	Inflammation
	Particle size	

BN is a graphical model that represents a probabilistic relationship among a set of nodes (Figure 2). The nodes represent the variables U = {A_i, ..., A_n} and the directed links between them indicate the relationship among the nodes. Each node is composed of a set of states. A node A_i is the parent of the child node A_j, if there is a link from A_i to A_j. BN specifies a unique joint probabilistic distribution of all nodes P(U) = P(A_1, ..., A_n), given by the product of all conditional probabilistic tables specified in BN:

$$P(U) = \prod_{i=1}^{n} P(A_i \mid pa(A_i))$$

where pa(A_i) are parents of node A_i and P(A_i|pa(A_i)) specifies a conditional probabilistic distribution. The calculations are based on Bayesian theory, where the probabilistic of event A at the condition of event B is expressed as:

$$P(A \mid B) = \frac{P(B \mid A) \times P(A)}{P(B)}$$

In which P(A) is the prior probability of A, P(B|A) is the probabilistic of B under the condition of a known event A and P(B) is prior probabilistic of B. An example of BN with six nodes is shown in Figure 2. The corresponding decomposition of the joint distribution of nodes is given by:

$$P(A_1,\ldots,A_6) = P(A_1)P(A_2)P(A_3)P(A_4 \mid A_1, A_2)P(A_5 \mid A_2, A_3)P(A_6 \mid A_4, A_5).$$

To calculate the joint distribution, unconditional distributions of $P(A_1), P(A_2), P(A_3)$ and conditional distributions $P(A_4 \mid A_1, A_2)P(A_5 \mid A_2, A_3)P(A_6 \mid A_4, A_5)$ should be specified. The nanomaterials hazard will be classified into four different categories which are none, low, medium, and high. The highest predicted probability become the indicator on the category of hazard.

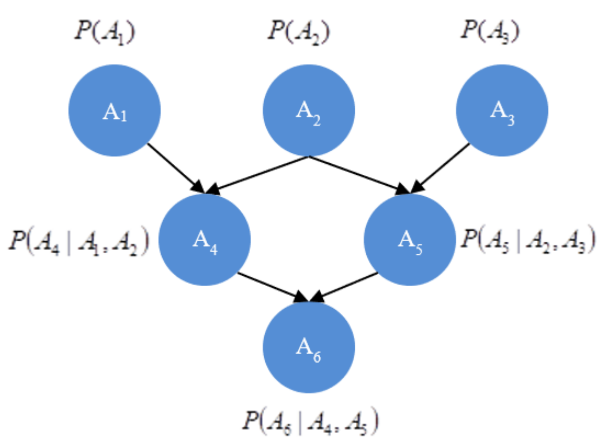

Figure 2. An example of a Bayesian Network showing the relationship between a set of nodes

Validation. The validation of the BN model is performed using the K-fold cross-validation method in which divides the data set into K parts of equal size, trains the network on K-1 parts, and tests it on the last, K^{th} part. The process is repeated K times, with a different part of the data being selected for testing. The accuracy, the confusion matrix, the Receiver Operating Characteristic (ROC) curve and calibration curve are monitor and observe to ensure the developed BN model can predict the hazard accurately. The diagonal cells in the confusion matrix will show the numbers of correctly identified instances for each of the classes and off-diagonal cells show incorrectly identified classes. The ROC curves for each of the states of each of the class variables indicate the quality of a model-independent of the classification decision. Calibration curve comparing the output probability to the observed frequencies in the data to measure the accuracy of a model (BayesFusion, 2019).

Implementation of Control Measures. In this work, the control band key is identified according to the Guideline on Control and Safe Handling of Nanomaterials 2018 (DOSH, 2018) as shown in Table 5. The probability obtained from the BN model is used to support and detailed out the control measure identified from Table 5. The results are very useful in improving understanding and hazard management strategies.

Table 5
Control band key

Band	Control measures
1	General ventilation and personal protective equipment (PPE)
2	Engineering controls and/or respirators, additional PPE
3	Containment (e.g. glove box)
4	Seek specialist advice

CONCLUSION

In this study, a conceptual framework for hazard assessment has been proposed by combining BN into the risk assessment guidelines proposed by DOSH. The implementation of the BN in this framework is very important for prediction purposes to resolve the data limitation issue for nanomaterials. By having this technique, the understanding of the risk can be improved and subsequently can encourage the development of an action plan to ensure the safety aspect while processing and handling nanomaterials. The implementation of the proposed framework to assess nanomaterials risk will be demonstrated in future work.

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Analysis of the Contributing Factors for Fatal Accidents due to Falls from Heights in Malaysia and the USA

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ABSTRACT

Working at heights has always been a concern for the process industry and construction industry. According to recent statistics, falls from heights are the leading cause for at least a third of all construction accidents, based on the accident reports from Malaysia, United States of America (USA) and Great Britain. Therefore, the aim of this research is to investigate the contributing factors for fatal accidents due to falls from heights based on published official data by government agencies such as Department of Occupational Safety and Health (DOSH) in Malaysia and Occupational Safety and Health and Administration (OSHA) in the USA. Thorough risk analysis of accidents due to falls from heights is needed as a step to improve the safety of workers and reduce the number of fatalities. The methodology used was developed through an in-depth literature review from relevant publications that discussed falls from heights investigations ranging from individual characters to management commitment and site conditions. The data is available and accessible to the public via OSHA and DOSH and can be obtained by browsing their websites. The data were analysed based on the relevant understanding of the description mentioned in the accident reports and its relationship with the contributing factors. Eventually, from the analysis, the factors which affect more the numbers of

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fatal accidents due to falls from heights were obtained. In this study, 105 fatal accidents due to falls from heights from Malaysia data and 101 fatal accidents from USA data were selected through a precise selecting process and analysed to determine which factor was the highest contributor to increasing the number of fatal workplace accidents due to falls from heights. Results indicate that a lack of effective management is the highest contributor to falls from height fatal accidents.

Keywords: Construction, falls from heights, fatal accidents, occupational safety, risk analysis

INTRODUCTION

Workplace Fatal Accidents (WFAs) have been and still are the main concern for many governments and employers due to the loss of workers lives. Loss of a person's life, regardless of whether high or low rates are still considered a costly loss for any employer, either economically or socially. That drives researchers to investigate these phenomena, therefore, various studies have focused on finding a solution for such a dilemma. Over the years, some countries have made a recognizable progress in reducing the number of accidents which resulted in positive improvement in reducing fatalities such as the United Kingdom, these improvements interpreted in real life statistics which indicated that the number of WFAs has dropped from 2.1 per 100,000 workers in 1981 to 0.5 per 100,000 workers in 2018/2019 (Health and Safety Executive, 2018). Similar challenges exist in other countries such as the United States and Malaysia, while they attempted to solve the fatalities problem hoping to achieve the same level of success as the United Kingdom, unfortunately, they did not achieve the same results in spite of the undeniable effort and research conducted. In Malaysia, statistics showed that the number of WFAs increased in the period between 2014 and 2017, the number went from 4.21 per 100,000 workers to 4.90 per 100,000 workers in Malaysia (Malaysia Department of Occupational Safety and Health, 2018). In the United States, statistics showed that the numbers went up from 3.3 per 100,000 workers to 3.5 per 100,000 (U.S. Bureau of Labour Statistics, 2014, 2018). According to published data, Falls From Heights (FFH) contributed to the whole number of WFAs by 30% in the United Kingdom which was interpreted into 35 fatal accident totals in 2017/2018 (HSE, 2018). The percentage was 39% in the United States which was interpreted into 381 fatal accident in 2017 and finally, 46% in Malaysia (Ayob et al., 2018) which was interpreted into 16 fatal accident in 2017/2018 (Malaysia Department of Occupational Safety and Health, 2018).

A considerable amount of literature has been devoted to finding the factors that affect workplace fatal accidents from different aspects in different countries to uncover these accidents economical and sociological effects. Kum and Sahin (2015) investigated arctic accidents, in spite of the differences between their study and this study, it was still beneficial to this study by adapting the methodology used to process the raw data that helped to develop the structure of this study.

Ayob et al. (2018) focused on workplace fatal accidents in the Malaysian construction industry by using a descriptive exploratory survey to determine both the patterns and contributing factors for fatal accidents. The results indicated the locations with the highest numbers of WFAs and types of accidents from the brief reports provided by the Department of Occupational Safety and Health in Malaysia. Results were too general as they only gave immediate causes for each type of accident. On the other hand, a study by Wong et al. (2016) associated human factors and root causes analysis to investigate falls from heights in Hong Kong construction industry using a systematic approach to analyse reports from the coroner's office. Results revealed that human factors were strongly linked to falls from heights fatal accidents and divided the cases into four general classes. The results from this study are a step forward to discovering the causes of falls from heights accidents, but it is narrowed by only analysing the human factors in falls from heights which may collide with other factors such as site conditions or weather conditions.

Furthermore, a study by Nadhim et al. (2016) was conducted in detail a review of all the studies that were related to finding factors or causes that led to fatal accidents to falls from heights by using three-phase methodology; searching the internet, selecting and analyzing using several statistical methods. The papers were clustered by journals, date, type of work, location, and accidents contributing to the most falls from accidents. The results of this study were limited and did not focus on finding the actual factors behind fatal accidents, instead of based on sample size. Results led to the discovery of several factors that affected falls from heights which are: risky activities, individual factors, site conditions, and management, agent and weather conditions. Besides that, earlier studies such as Huang and Hinze (2003) had tackled this issue and analyzed case reports in spite of the hardships faced at that time. The study focused on analysing case reports collected from the OSHA in the USA at the time. The data were clustered and analyzed based on several variables such as age, gender, type of fall and height of fall causes of fall accidents. Results indicated that the lack of training is the major contributor to fall from heights accidents especially in occupations such as a roofer, carpenters, labourers, and structure metalworkers. Several variables that control the occurrences of these accidents changes have been occurring since the time this paper was published; technology and safety awareness have been developed and several variables could affect the result of this study.

On a more precise note, this topic has not received a great deal attention both inside and outside of Malaysia such as the study by Mohammad and Hadikusumo (2017) which identified safety intervention practices in the Malaysian construction industry. The outcome was to determine a guide for behavioural safety performance in the construction industry. Although the approach is a good start towards behavioural safety, the study did not focus on finding solutions for the current high numbers of accidents. The study if implemented correctly, could contribute to the long-term effect. Other studies such as Ismail et al. (2012); Marhani et al. (2013); Ranjan (2019); Saifullah and Ismail (2012) and Zin and Ismail (2012), focused mostly on behavioural factors and management systems.

The opposite goes for the USA, as several studies have been published that focused on workplace fatal accidents due to falls from height, some of the studies tried to implement technology into occupational safety and health such as Antwi-Afari and Li (2018); Gómez-de-Gabriel et al. (2019); Jebelli et al. (2016); Ohdo et al. (2011); Umer et al. (2018); Yang et al. (2017) and Zhang et al. (2015) but the statistics published each year indicate the opposite, as the number of accidents in the United States had increased. That leads to the believe that there is a gap that has to be addressed. Therefore, this research addresses falls from heights in terms of the contributing factors such as human, managerial and weather factors as well as variables such as location, date, type and time of fall to determine which factors affect more of these variables and to compare the obtained results from different countries.

MATERIALS AND METHODS

This study was conducted to detect the factors that could affect workplace fatal accidents and the time and location patterns that could increase or decrease the number of fatal accidents in Malaysia and the United States of America. The study acknowledges that knowing these factors in different accidents scenarios could greatly contribute to preventing future accidents.

Data Collection

In order to collect the necessary data, this research used a database available to the public from two different occupational safety and health government agencies. Accident reports published by the Department of Occupational Safety and Health in Malaysia (DOSH) and the Occupational Safety and Health Administration (OSHA) in the USA were selected in this respect.

Data Selection

When analysing a specific type of accident in both DOSH and OSHA database, the information is usually either incomplete or the description is rather short and does not contain the full details on the timeline of the accident. This requires a thorough search for a specific type of accident, which can be performed by consulting accident reports from different databases. Due to the lack of the full reports by DOSH and OSHA which included just a summary that had a few details such as location referred to as State, date, accident type and a brief description of the accident sequence. All the related data would be collected based on the description and provided a type of fall. Table 1 shows the sample reports published by DOSH and OSHA. Accident identifier is an added reference to put all accidents in chronological order, the date indicates the date of the accident, the state is the location of the accident, accident type indicates how the worker died and finally the description is a short summary of the accident events.

Table 1
Sample of reports published by both DOSH and OSHA

Accident Identifier	Date	State	Accident Type	Description	
MY001	06/09/2018	Pulau Pinang	**Died falling from a height**	A general worker had **fallen from level 6** as he was **walking the scaffold's temporary ladder**	i) Unsafe access to the temporary ladder ii) Wall opening was not properly covered
US001	03/29/2018	Georgia	A worker **died in fall** from a roof.	At **2:54 p.m.** on **March 29, 2018**, an employee was walking across a low sloping metal roof on a steel building during the repair of a roof leak. The employee **stepped on a fiberglass skylight and fell through.** The employee **fell 16 feet to the concrete floor.** The employee sustained multiple blunt force trauma injuries and later died.	

Among these reports, an extensive selecting process was carried out. For DOSH, due to the low number of accident reports published, it was not necessary to use any method to select the data, but just manually collecting all the cases with falling from heights title. The number was only 382 accidents in the timeframe of 8 years (from 2010 to 2018), falls from heights accounted for 27.48% of all the published cases which was interpreted into 105 cases report.

The opposite was for the USA, due to the extensive number of accidents and a variety of accident types in the OSHA websites, a filtering method was implemented to determine the falls from heights accidents among others. The method filtered accidents with only the word “fall” included in the description and filtered all workplace falls from heights/elevation accidents. Another variable was used to select the cases reports, not all cases published had a description of the accidents, only accidents that had a description were selected. A total of 101 accident in the period of 6 months (from October 2017 to March 2019). Most reports included only the immediate causes of the accidents, there was no deeper analysis to extract the root causes and the contributing factors. The highlighted areas in Table 1 are an example of how accident description was used to determine which category of factors that accident would be placed.

Data Analysis

Classification of Factors Used in the Study. To provide systematic analysis for the work, a proven classification of factors contributing to accidents scheme had been adopted for this work. The classification was obtained from the work done by Nadhim et al. (2016) and is shown in Table 2.

Table 2

Classification of factors contributing to accidents from Nadhim et al. (2016)

Contributing Factors Classification	Contributing Factors which Lead to Accidents
Risky Activities	Working at height: With complexity, hardship, prolong tasks
Individual Characteristics	- Demography: Age, gender, weight, ethnicity. - Knowledge level: Lack of education, experience, training. - Human behaviours: Misjudgement, attitude, unsafe behaviour & carelessness. - Workers health/characteristics: Fatigue, sleep deprivation or depression
Site Conditions	- Insufficient lighting & illumination - Unprotected/defective platform & surface
Organization/ Management	- Small-medium sized companies: Lack of training programs - Contractors & Sub-contractors: Lack of proper/safe equipment - Shift work: Night shifts and break periods - Project timeline: Pressure to accelerate
Agent	Improper position or defective: Ladder/scaffold (erecting/ dismantling)
Weather/ Environmental Conditions	Frost, snow, heavy rain, humid extreme temperatures, noise, dust.

Table 2 indicates all the factors that could affect the number of falls from heights accidents, the same factors would be used to determine which would affect the number of accidents based on the descriptions from reports collected from both DOSH and OSHA. An example of how the collected data was interpreted into the classification is shown in Table 3. Based on the description of the accidents in Table 1, the authors categorised the accidents into respective classification. Each accident could have one or more factors influencing it.

Table 3
Sample of the analysed data

Accident Identifier	Date	Location	Risky Activities	Individual Characteristics	Site Conditions
MY001	06/09/2018	Pulau Pinang			x
US001	03/29/2018	Georgia		x	x

Accident Identifier	Date	Location	Organization/ Management	Agent	Weather/ Environmental Conditions
MY001	06/09/2018	Pulau Pinang		x	
US001	03/29/2018	Georgia	x		

RESULTS AND DISCUSSION

Analysis of Malaysian Data

Results in this section were the outcome of an extensive systematic analysis of workplace fatal accidents reports obtained from DOSH and OSHA. A total of 206 fatal accident reports were analyzed to extract the factors that can affect accidents by both date and location (Table 3). Results from the analysis of 105 accident reports from Malaysia found that several factors could affect accidents numbers, the two main contributing factors were management and individual characteristics, other factors such as risky activities and agent had a small or negligible effect, weather and environmental factors were not a factor due to the lack of information on the accident reports description. Furthermore, different locations and dates seem to have an effect on these accidents.

Classification by Year

Regarding the dates of the accidents (Figure 1), 2014 was the highest in terms of accident numbers which helped identify the contributing factors that could have a direct and/or indirect effect on falls from height accidents.

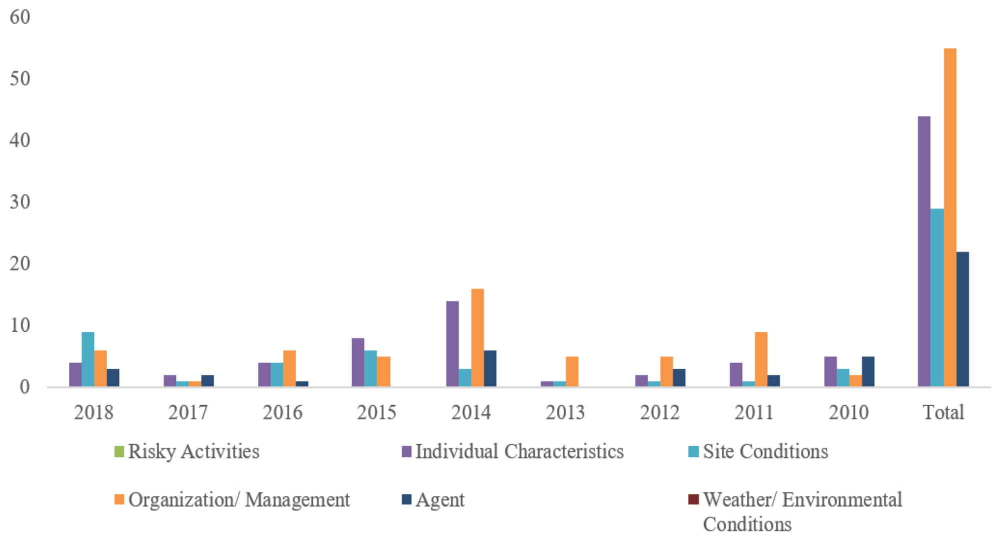

Figure 1. Malaysian data by date

Table 4 shows the number of accident reports and the number of factors affecting those accidents by date. The total number of accidents was 105 based on the reports collected from DOSH and the total of contributing factors was 151 that were extracted in accordance to the accident report description, a factor or more could affect one accident. The average of 11 accidents (10%) was recorded in three different years which were 2011, 2012, and 2016 which indicated that with all the laws and regulations available 11 accidents per year still happened. The year 2014 recorded the highest number of accidents with a total of 28 accidents that was interpreted into 26% of all accidents; 15 of these accidents were in the state of Johor and 4 in the state of Pulau Pinang. In the following year 2015 was ranked next with 16 accidents (15%) and it spread over several states. There was a relatively low number of accidents recorded in 2017 with 4 accidents. These results could be considered a progress if the year 2018 did not have 12 accidents; meaning that the decrease in accidents numbers in 2017 did not necessarily signify an improvement in preventing falls from heights accidents but it might be caused by external factors; that were likely linked to underreporting or more likely that the accidents occurred during that year were not accidents due to falls from heights. The available statistics support this claim as DOSH in 2017 recorded a higher number of worker fatalities with 3.5 per 100,000 workers, which is still a valuable point to consider when trying to extract which factors affect work at heights.

Table 5 shows that the contributing factors registered their peak in 2014 which also had the highest number of accidents but that does not necessarily mean that there exists a relation with accident number and the contributing factors since 2018 was the second-highest number of contributing factors but fewer accidents numbers than 2015. According to Table 5, the results support the conclusion from the table where management and individual characteristics are the main contributing factors that could affect accidents numbers. Nevertheless, the year 2018 witnessed the appearance of a new factor which was site conditions, that was overlooked in the past years. From the data in Table 5, it was noticeable that site conditions started contributing to accidents number since the year 2015 until it reached its highest number in 2018 which was 9. On the opposite, there was an improvement in management and individual characteristics factors from 16 in 2014 to 5 and then steadily 6 in 2018 and 2016. The same goes for individual characteristics which went down from 14 in 2014 to 8 in 2015 and then steadily at 4 in 2016 and 2018 which is a good indicator that these factors are getting some attention but the number of accidents is still the same or increasing, focusing on some factors and neglecting others is not as effective but it is still considered as an improvement since site conditions could be considered as reactive factor.

Table 4
Malaysian data by date

Year	Number of Accidents	Contributing Factors
2018	12	22
2017	4	6
2016	11	15
2015	16	19
2014	28	39
2013	6	7
2012	11	12
2011	11	16
2010	6	15
Total	105	151

Table 5
Classification of Malaysian data based on date

Year	Classification of Contributing Factors to Accidents					
	Risky Activities	Individual Characteristics	Site Conditions	Organization/ Management	Agent	Weather/ Environmental Conditions
2018	-	4	9	6	3	-
2017	-	2	1	1	2	-

Table 5 *(Continued)*

Year	Classification of Contributing Factors to Accidents					
	Risky Activities	Individual Characteristics	Site Conditions	Organization/ Management	Agent	Weather/ Environmental Conditions
2016	-	4	4	6	1	-
2015	-	8	6	5	-	-
2014	-	14	3	16	6	-
2013	-	1	1	5	-	-
2012	-	2	1	5	3	-
2011	-	4	1	9	2	-
2010	-	5	3	2	5	-
Total	-	44	29	55	22	-

Classification by Location

Regarding the location of the accidents (Figure 2), three cities emerged as they had the highest numbers of accidents as the other states which were Johor, Pulau Pinang and Kuala Lumpur, these numbers eventually led to noticeable results on which contributing factors could positively affect accident numbers.

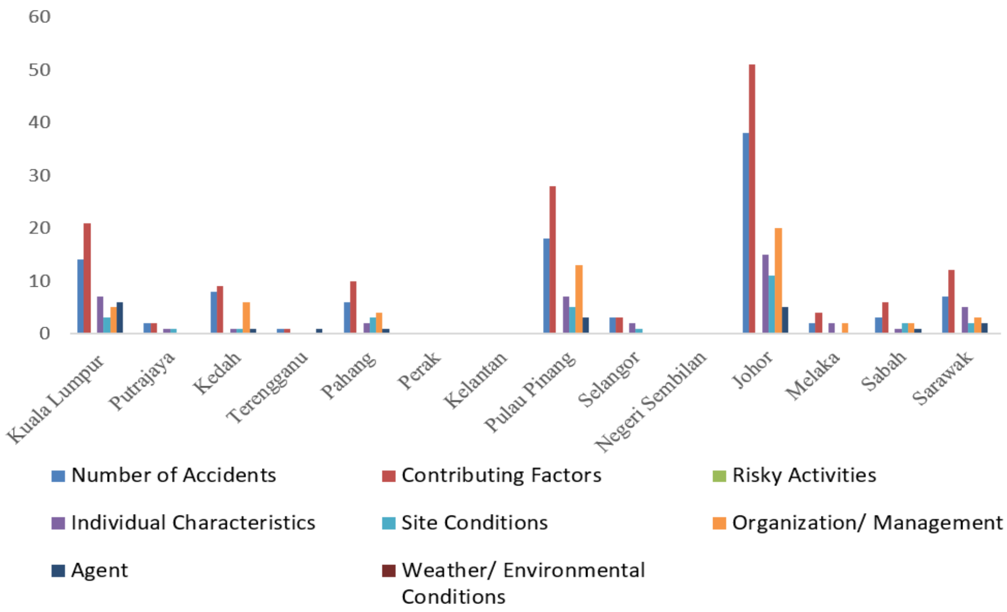

Figure 2. Malaysian data by location

Table 6 shows that Johor ranked the first with 38 accidents out of 105, a total of 36%, secondly came Pulau Pinang with 18 accidents; 17% of all accidents and third was Kuala Lumpur that contributed to 13% of all accidents which was 14 accidents. These numbers indicate that the focus to reduce the numbers of fatal accidents should be as these three states combined contributed to 66% of the total of accidents as in 70 accident in 9 years, the rest of the states had fewer accidents but it is not a major concern since the highest was 8 accidents in 9 years in Kedah, which is also one of the biggest states in Malaysia.

The size of the state is a major factor in accidents numbers since the budget will be bigger and therefore more projects which will eventually lead to increasing the workforce that will affect accident numbers and the factors contributing to them directly. The increase in accident numbers meant the increase in the contributing factors. Johor ranked first with 51 contributing factors for 38 accidents, which means 34% of all the contributing factors (Table 7). This indicates that an accident does not necessarily have to have only one factor but several factors possibly affecting the transformation from a near miss to a non-fatal or a fatal accident. Pulau Pinang was second with 19% with 28 factors for 18 accidents, an average of 1.5 factors for each accident.

Table 6
Malaysian data by location

Location	Number of Accidents	Contributing Factors
Kuala Lumpur	14	21
Putrajaya	2	2
Kedah	8	9
Terengganu	1	1
Pahang	6	10
Perak	-	-
Kelantan	-	-
Pulau Pinang	18	28
Selangor	3	3
Negeri Sembilan	-	-
Johor	38	51
Melaka	2	4
Sabah	3	6
Sarawak	7	12
Perlis	3	4
Total	105	151

The other locations lack the alarming accident numbers, which either means that falls from heights is not a major concern in these states or that there is a shortage of reporting accidents. These states most likely had small projects where a safety site supervisor was not a requirement by DOSH and the supervisor was the one that had to remind the workers of safety. In some cases, there was no supervision at all but it still provided necessary data that helped with identifying the contributing factors to fatal falls from heights. It could also indicate that Johor, Pulau Pinang and Kuala Lumpur had received more development projects during that time period, unlike the other states. The highest number for the contributing factors was either organization/management or individual characteristics, these two combined are 66% of all contributing factors, which highlight the main problem that was management involvement and human factors. While clearly in Johor and Pulau Pinang management was the main issue; Kuala Lumpur seemed to have a problem with human factors and the individual characteristics of the workers which could relate to (Zerguine et al., 2017).

Table 7

Classification of contributing factors based on Malaysian states

Location	Classification of Contributing Factors to Accidents		
	Risky Activities	Individual Characteristics	Site Conditions
Kuala Lumpur	7	7	3
Putrajaya	-	1	1
Kedah	-	1	1
Terengganu	-	-	-
Pahang	-	2	3
Perak	-	-	-
Kelantan	-	-	-
Pulau Pinang	-	7	5
Selangor	-	2	1
Negeri Sembilan	-	-	-
Johor	-	15	11
Melaka	-	2	-
Sabah	-	1	2
Sarawak	-	5	2
Perlis	-	1	-
Total	-	43	29

Table 7 *(Continued)*

Location	Classification of Contributing Factors to Accidents		
	Organization/ Management	Agent	Weather/ Environmental Conditions
Kuala Lumpur	6	-	-
Putrajaya	-	-	-
Kedah	6	1	-
Terengganu	-	1	-
Pahang	4	1	-
Perak	-	-	-
Kelantan	-	-	-
Pulau Pinang	13	3	-
Selangor	-	-	-
Negeri Sembilan	-	-	-
Johor	20	5	-
Melaka	2	-	-
Sabah	2	1	-
Sarawak	3	2	-
Perlis	1	2	-
Total	55	20	-

Management is considered a deeper factor since it does not affect accidents happening directly unlike other factors such as agent, site conditions. Human factors can be both a direct and indirect factor, this indicates how deep the issue on some states among others can be.

Analysis of USA Data

The same analysis in Malaysia was applied for the data collected from OSHA. A total of 101 workplace fatal accident reports due to falls from heights were analysed to determine which factor could affect the arising numbers of accidents by date, type of fall and time of fall (Table 8). Results found were identical to those from the analysed Malaysian data where management and individual characteristics could drastically affect accidents due to falls from heights.

Classification by Date

Table 8 shows that October 2017 had the highest number of accidents in the period of 6 months with 23 accident 22%, followed by December 2017 and November 2017 with

22 and 20 accidents respectively. On the other hand, February 2018 recorded the lowest number of accidents with 11 accidents followed by January 2018 with 12 and finally in March 2018 with 13 accidents as seen in Figure 3. What these numbers conclude is that the last months of the year are categorized in most the cases with the end of projects and employers need to catch deadlines by finishing the scheduled tasks before the end of the year. Rushing tasks could lead to neglecting safety rules and regulations which resulted in recording a higher number of accidents and factors leading to these accidents. It also means that employees are tired of working all year and trying to finish their tasks so they could enjoy their holiday earlier. Both human and managerial factors could be the results of the high numbers of accidents especially at the end of the year.

Table 8
USA data by date

Month/Year	Number of Accidents	Contributing Factors
March 2018	13	22
February 2018	11	18
January 2018	12	16
December 2017	22	29
November 2017	20	25
October 2017	23	32
Total	101	142

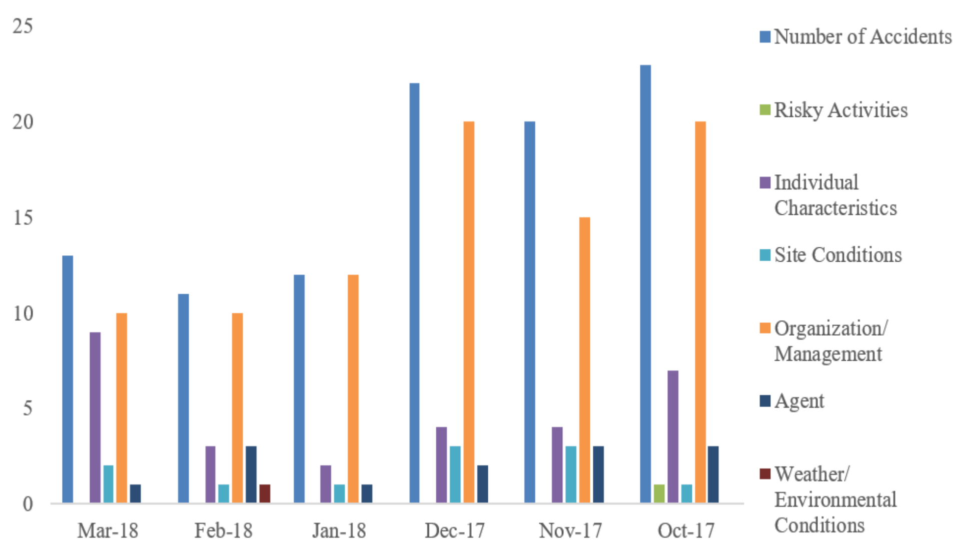

Figure 3. USA data by date

Table 9 also indicates that there was a considerable drop in accidents numbers by almost 50% from 22 accidents as an average in 2017 last quarter to 12 accidents as an average of 2018 first quarter. That is due to several reasons including that management did not rush projects deadlines as an urgent matter which proves more that management commitment has a direct effect in accident numbers. It also means that workers are back from their long year end holiday and that they got plenty of rest and spent time with their family which also are individual characteristics that share the same effect as management in controlling the numbers of accidents.

Management and individual factors such as scheduling work times, extra shifts and break periods could directly affect workers physically and mentally and reducing and increasing work stress which could have a positive effect on performing work safely.

Table 9

Classification of the USA contributing factors by date

Month/ Year	Classification of Contributing Factors to Accidents					
	Risky Activities	Individual Characteristics	Site Conditions	Organization/ Management	Agent	Weather/ Environmental Conditions
March 2018	-	9	2	10	1	-
February 2018	-	3	1	10	3	1
January 2018	-	2	1	12	1	-
December 2017	-	4	3	20	2	-
November 2017	-	4	3	15	3	-
October 2017	1	7	1	20	3	-
Total	1	29	11	87	13	1

Classification by Type of Fall

Table 10 presents the types of fall from heights which is a different type of data that is not available in reports extracted from the Malaysian reports. According to Table 10, falls from roofs are the most common type of accidents in the United States, with 43 out of 101 accidents (42%) in 6 months. Secondly comes scaffolds and ladders with 22 (21%) and 18 (17%) respectively. It is clear that the focus should be determining the factors affecting tasks performed on roofs where there is hardly any supervision or measures of preventing these falls. Rules and regulations by OSHA could be very beneficial but there is no follow up.

Table 10

The USA data by types of fall

Type of Fall	Number of Accidents	Contributing Factors
Roof	43	60
Ladder	18	22
Scaffold	22	35
Other	18	28
Total	101	145

Table 11 shows that management and individual characteristics are the main factors contributing to accidents with 60% and 20% respectively. Most roofing jobs are conducted by small and medium contractors where rules of safety are not as important as finishing the job early and get paid. Most clients do not bother to do a background check on safety records of contractors, unlike big companies that have a reputation to protect. Other types of fall are scaffolds and ladders which are what most workers use to perform work at height task. The contributing factors show that management and individual characteristics contribute to most of these accidents either by not supervising workers on roofs, scaffolds and ladders (Figure 4). If a worker is at one place for an extended period of time, he would lose his sense of direction and may blend with his surrounding environment that leads to loss of balance. Another cause could be vertigo as the workers fail to report that they have vertigo and management does not commit much to asking or performing the test on potential workers that would have to work at heights. Other factors could be neglected due to the minimal contribution to accidents numbers.

Table 11

Classification of the USA contributing factors by type

Type of Fall	Classification of Contributing Factors to Accidents					
	Risky Activities	Individual Characteristics	Site Conditions	Organization/ Management	Agent	Weather/ Environmental Conditions
Roof	-	10	6	39	4	1
Ladder	-	6	-	16	-	-
Scaffold	1	11	2	17	4	-
Other	-	3	4	16	5	-
Total	1	30	12	88	13	1

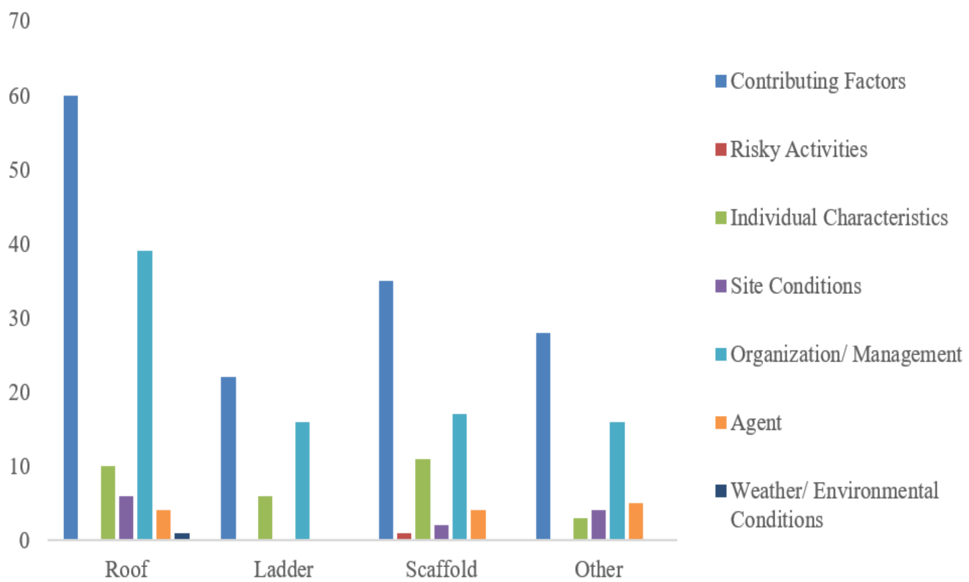

Figure 4. USA data by type of fall

Classification by the Time of Fall

Table 12 shows that fatal accidents occurred more frequently from 8 a.m. to 12 p.m. (42%), 12 p.m. to 4 p.m. (29%) and 4 p.m. to 8 p.m. (20%) than in other time periods. These periods could be considered the normal work period for most companies. The highest rates of accidents occurred at the beginning and middle job period, whereas the third time period may indicate the regular time table but it may also mean overtime or shift work (Figure 5). It is a clear indication that most supervisors do not bother doing the morning routine which is to check any changes on-site that happened overnight, performing their toolbox talks which work as a reminder for safety rules and as an induction to any changes on-site according to Huang and Hinze (2003), these daily supervisors tasks can be considered both managerial and human factors.

Table 12
The US data by time of fall

Time	Number of Accidents	Contributing Factors	Time	Number of Accidents	Contributing Factors
12 a.m. - 4 a.m.	1	1	4 p.m. - 8 p.m.	19	31
4 a.m. - 8 a.m.	2	3	8 p.m. - 12 a.m.	4	5
8 a.m. -12 p.m.	40	57	Total	94	135
12 p.m. - 4 p.m.	28	38			

Table 13 shows that the most influencing factors are management 57% and individual factors 19% of all contributing factors to accident numbers and that is due to the management work schedule and negligence of workers mental fatigue regardless of physical fatigue by forcing additional hours. This can lead to a case of work stress where the worker would either try to rush the task without paying attention to safety rules or that there is some site modification that happened overnight during a night shift or an after scheduled work hours. These changes, if not communicated correctly by management to workers, may lead to unwanted events such as fatal accidents especially if it involves work at heights activities according to Kaskutas et al. (2013).

Table 13
Classification of the USA contributing factors by time

Time	Classification of Contributing Factors to Accidents					
	Risky Activities	Individual Characteristics	Site Conditions	Organization/ Management	Agent	Weather/ Environmental Conditions
12 a.m. - 4 a.m.	-	-	-	1	-	-
4 a.m. - 8 a.m.	-	1	-	2	-	-
8 a.m. - 12 p.m.	1	10	6	35	5	-
12 p.m. - 4 p.m.	-	8	1	26	3	-
4 p.m. - 8 p.m.	-	8	3	16	3	1
8 p.m. - 12 a.m.	-	1	-	3	1	-
Total	1	28	10	83	12	1

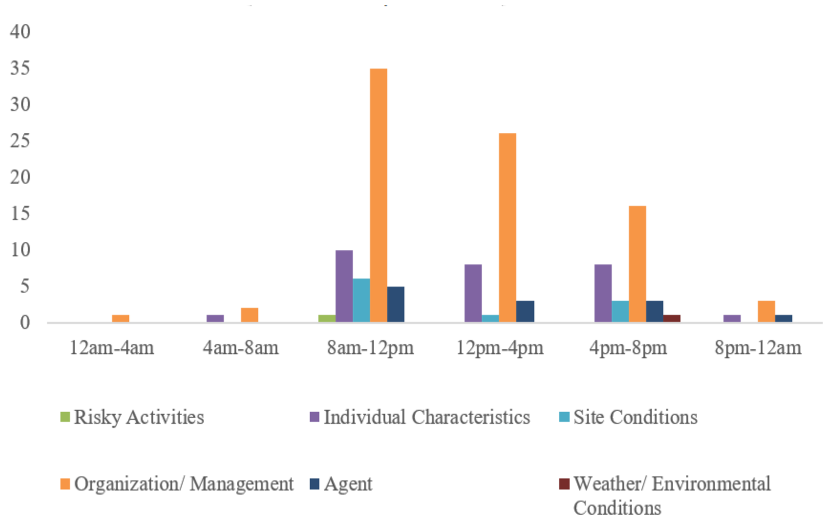

Figure 5. USA data by time of fall

It is fair to state that factors can positively or negatively affect the work environment by influencing accidents by turning near misses into an actual fatal or non-fatal accident. Management involvement in safety matters can directly affect what type of accidents happens and prevents fatal accidents from occurring by implementing an effective management system according to rules and regulations that are made through countless research such as by Ismail et al. (2012). Individual characteristics and human factors could also be an important factor to consider where a worker should be aware of his surroundings and have good safety awareness because safety is not just some rules to follow but a strong conviction that it is his ally.

Comparison between Malaysia and the USA Data

Malaysia and USA are two different countries, whether geographically or culturally. That does not necessarily mean that they do not share some common ground. Both Malaysia and the USA have high rates of fatal falls from heights (Malaysia Department of Occupational Safety and Health, 2018). Regardless of the size where the USA is larger than the size of Malaysia with 9,833,520 km^2 compared to 330,803 km^2 and a population where the USA is ten times the population of Malaysia with 327,167,434 million compared with 32,049,700 million. Despite these differences, Malaysia and the USA have both faced some challenges regarding falls from heights accidents; countless efforts went into trying to reduce fatal falls from heights that they proved to be a threat to be recognized.

Previous data showed in Table 4 indicated that the number of workplace fatal accidents due to falls from height happened in Malaysia in the past 9 years which was 105 accidents could occur in the USA in a period of only 6 months with 101 accidents due to the population and size of both countries. Regardless of that, the fatal falls from heights accidents percentage in Malaysia is higher than the one in the USA with 46% to 39%. The USA has more surface to cover and more individual projects to control, safety specialist will have a hard time to cover all that area, especially that most of the roofing projects will not last more than few weeks. The opposite goes for Malaysia, Johor as the largest state with recorded fatal accidents, does not have many small projects but many big developments according to Construction Industry Development Board (CIDB) which can be easier to control.

No matter what differences Malaysia and USA share, it is clear that falls from heights are a major concern for both countries according to yearly published reports by DOSH (Malaysia Department of Occupational Safety and Health, 2018) and OSHA (U.S. Bureau of Labour Statistics, 2018). Previous data show that both countries care a great deal for this challenge, both have dedicated administration specialized in workplace accident; DOSH in Malaysia and OSHA in the USA. Both administrations provided an open database for fatal accidents and produced countless rules and regulations in an effort to eliminate or at least minimize fatal accidents. The similarities between the two countries do not stop here, based on the analysed data from both Malaysia and USA, the two countries share the same two factors that can influence works at heights which are management and individual characteristics, no matter what type of data was analysed. For Malaysia, managerial factors recorded 55 factors compared with an average of 85 for the USA. Individual characteristics factor did not fall far from the tree wherein Malaysia it recorded an average of 43 compared with an average of 29 for the USA.

It is definite from the above results that Malaysia and the USA share common factors that could affect workplace fatal accidents due to falls from heights. Management involvement in safety matters and individual and human factors are the two most influencing factors in accidents happenings. Regardless of the types of data analysed, there is always an apparent indication that points towards management and individual factors. These two factors should be addressed immediately due to the effect they have on both workers and employer's moral, legal and economic costs.

CONCLUSION

Construction is one of the vital sectors in the international economy. Works at height are part of construction daily activities. Falls from heights accident is a problem that the construction sector is suffering from all over the world. It was necessary to address that problem in this research due to the increasing numbers of workplace falls from heights accidents. This study contributes to the body of knowledge by finding the contributing factors to fatal falls from heights accidents relying on two types of statistics produced by Malaysia and the USA. Based on the study of Malaysian and USA data, this study found that the two major factors that lead to fatal falls from heights accidents are managerial factors, that include sub-factors such as management involvement in safety, safety management systems, safety communications, work at heights safety equipment purchasing, supervision of employees, initial and pre-task training and safety culture within the company can greatly affect the occurrence of fatal accidents. By implementing an effective management system, fatal accidents can easily change into a non-fatal or near misses. Human factors and individual characteristics of workers are the second-highest contributing factors and go hand by hand with managerial factors. Another outcome of the study is that fatigue could greatly affect workplace accidents, not just physical fatigue but also mental fatigue. Future studies should focus on both managerial and human factors, this study was conducted based on the reports published by only two countries. The reports used in this study had limited descriptions. The study focused only on fatal accidents due to falls from heights.

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Optimum Plant Design for Relief Safety System

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ABSTRACT

Pressure relief system is a system to prevent overpressure inside protected equipment that exceeds its maximum allowable working pressure (MAWP) to disposal treatment. Relief system is designed on two different plant case studies, which are dimethyl-ether and ethylbenzene plants by using conventional design procedure. Nevertheless, the conventional design steps are not considering cost optimization of plant installed with relief system. Thus, the design pressure of protected equipment, piping diameter, and disposal treatment is set to be manipulated variables to determine the cost minimization. Pressure drops of inlet piping and backpressure are as constraint variables due to standard requirements. The standards state that inlet piping pressure drops should be below 3% of set pressure and outlet piping pressure drop to set pressure percentage based on range to determined types of the relief valve to be used. From that, optimum plant design with consideration of pressure relief system's installation can be achieved by calculating the total cost of plant designed with relief system when set pressures are changed. As a result, dimethyl-ether plant shows a minimum point of the total cost at 170% of set pressure increment, which is lower than its original design. On the other hand, ethylbenzene plant gives optimum point at original design as the total cost is higher at set pressure increment.

Keywords: Dimethyl-ether, ethylbenzene, plant optimization, relief system, set pressure variation

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INTRODUCTION

Background of Study

Pressure relief system is a preventive system to encounter excessive pressures inside pipelines and equipment. The system is designed to automatically relieve liquids or gases to atmosphere or any safe locations depending on properties of discharge materials and close when the pressure is back to the normal condition (Patil & Sondur, 2013). The excessive pressures are mainly due to some reasons such as blocked-outlet, exposed to external fire, thermal expansion, runaway chemical reaction, heat exchanger tube rupture, and cooling system failure (Hellemans, 2009). Pressure relief system consists of pressure relief devices, piping and downstream process equipment to the safe handling process of materials discharged, as shown in Figure 1. Locating relief devices are based on definitive guidelines (Crowl & Louvar, 2011), which pressure relief devices are located at any possible pressure accumulation due to operating failure in the plant. Several scenarios are listed that contribute to overpressure problem and the worst-case is chosen as the governing scenario by comparing the venting area required to reduce the excessive pressure. The sizes of relief devices can be computed by determined relief loads of discharged materials, the physical states of the fluids, and its relieving conditions. In the normal conceptual design of a safety relief system (Crowl & Louvar, 2011) however, consideration of the optimum cost of the plant with pressure relief system installation has been neglected.

Thus, optimum design of plant and pressure relief system is being considered by manipulating design pressure of equipment-also called as relief device's set pressure, sizes of piping diameter and disposal treatment design. As for project case studies, dimethyl-ether (DME) and ethylbenzene (EB) plants are being used.

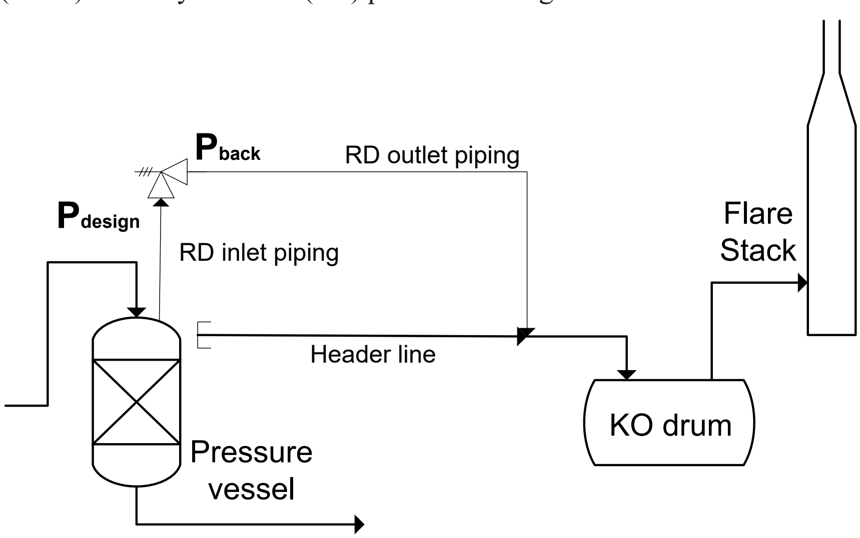

Figure 1. Typical relief system

Problem Statement

This project is proposed to provide an alternative approach to the conventional method of relief and flare system design. In the conventional method, process engineers already decide the design and the set pressure based on the mass balances without considering any cost calculation. This current work aims to include the cost calculation in the design where an optimum set pressure is going to be found that lead to minimum plant cost regarding this safety feature. This study covers the design of the relief system, cost estimations, and varying the design pressure and hence, the set pressure of the relief valves, calculation of backpressure and disposal treatment design to minimize the plant overall cost. The total cost of plant designed, which is the summation of costs including relief device, disposal treatment and protected equipment. Changes of the design pressure of protected equipment will be affecting pressure drops the percentage of inlet piping and backpressure of relief device which are associated with the changes of piping size, equipment strength and Knock-Out (KO) drum. Therefore, the cost of equipment, KO drum and piping is changing. From the manipulative actions, the most optimum plant design with the relief system is chosen based on the most economical total costs calculated.

MATERIALS AND METHODS

The methodology of the project is illustrated in flowchart form in Figure 2.

Relief Sizing

Possible scenarios are listed on located relief device, while calculation of relief loads and relief sizing is referring to American Petroleum Institute Standards, API RP 520 Part I and API Std 521 (API RP 520 Part I & Part II, 2011), based on relieving scenarios and flow states. Data of plants' streams were from iCON process simulation-main reference (Turton, 2012).

Backpressure was calculated as in Equation (1) and pressure drops across piping using Darcy-Weishbach Equation, Equation (2), where the pressure of KO-drum is set at 1.1 barg.

$$P_{back} = P_{at\ KO\ drum} + \Delta P_{across\ outlet-piping} \tag{1}$$

$$\Delta P = f_D \frac{L}{D} \frac{\rho v^2}{2} \tag{2}$$

Relief Downstream Design

The worst-case scenario for each relief valve was selected based on the biggest venting area calculated. Thus, the design of the relief downstream system was focused on these worst scenarios. The calculation to design knock-out (KO) drum and flare were referred to API Std 521 (American Petroleum Institute, 2014).

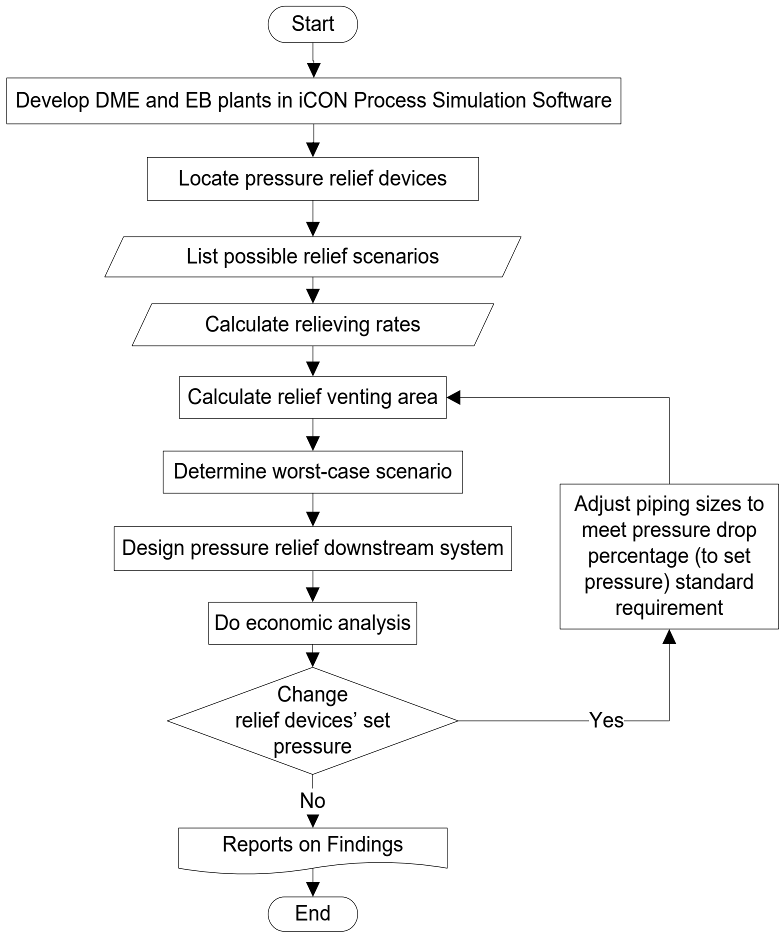

Figure 2. Project methodology

Economic Analysis

Total plant cost was done on the actual plant with relief system design as basis value for analysis. Set pressure of each relief valves was increased by a certain percentage to study the sensitivity of cost elements and total plant cost towards the changes. Equipment cost was estimated using CAPCOST BETA Spreadsheet, available at https://www.eng.famu.fsu.edu/~palanki/design/lectures/CAPCOST/CAPCOST.XLS, with CEPCI value of 591.335 (Jenkins, 2018), flare costing (Stone et.al., 1992) as in Equation (3), while, piping cost and relief valve were referred to products catalogue, US Pipe Fabrication (U.S. PIPE, 2018) and Flomatic Valves (FOLOMATIC, 2020).

$$C_F(\$) = (78.0 + 9.14D + 0.749L)^2 \tag{3}$$

RESULTS AND DISCUSSION

Relief Sizing

Relief valves were located on DME and EB plants and possible scenarios contributed to pressure built-up were determined. The locations are as in Figure 3 and Figure 4.

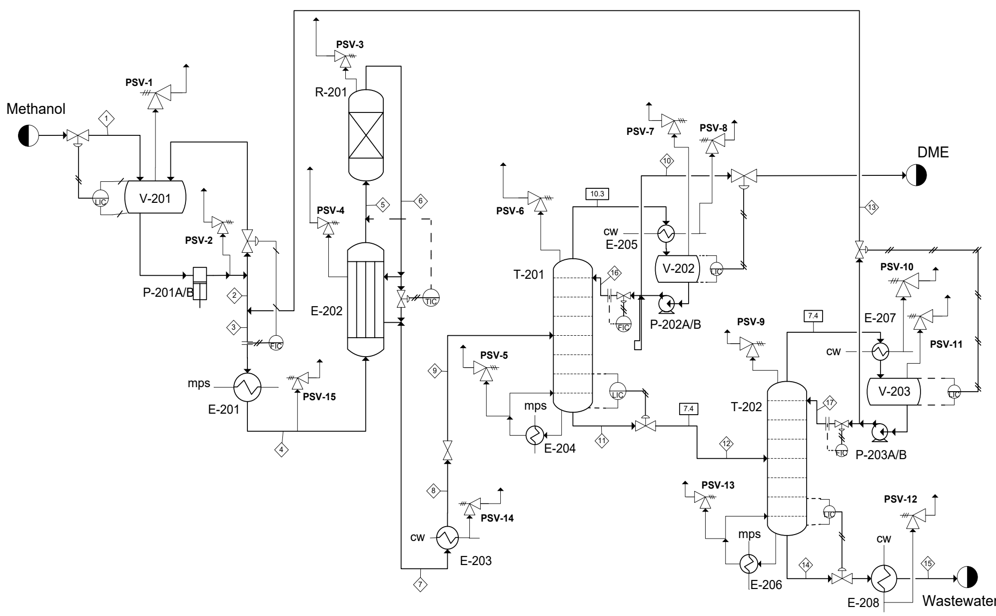

Figure 3. Relief valves location on DME plant

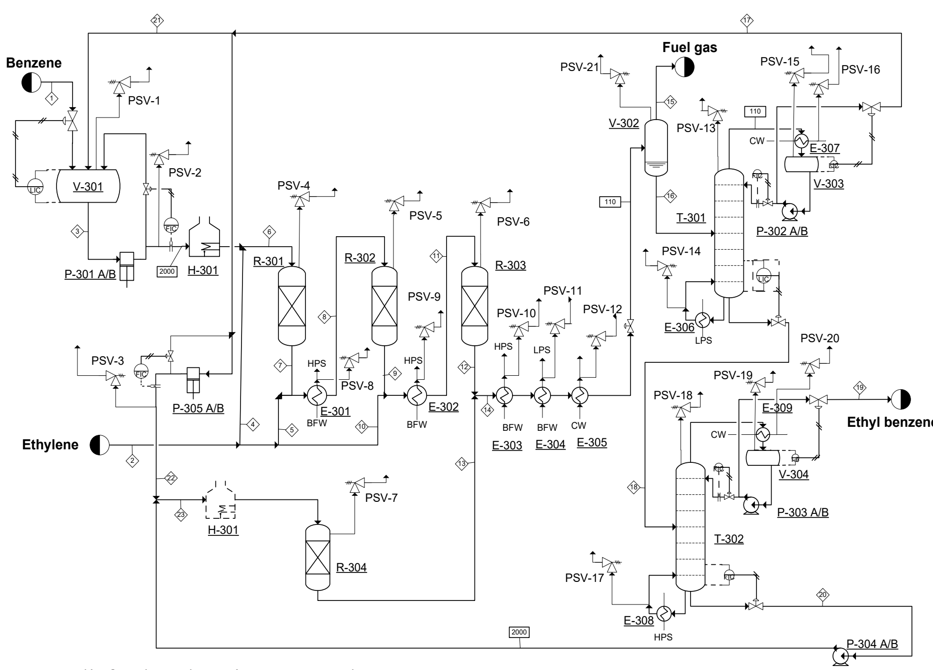

Figure 4. Relief valves location on EB plant

Relief sizing for all possible scenarios of each relief valves is summarized in Table 1 and Table 2 for the DME and EB plants, respectively.

Table 1
The possible and worst-case scenario for each relief valves on DME plant

PRV[1]	PE[2]	Possible scenario	Area (in^2)	Worst-case scenario
1	V-201	Fire Case	0.59	Automatic Control Failure
		Automatic Control Failure	1.18	
		Overfilling storage	1.18	
2	P-201 A/B	Closed-outlet	0.09	Closed-outlet
3	R-201	Chemical reactions	2.71	Chemical reactions
		Abnormal Process Heat Input	2.70	
4	E-202	Abnormal Process Heat Input	2.50	Abnormal Process Heat Input
		Heat-exchanger equipment failure	0.01	
5	E-204-Cold stream	Abnormal Process Heat Input	0.37	Abnormal Process Heat Input
		Hydraulic expansion	0.01	
		Closed-outlet at bottom T-201 outflow	0.05	
6	T-201	Accumulation of non-condensable at condenser	1.24	Accumulation of non-condensable at condenser
		Cooling failure of condenser	1.24	
		Top-tower reflux failure	1.24	
7	V-202	Closed-outlet	0.11	Cooling failure of condenser
		Cooling failure of condenser	0.53	
		Overfilling storage	0.19	
8	E-205 CW[3]stream	Abnormal Process Heat Input	0.41	Abnormal Process Heat Input
		Hydraulic expansion	0.01	
9	T-202	Accumulation of non-condensable at condenser	1.48	Accumulation of non-condensable at condenser
		Cooling failure of condenser	1.48	
		Top-tower reflux failure	1.48	

Table 1 (Continued)

PRV[1]	PE[2]	Possible scenario	Area (in^2)	Worst-case scenario
10	E-207 CW stream	Abnormal Process Heat Input	0.98	Abnormal Process Heat Input
		Hydraulic expansion	0.01	
		Cooling failure of condenser	1.49	
		Overfilling storage	0.09	
11	V-203	Closed-outlet on vessel	0.09	Cooling failure of condenser
		Cooling failure of condenser	1.49	
		Overfilling storage/ surge vessel	0.09	
12	E-208 CW Stream	Abnormal Process Heat Input	0.19	Abnormal Process Heat Input
		Hydraulic expansion	0.00	
13	E-206 Cold stream	Abnormal Process Heat Input	0.76	Abnormal Process Heat Input
		Hydraulic expansion	0.01	
		Closed-outlet at bottom T-202 outflow	0.03	
14	E-203 CW stream	Abnormal Process Heat Input	0.28	Abnormal Process Heat Input
		Hydraulic expansion	0.00	
15	E-201 Cold stream	Abnormal Process Heat Input	2.00	Abnormal Process Heat Input
		Hydraulic expansion	0.08	

Notes: [1] Pressure relief valve, [2] Protected equipment, [3] Cooling water

Table 2

Possible and worst-case scenarios for each relief valves on EB plant

PRV	PE	Possible scenario	Area (in^2)	Worst-case scenario
1	V-301	Fire Case	0.47	Automatic Control Failure
		Automatic Control Failure	0.54	
		Overfilling storage	0.54	
2	P-301 A/B	Closed-outlet	0.16	Closed-outlet
3	P-305 A/B	Closed-outlet	0.03	Closed-outlet

Table 2 *(Continued)*

PRV	PE	Possible scenario	Area (in^2)	Worst-case scenario
1	V-301	Fire Case	0.47	Automatic Control Failure
		Automatic Control Failure	0.54	
		Overfilling storage	0.54	
2	P-301 A/B	Closed-outlet	0.16	Closed-outlet
3	P-305 A/B	Closed-outlet	0.03	Closed-outlet
4	R-301	Chemical reactions	2.80	Abnormal Process Heat Input
		Abnormal Process Heat Input	2.81	
5	R-302	Chemical reactions	2.72	Chemical reactions
6	R-303	Chemical reactions	2.77	Chemical reactions
7	R-304	Chemical reactions	0.88	Abnormal Process Heat Input
		Abnormal Process Heat Input	8.56	
8	E-301 BFW[4] stream	Abnormal Process Heat Input	0.16	Abnormal Process Heat Input
		Hydraulic expansion	0.00	
9	E-302 BFW stream	Abnormal Process Heat Input	0.18	Abnormal Process Heat Input
		Hydraulic expansion	0.00	
10	E-303 BFW stream	Abnormal Process Heat Input	0.77	Abnormal Process Heat Input
		Hydraulic expansion	0.01	
11	E-304 BFW stream	Abnormal Process Heat Input	1.04	Abnormal Process Heat Input
		Hydraulic expansion	0.02	
12	E-305 CW stream	Abnormal Process Heat Input	0.40	Abnormal Process Heat Input
		Hydraulic expansion	0.01	
13	T-301	Accumulation of non-condensable	6.45	Accumulation of non-condensable
		Cooling failure	6.45	
14	E-306 Cold stream	Abnormal Process Heat Input	12.31	Abnormal Process Heat Input
		Hydraulic expansion	0.14	
		Blocked-outlet at bottom of T-301	0.41	
15	V-303	Blocked-outlet	0.46	Cooling failure
		Cooling failure	6.37	
		Overfilling storage	0.46	
16	E-307 CW Stream	Abnormal Process Heat Input	3.03	Abnormal Process Heat Input
		Hydraulic expansion	0.04	

Table 2 *(Continued)*

PRV	PE	Possible scenario	Area (in^2)	Worst-case scenario
17	E-308 Cold Stream	Abnormal Process Heat Input	8.41	Abnormal Process Heat Input
		Hydraulic expansion	0.08	
		Blocked-outlet at bottom of T-302	0.06	
18	T-302	Accumulation of non-condensable	4.76	Accumulation of non-condensable
		Cooling failure	4.76	
19	V-304	Blocked-outlet	0.42	Cooling failure
		Cooling failure	4.76	
		Overfilling storage	0.42	
20	E-309 CW Stream	Abnormal Process Heat Input	2.13	Abnormal Process Heat Input
		Hydraulic expansion	0.03	
21	V-302	Overfilling storage	0.71	Overfilling storage
		Fire Case	0.33	

Notes: [4] Boiler feed water

Worst-case scenarios relief system details for the DME and EB plants are tabulated in Table 3 and Table 4, respectively.

Relief Downstream System

Relief downstream system consisted of RV outlet piping, KO drum and flare which required to safe handling relieving materials. Thus, the design of the KO drum and flare was based on worst vapour and the liquid case of scenarios. The design is tabulated in Table 5.

Economic Analysis

An economic analysis of actual designs was performed to be used as baseline values. As a side note, 100% increment was the actual set pressure of the plants. Results and discussion of economic analysis are summarized and illustrated in Table 6 and Table 7.

Based on the obtained data, graphs of elements' cost and total cost were plotted for both plants. As illustrated, along with setting pressure increment, costs of piping and flare were deflating while costs of the protected equipment and KO drum were inflating, refer to Figure 5 and Figure 6.

Table 3
Relief sizing for DME plant, header diameter is set at 350 mm

PSV	Protected equipment	Worst-Case Scenario	W kg/h	T_{relief} °C	P_{relief} bar	P_{set} bar	Piping Diameter D_{inlet} mm	Piping Diameter D_{outlet} mm	%PD $_{inlet}$	%PD $_{outlet}$	Relief Device Type	A in^2
1	V-201	Automatic Control Failure	8370.00	69.06	1.21	1.10	150	250	1.59	3.32	Conventional	1.18
2	P-201A/B	Closed outlet at piping	8370.00	159.15	17.05	15.50	100	150	2.14	5.17	Conventional	0.09
3	R-201	Chemical reactions	10490.00	400.00	16.17	14.70	250	400	2.26	7.70	Conventional	2.71
4	E-202	Abnormal Process Heat Input	10490.00	400.00	16.50	15.00	250	350	2.84	10.10	Balanced-Bellow	2.50
5	E-204 - Cold stream	Abnormal Process Heat Input	1331.68	173.70	12.10	11.00	125	200	1.97	2.57	Conventional	0.37
6	T-201	Accumulation of non-condensable at condenser	8140.00	51.95	11.66	10.60	200	300	2.33	7.61	Conventional	1.24
7	V-202	Cooling failure of condenser	8140.00	50.81	11.33	10.30	200	350	2.40	4.14	Conventional	0.53

Table 3 *(Continued)*

PSV	Protected equipment	Worst-Case Scenario	W kg/h	T_{relief} °C	P_{relief} bar	P_{set} bar	Piping Diameter D_{inlet} mm	Piping Diameter D_{outlet} mm	%PD $_{inlet}$	%PD $_{outlet}$	Relief Device Type	A in^2
8	E-205 CW stream	Abnormal Process Heat Input	1391.36	183.68	11.00	10.00	150	200	1.28	8.06	Conventional	0.41
9	T-202	Accumulation of non-condensable at condenser	5750.00	129.87	8.36	7.60	250	350	1.50	7.83	Conventional	1.48
10	E-207 CW stream	Abnormal Process Heat Input	2640.92	168.51	7.70	7.00	200	300	2.19	8.30	Conventional	0.98
11	V-203	Cooling failure of condenser	5750.00	128.36	8.03	7.30	250	350	1.51	9.13	Conventional	1.49
12	E-208 CW Stream	Abnormal Process Heat Input	531.73	174.06	8.80	8.00	125	150	1.07	4.78	Conventional	0.19
13	E-206 Cold stream	Abnormal Process Heat Input	2572.57	187.73	12.10	11.00	200	250	0.86	4.82	Conventional	0.76
14	E-203 CW stream	Abnormal Process Heat Input	1103.34	199.10	15.40	14.00	125	150	1.48	4.38	Conventional	0.28
15	E-201 Cold stream	Abnormal Process Heat Input	12959.11	157.77	16.50	15.00	250	350	1.88	8.68	Conventional	2.00

Table 4

Relief sizing for EB plant, header diameter is set at 900 mm

PSV	Protected equipment	Worst-Case Scenario	W kg/h	T_{relief} °C	P_{relief} bar	P_{set} bar	Piping Diameter		%PD inlet	%PD outlet	Relief Device Type	A in^2
							D_{inlet} mm	D_{outlet} mm				
1	V-301	Automatic Control Failure	17952.20	117.04	2.75	2.50	200	300	0.73	9.66	Conventional	0.54
2	P-301 A/B	Closed outlet	17952.20	227.90	21.84	19.85	125	250	1.27	3.38	Conventional	0.16
3	P-305 A/B	Closed outlet	3130.60	228.25	22.00	20.00	65	100	2.38	5.69	Conventional	0.03
4	R-301	Abnormal Process Heat Input	18797.90	480.00	24.20	22.00	200	350	2.34	7.75	Conventional	2.81
5	R-302	Chemical reactions	19784.70	500.00	24.20	22.00	200	350	2.31	8.57	Conventional	2.72
6	R-303	Chemical reactions	20771.50	500.00	24.20	22.00	200	350	2.39	8.76	Conventional	2.77
7	R-304	Abnormal Process Heat Input	4616.50	525.00	24.20	22.00	300	450	0.02	0.04	Conventional	1.03
8	E-301 BFW stream	Abnormal Process Heat Input	871.59	221.71	24.20	22.00	80	125	1.24	5.22	Conventional	0.16

Table 4 *(Continued)*

PSV	Protected equipment	Worst-Case Scenario	W kg/h	T_{relief} °C	P_{relief} bar	P_{set} bar	Piping Diameter D_{inlet} mm	Piping Diameter D_{outlet} mm	$\%PD_{inlet}$	$\%PD_{outlet}$	Relief Device Type	A in^2
9	E-302 BFW stream	Abnormal Process Heat Input	1148.54	221.71	24.20	22.00	80	125	2.15	9.80	Conventional	0.18
10	E-303 BFW stream	Abnormal Process Heat Input	4466.53	221.71	24.20	22.00	150	250	1.40	7.18	Conventional	0.77
11	E-304 BFW stream	Abnormal Process Heat Input	5479.92	221.71	24.20	22.00	150	300	2.11	4.36	Conventional	1.04
12	E-305 CW stream	Abnormal Process Heat Input	2190.28	221.71	24.20	22.00	100	200	2.56	5.30	Conventional	0.40
13	T-301	Accumulation of non-condensable	18482.25	125.28	3.30	3.00	400	600	1.84	33.82	Balanced-Bellow	6.45
14	E-306 Cold stream	Abnormal Process Heat Input	26850.37	176.59	2.20	2.00	500	750	2.33	21.31	Balanced-Bellow	12.31
15	V-303	Cooling failure	18482.25	125.28	3.30	3.00	400	600	1.95	32.20	Balanced-Bellow	6.37
16	E-307 CW Stream	Abnormal Process Heat Input	3224.05	123.15	2.20	2.00	300	600	2.43	9.14	Conventional	3.03

Table 4 *(Continued)*

PSV	Protected equipment	Worst-Case Scenario	W kg/h	T_{relief} °C	P_{relief} bar	P_{set} bar	Piping Diameter D_{inlet} mm	Piping Diameter D_{outlet} mm	$\%PD_{inlet}$	$\%PD_{outlet}$	Relief Device Type	A in^2
17	E-308 Cold Stream	Abnormal Process Heat Input	15485.01	216.90	2.20	2.00	400	500	2.09	37.75	Balanced-Bellow	8.41
18	T-302	Accumulation of non-condensable	15841.71	186.63	3.30	3.00	350	750	2.20	6.84	Conventional	4.76
19	V-304	Cooling failure	15841.71	186.63	3.30	3.00	350	750	2.20	6.96	Conventional	4.76
20	E-309 CW Stream	Abnormal Process Heat Input	2331.63	123.15	2.20	2.00	300	600	1.27	4.47	Conventional	2.13
21	V-302	Overfilling storage/ surge vessel	25387.90	60.68	2.75	2.50	200	350	1.37	5.02	Conventional	0.71

Table 5

Relief downstream design

Plant		DME	EB
KO Drum	Length (m)	3.0	3.5
	Diameter (m)	1.7	2.5
	Materials of Construction	SS	SS
	Design Pressure (Barg)	16.5	24.2
Flare	Stack Diameter (m)	0.26	0.29
	Stack Height (m)	50.00	100.00
	Minimum distance from the epicentre of the flame to the object considered (m)	568.83	1104.46
	Grade distance from flare (m)	575.90	1117.40

Table 6

DME's cost fluctuation due to set pressure increment, in mil RM

P_{set} Increment	Piping Cost	PRV cost	PE Cost	KO Drum Cost	Flare Cost	Total Cost
100%	1.969	0.122	1.388	0.207	0.373	4.061
110%	1.969	0.122	1.388	0.219	0.373	4.073
130%	1.836	0.123	1.422	0.269	0.379	4.028
170%	1.675	0.123	1.465	0.343	0.361	3.966
200%	1.593	0.123	1.496	0.395	0.359	3.967
230%	1.520	0.123	1.527	0.566	0.361	4.096
300%	1.455	0.123	1.598	0.566	0.352	4.093

Table 7

EB's cost fluctuation due to set pressure increment, in mil RM

P_{set} Increment	Piping Cost	PRV Cost	PE Cost	KO Drum Cost	Flare Cost	Total Cost
100%	12.277	0.291	7.260	0.694	0.789	21.311
110%	13.335	0.245	7.583	0.754	0.780	22.697
120%	13.244	0.233	7.913	0.814	0.807	23.011
130%	13.105	0.225	8.250	0.874	0.807	23.263
140%	12.882	0.218	8.595	0.934	0.807	23.436
150%	11.670	0.212	8.947	0.994	0.807	22.632
155%	11.445	0.210	9.126	1.025	0.808	22.615
160%	11.445	0.209	9.307	1.055	0.818	22.833

Table 7 *(Continued)*

P_{set} Increment	Piping Cost	PRV Cost	PE Cost	KO Drum Cost	Flare Cost	Total Cost
170%	11.496	0.205	9.674	1.115	0.818	23.308
180%	11.431	0.203	10.049	1.175	0.818	23.675
200%	10.230	0.197	10.820	1.296	0.818	23.360
210%	10.113	0.195	11.217	1.357	0.818	23.700
220%	10.054	0.194	11.621	1.417	0.818	24.105

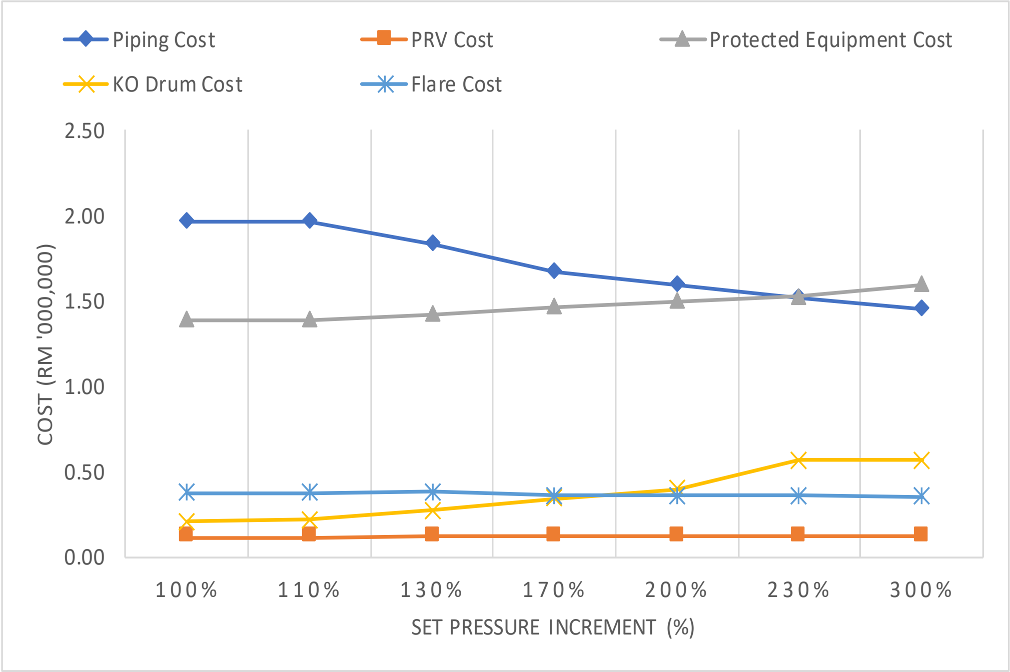

Figure 5. Elements' cost inflation and deflation with an increment of set pressure for DME plant.

This can be explained, when the set pressure is increased, more tolerable pressure drops across piping is acceptable to have within the allowable percentage of pressure drop to set pressure, Equation (4). Therefore, the piping diameter was altered to be smaller than actual design and it reduced the cost of piping. On the other hand, when the set pressure was increased, the design pressure of protected equipment was also increased to withstand higher pressure than the usual design. Hence, its price was raised. Same goes to KO drum, which was designed to withstand the maximum pressure of vapour case. Thus, design pressure of the drum was changed and so did its cost.

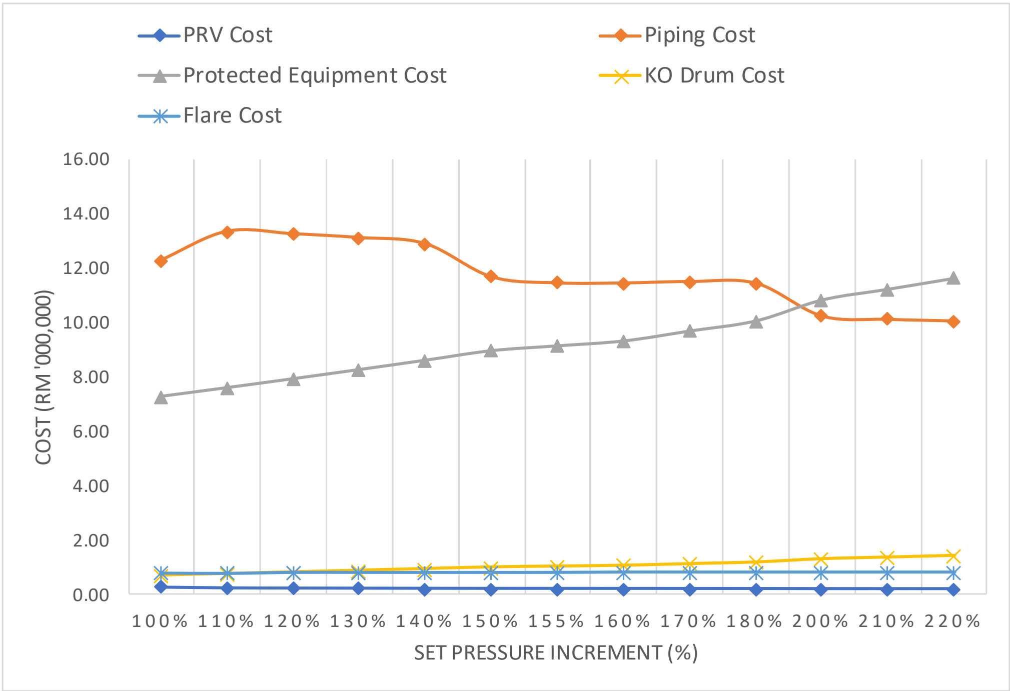

Figure 6. Elements' cost inflation and deflation with an increment of set pressure for EB plant

$$P_{drop}\% = \frac{P_{drop}}{P_{set}} \times 100\% \tag{4}$$

However, the trend of PRV costs behaved differently between the DME plant and EB plant. PRV cost of DME plant was slightly increasing while EB plant was slightly reducing when the set pressure was increased. The reason is PRV sizing (refer to relief sizing Equation (American Petroleum Institute, 2000)) is depending on two variables, upstream pressure, P_1 and backpressure, P_2 of PRV. Thus, the sizing is affected by domineering of these two variables. For case 1, when upstream pressure was dominant, increases of upstream pressure would reduce the size of the relieving area, thus reducing the PRV cost. In contrast, case 2 was when backpressure was more dominant than upstream pressure, increases of backpressure resulting increased of relieving area. For a side note, the backpressure was increased when pressure drops throughout the piping were raised throughout reducing of piping diameter process. So, by looking at the trends given by both plants, PRV cost of DME is falling under case 2 while PRV cost of EB is case 1.

Following, the total cost of DME and EB plants are plotted as in Figure 7 and Figure 8. As for the DME plant, it shows good expecting results when setting pressure was changed. In Figure 7, it shows that at 170% increment of set pressure, the total cost of the plant was at the minimum point compared to other increments including the original plant's cost. Despite DME plant's result, the minimum point of EB plant remained at the actual design of the plant even though there was a peak at range of 150% to 155%, but it was not the lowest point compared to the original design. In conclusion, EB actual plant design is the optimum design and does not require to increase set pressure of all PRVs to have lower total cost while DME shows its optimum plant design at set pressure increment of 170%.

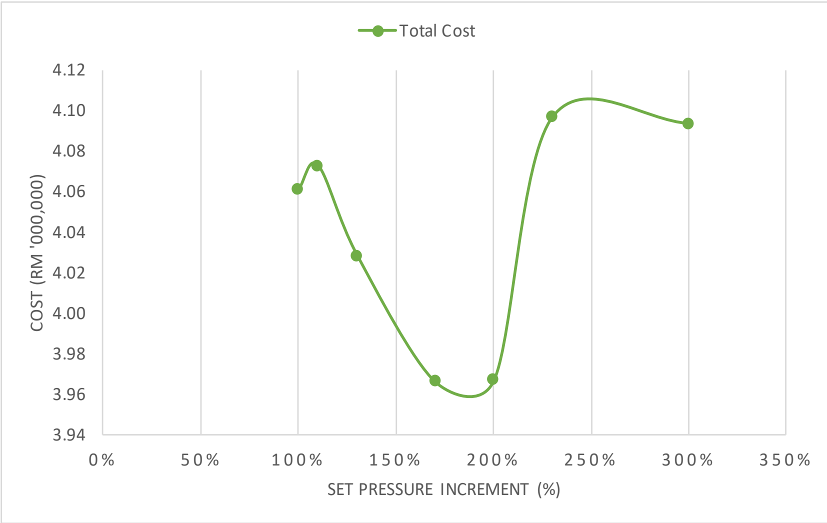

Figure 7. Changes of DME plant's total cost vs increment of set pressure

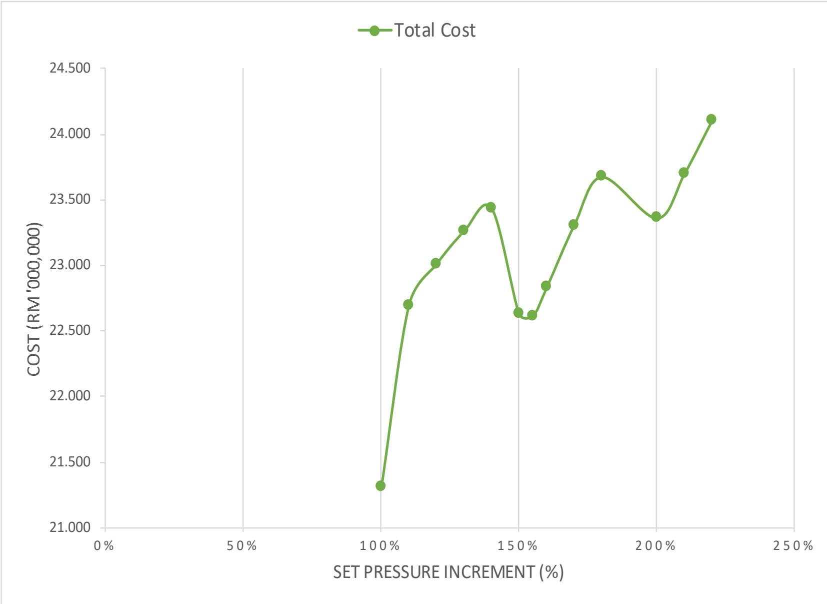

Figure 8. Changes of EB plant's total cost vs increment of set pressure

CONCLUSION

Pressure relief system is a precautionary system towards unwanted incidence inside the plant which dealing with excessive pressure built inside the plant system. The system consists of a relief device, piping and disposal system. In this project, the pressure relief system is designed by using a different approach than the conventional method. The different approach is by increasing pressure for protected equipment, changes of backpressure of PRV and disposal system design. The manipulation process affects the total cost of plant design due to higher allowable pressure drops across piping hence, the smaller pipe diameter is required and increase of protected equipment cost due to increment of design pressure. From that, a comparison of DME's total cost gives a minimum point at 170% of set pressure increment. On the other hand, EB plant's minimum point is at the original plant design despite a low peak at range of 150% to 155%, which still has a higher cost than the original design.

Recommendation

Based on the study done, there is an issue to determine a reasonable interval of set pressure increment which is to be implemented in industrial equipment design. This is because increasing the design pressure of equipment for optimization of the relief system may not be feasible anymore when the set pressure is increased further. Secondly, we recommend postulating a maximum point of pressure increment for feasible relief system.

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Evaluation of Plated versus Grated Process Deck in Floating Production Storage and Offloading (FPSO) from Explosion Perspective using SAFETI OFFSHORE

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ABSTRACT

Vapor cloud explosion is one of the major threats to Floating, Production, Storage and Offloading (FPSO) facilities due to its congested and confined nature. Reduction in explosion overpressure can be achieved by improving the ventilation in FPSO. During early design stage of FPSO, designers consider providing grated process decks to improve the ventilation. However, there is limited research on the comparison of the explosion overpressure between the grated deck and the traditional plated deck. In this study, Vapor Cloud Explosion perspective of plated versus grated process deck in typical FPSO was evaluated by utilizing Det Norske Veritas's (DNV) SAFETI OFFSHORE modelling tool. Representative leak scenarios were selected based on frequency analysis of major accident hazards associated with typical FPSO facility. This study revealed that the overpressure exceedance frequency in plated process deck was higher than the grated process deck for the selected scenario. This serves as quantitative guidance for designers to select an inherently safer type of decks in FPSOs from explosion perspective during the preliminary design stage. However, a detailed Computational Fluid Dynamics (CFD) study is recommended to get an insight of dangers associated with the presence of plated and grated process decks in FPSO, by considering all the parameters and conditions applicable.

Keywords: Grated deck, hazard identification, plated deck, Vapor Cloud Explosion

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INTRODUCTION

Nowadays, Floating Production Storage and Offloading (FPSO) systems are the preferred choice of offshore operators due to its suitability for marginal fields, mild & harsh marine environments. The topside process modules in FPSO are mostly open and aids ventilation of potentially flammable gas from accidental release. However, congestion and confinement in FPSO topsides make it prone to significant Vapor Cloud Explosion (VCE) loads. When flammable materials released to the atmosphere, dispersed and found ignition source after some time delay, will result in VCE. The main factors determining the consequences of VCE are the type of fuel, ignition source, cloud size, turbulence, confinement, and weather.

Type of Fuel

To form a vapour cloud, the released material must be inflammable and at suitable concentrations in atmosphere between Lower Explosive Limit (LEL) and Upper Explosive Limit (UEL) (Nolan, 2018).

Ignition Source

To initiate the explosion, an ignition source is required. More severe explosions may result from higher energy ignition sources compared to lower energy ignition sources.

Cloud Size

VCE results only when the adequate size of flammable vapour cloud is formed before ignition, otherwise the ignition results in a large fire, jet flame or fireball. VCE was analysed and found delay times from 6s to as long as 60 min. The study on historical data on ignition delays, reveals that ignition delays from 1 to 5 min is enough for generating the most probable vapour cloud explosion (Lenoir & Davenport, 1992).

Turbulence

For the VCE to occur, the flame front should accelerate at specific speeds, this depending on turbulence inside the vapour cloud. Interactions of flame front with obstacles such as process equipment, pipe rack and structures result in turbulence. The explosion overpressure and the flame speed are directly proportional to each other. The flame speed influences the blast overpressure strongly. In the absence of turbulence, under laminar or near-laminar conditions, flame speeds are too low to produce significant blast overpressure.

Confinement

A rapid increase in explosion overpressure results when the cloud is confined by obstacles, during combustion. The degree of confinement in FPSOs, with their congested equipment topside modules layout and structures, is usually high which makes it more prone to VCE.

Weather

Stable atmospheres lead to large vapour clouds. The Pasquill stability classes, neutral-D, slightly stable-E and stable-F leads to very large vapour clouds.

VCE is not the prominent hazard which influences the concept selection decision, but this is the foremost concern from fire accidental events perspective. After Piper Alpha Disaster on July 6th, 1988, the offshore industry is more focus on preventing, reducing and eliminating the probability of the fire and explosion. But still, accidents occur. There are about 14 explosions and 257 fire incidents were reported at floating units in the United Kingdom continental shelf between 1990 to 2007 (Oil & Gas UK, 2009). In many cases, the release of hydrocarbons and fire may be a more important mode of escalation than direct structural damage (Brighton et al., 1995). Hence it is important to put a substantial amount of work towards reducing the risks associated with fire and explosion in offshore facilities.

The assessment of explosion risk analysis in offshore safety cases by Brighton et al. (1995) suggests optimizing the natural ventilation to avoid vapour cloud explosion in offshore structure. Large scale experimental stoichiometric natural gas/air explosions by Tomlin et al. (2015) prove that high and destructive overpressures can be formed even from explosions in enclosures with no congestion when the vent opening prevents adequate discharge.

By enhancing natural ventilation in FPSOs, the likelihood and consequence of VCE can be reduced by diluting and dispersing the vapour cloud. This can be achieved by providing grated decks instead of plated decks in process deck level 1. The Piper Alpha case study by Holdo et al. (1998) explored the dangers connected with grated floors in offshore structure based on qualitative and quantitative approach; Qualitative approach situates, large vapour cloud formation due to diffusion of flammable vapour to other parts of platform, caused the accident, and quantitative CFD study results in lower explosion overpressure in presence of grated deck. The study of the effect of 30% grated deck in cargo deck explosion of FPSO by Berg et al. (2000) utilized computational fluid dynamic modelling revealing that an average of 25% reduction in explosion overpressure at cargo deck was achieved while using grated process deck. However, there is a very limited amount of study on explosion simulation introducing a grated deck in FPSO, making it difficult for the present designer to take qualitative decisions on using plated or grated decks, as explosion risk reduction measure. The lack of information and guidance on the risk associated with grated process deck in FPSO makes it significant for the explosion prospective evaluation of plated versus grated process deck.

The objective of the study was to evaluate the influence of the presence of plated and grated process deck in a typical FPSO facility by quantifying the potential overpressure exceedance frequencies. Therefore, the following steps were detailed and reported within this study:

i. Identification of major accident hazards associated with typical FPSO topside process modules
ii. High potential leak scenario identification by frequency analysis
iii. Explosion simulation of typical FPSO in with plated and grated process deck
iv. Evaluation of results

The study utilized DNV's Safety Offshore modelling tool for explosion modelling. The typical FPSO facility studied is an external turret-mounted type offshore floating installation, intended to operate approximately 175 km offshore and 2300 m water depth in the Dutch part of North Sea. The FPSO facility is 200 m in length and 50 m in width and capable of producing 120 to 150 barrels of oil per day. The FPSO is in the preliminary design phase.

MATERIALS AND METHODS

The overall methodology framework of this study is given in Figure 1.

Figure 1. Overall methodology framework

Hazard Identification

Initiating release events that could result from Major Accident Hazards (MAHs) in typical FPSO facility were identified through Hazard Identification (HAZID). The methodology applied for HAZID used in this study was based on identifying top events resulting from hazards associated with hydrocarbons in the topside of typical FPSO and its causes, consequences, preventive controls and mitigation measures (ISO 17776, 2000).

Frequency Analysis

The likelihood of potential occurrence of the identified MAH associated with topside hydrocarbon processes was estimated by frequency analysis using historical leak frequency data and "parts count" approach. The failure case selected for this study was process leaks from topside modules. Leak size was selected based on hole size. The representative hole size used in this study was 25 mm to estimate the likelihood of potential release scenario. The topside hydrocarbon process modules which were identified as major accident hazards in HAZID were further divided into isolatable sections, by sectionalizing based on the locations of isolation valves that are intended to operate in the event of a detected release. Parts Count for each isolatable section was done by counting of each piping, valves and fittings along the hydrocarbon process lines. The valves, flanges and pipes were counted based on their diameter, D and divided into 3 categories which are (i) small, D ≤ 3”, (ii) medium, 3” < D ≤ 11”, and (iii) large, D > 11”. The failure frequency for each isolatable section was calculated using Equation [1] by multiplying the sum of the number of components (parts count) by historical failure rate corresponding to 25 mm hole size (Spouge, 1999).

$$F = \sum_{i=1}^{n} \boldsymbol{n_i f_i} \qquad [1]$$

Where:
n_i = number of components i
f_i = failure frequency of components i

The high potential leak scenario was selected by comparing the calculated failure frequencies for individual isolatable section.

Explosion Analysis

The high potential leak scenario for topside process modules was processed through SAFETI OFFSHORE V7.53 software to find the effects of VCE in typical FPSO facility with plated and grated process deck. The following failure cases modelled for process release event are (1) no isolation and blowdown functioning, (2) system with only blowdown functioning, (3) system with only isolation functioning, (4) system with isolation and blowdown functioning

The wind speed and atmospheric conditions widely influence the behaviour of vapour cloud explosions and their consequences. For this study, a wind speed of 7 m/s, the average potential wind speed measured in the Dutch part of the North Sea offshore was considered (Brand, 2008). The FPSO is swiveled around the turret mooring and always located at the downstream of the prevailing wind. Pasquill stability class D, which is a typical atmospheric stability class for offshore conditions regardless of wind speed (Oil & Gas UK, 2009) was selected for this study.

The geometrical model was built in the SAFETI OFFSHORE tool using the typical FPSO layout, deck layout and module equipment layout. Two models were built for this study, one with Plated Process deck and another with Grated process deck. The ventilation inside modules depends on the obstacles like the wall or deck in the direction of the wind. Even though the topside modules are open in all directions, the ventilation is obstructed by obstacles like equipment, pipe racks, walls and decks. In the case of decks, the ventilation differs widely for plated and grated type decks. For plated type decks the ventilation from the direction of the plated deck is considered as zero since the plated deck is solid plate without any opening for ventilation. For the grated deck, the ventilation depends upon the fraction of opening presents in the grated plate. In this study, 50% opening fraction was considered for the grated deck. Physical effects raised from vapour cloud explosion considered were blast overpressure loads, these are analysed in terms of impacts on equipment and structures. The overpressure impact criteria considered for this study is given in Table 1.

Table 1

Overpressure impact criteria

Overpressure	Impact
≥ 0.1 bar	Bridges and lifeboats impaired / cladding blown off / glass projectiles from windows or falling ceilings
≥ 0.35 bar	Heavy damage to buildings and process plant within module, sufficient to cause impairment to escape routes, temporary refuge, and lifeboats

The probabilistic analysis was performed using a Monte Carlo approach to derive the overpressure exceedance curve at each defined target on the facility. The cumulative overpressure-frequency curve from the explosion source defined in the facility provided the overpressure exceedance curve.

Evaluation

The overpressure curves were utilized for the evaluation of the effects of vapour cloud explosion due to the presence of grated and plated process deck in typical FPSO facility.

RESULTS AND DISCUSSION

Hazard Identification

In typical FPSO facility, well fluids and hydrocarbons (liquid/gas) were identified as the major accident hazards with potential severity of a level of ‘5’ in one of the consequence categories of People, Asset, Environment and Reputation.

Frequency Analysis

The probability of potential occurrence of the identified MAHs associated with topside hydrocarbon processes was estimated using historical leak frequency data and “parts count” approach. By comparing the calculated failure frequencies for individual isolatable section, the leak from isolatable section after downstream of Free Water KO Drum (Liquid) to Crude-Crude Exchangers, interstage heaters and inlet of the flash vessel was selected as the high potential leak scenario with the frequency of 1.27E-02 for the typical FPSO facility.

Explosion Analysis

The selected high potential leak scenario was processed through the SAFETI OFFSHORE modelling tool to find the effects of VCE in a typical FPSO facility with plated and grated process deck. For the selected isolatable section, the flammable inventory and process stream conditions are given in Table 2.

Table 2
Flammable inventory process condition for selected isolatable section

Properties	Conditions
Vapor Fraction	0.09
Fluid Characteristic	Slightly Stabilised Crude, Liquid Phase
Density (Kg/m^3)	263.05
Volume (m^3)	34.8
Operating Pressure (barg)	2.5
Operating Temperature (deg. C)	39.6
Molecular weight	238.18

The main deck on the typical FPSO facility was set as an explosion target for this study to obtain the overpressure exceedance curves from the SAFETI OFFSHORE tool. The overpressure exceedance frequency curves were generated by plotting the exceedance frequency versus explosion overpressure resulted from the explosion. From the modelled scenarios of the selected isolatable section, the frequencies corresponding to explosion impact criteria, 0.1 barg and 0.35 barg were compared based on 25 mm hole size and the adopted failure scenarios for this study.

Overpressure Exceedance Frequency

The overpressure exceedance frequency curves of grated and plated process deck resulted from a 25 rmm leak are given in Figure 2 and Figure 3 respectively.

Table 3 summarizes the overpressure exceedance curves for 25 mm leak from Figure 2 and Figure 3.

When no isolation and blowdown functioning in selected isolatable Section of typical FPSO facility, the explosion overpressure exceedance frequency in presence of plated process deck level 1 was 19.6% higher than the grated process deck level 1 for 0.1 barg overpressure. For 0.35 barg overpressure, the explosion overpressure exceedance frequency in presence of plated process deck level 1 was 10.3% higher than the grated process deck level 1.

Table 3

Overpressure exceedance frequency for 25 mm leak

Failure scenarios	Overpressure Exceedance Frequency per year			
	For 0.1 barg		For 0. 35 barg	
	Plated	Grated	Plated	Grated
No isolation and blowdown functioning	2.674E-08	2.236E-08	1.577E-08	1.430E-08
System with only blowdown functioning	2.263E-07	1.708E-07	1.315E-07	1.164E-07
System with only Isolation functioning	1.801E-07	1.315E-07	1.124E-07	9.630E-08
System with Blowdown and Isolation functioning	9.900E-07	8.030E-07	5.946E-07	5.274E-07

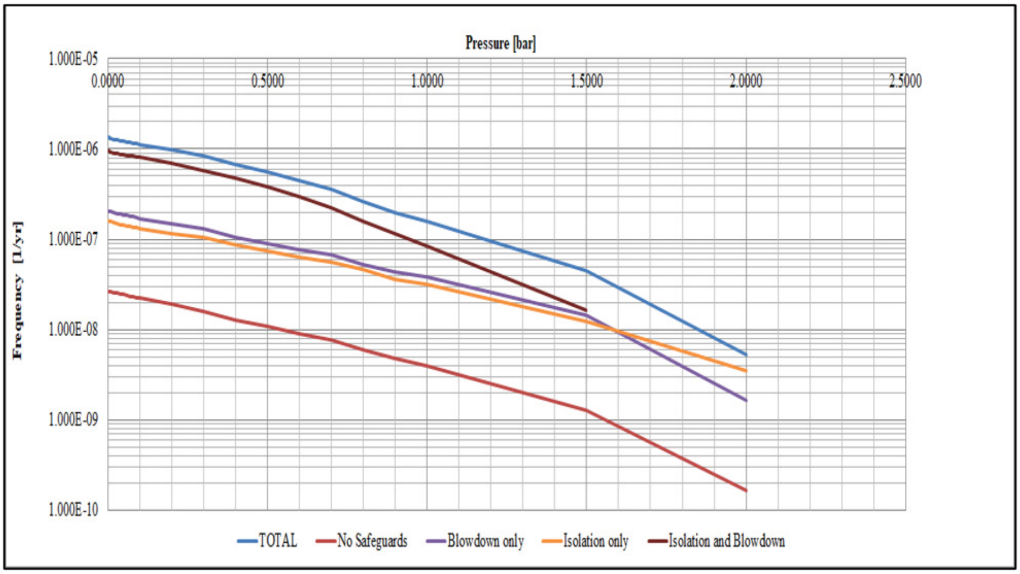

Figure 2. Explosion overpressure exceedance curves for 25mm leak (grated process deck)

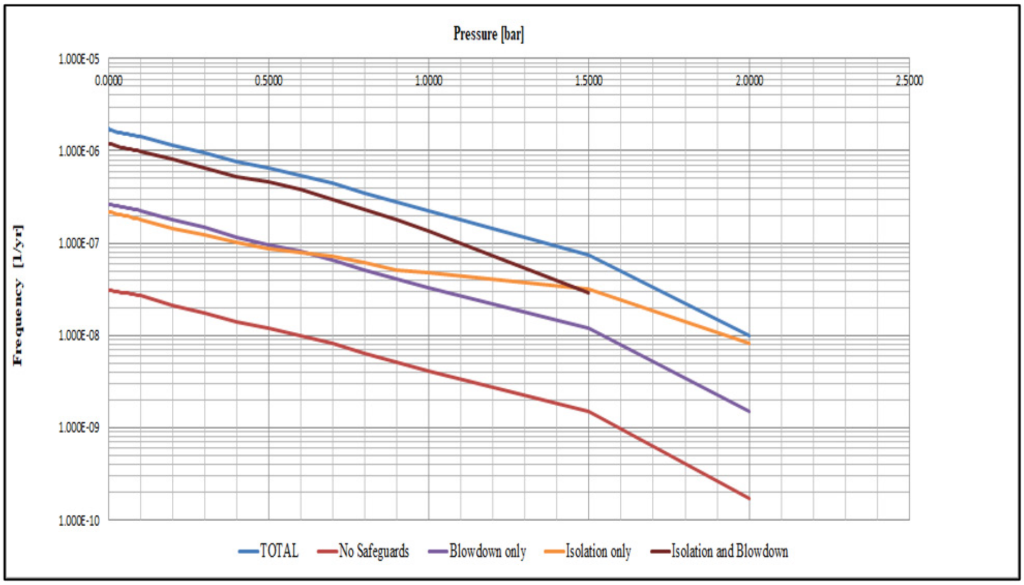

Figure 3. Explosion overpressure exceedance curves for 25mm leak (plated process deck)

Similarly, for the system with only blowdown functioning in selected isolatable Section of typical FPSO facility, the explosion overpressure exceedance frequency in presence of plated process deck level 1 was 32.5% higher than the grated process deck level 1 for 0.1 barg overpressure. For 0.35 barg overpressure, the explosion overpressure exceedance frequency in presence of plated process deck level 1 is 13% higher than the grated process deck level 1.

Also, while the system with only isolation functioning, in selected isolatable Section of typical FPSO facility, the explosion overpressure exceedance frequency in presence of plated process deck level 1 was 37% higher than the grated process deck level 1 for 0.1 barg overpressure. For 0.35 barg overpressure, the explosion overpressure exceedance frequency in presence of plated process deck level 1 was 16.7% higher than the grated process deck level 1.

Likewise, for a system with blowdown and isolation functioning in selected isolatable Section of typical FPSO facility, the explosion overpressure exceedance frequency in presence of plated process deck level 1 was 23.3% higher than the grated process deck level 1 for 0.1 barg overpressure. For 0.35 barg overpressure, the explosion overpressure exceedance frequency in presence of plated process deck level 1 was 12.7% higher than the grated process deck level 1.

In selected Isolatable section of typical FPSO facility, all failure scenarios in the presence of plated process deck level 1 led to high explosion overpressure exceedance frequencies compared to grated process deck level 1.

DISCUSSION

The overpressure curves were utilized for the evaluation of effects due to the presence of grated and plated process deck in a typical FPSO facility. In general, industrial practice the total exceedance frequency obtained from the explosion analysis is considered to provide safeguards and alternative design solutions to avoid catastrophic consequences. In this study, for the evaluation of results obtained from SAFETI OFFSHORE simulation, the total overpressure exceedance frequencies for the selected isolatable section with respect to the type of process deck is calculated by adding all exceedance frequencies for all scenarios. For better understanding, the comparison of overpressure exceedance frequencies for plated and grated process decks in typical FPSO are shown in Figure 4.

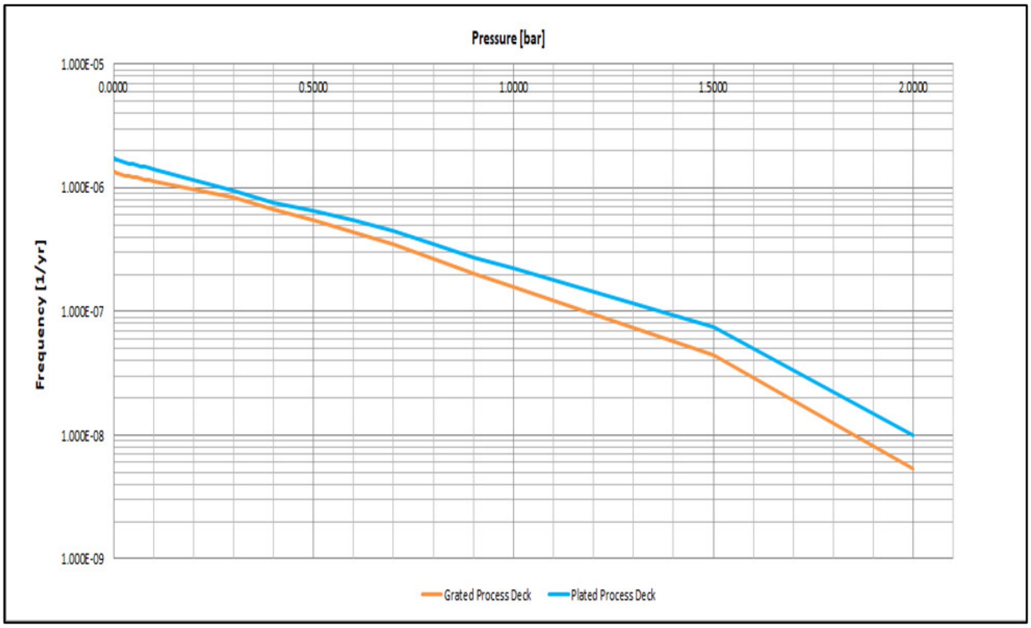

Figure 4. Explosion overpressure exceedance curves for plated and grated process deck

The total overpressure exceedance frequencies for plated and grated process deck in typical FPSO facility are given in Table 4.

Table 4

Total overpressure exceedance frequency

Overpressure	Overpressure Exceedance Frequency per year	
	Plated	Grated
For 0.1 barg	1.423E-06	1.128E-06
For 0. 35 barg	8.543E-07	7.544E-07

From Table 4, it was observed that the explosion overpressure exceedance frequencies for plated process deck were greater by 26.2% than the explosion overpressure exceedance frequencies in grated process deck for 0.1 barg and 13.2% higher in the plated deck than grated for 0.35 barg overpressure. The high explosion overpressure in plated process deck was due to the ignition of the undiluted flammable vapour cloud.

In the presence of grated process deck, the vapour cloud is diluted with natural ventilation and results in less explosion overpressure compared to the plated deck. There is a significant difference observed between the exceedance overpressures frequencies of plated and grated process deck in a typical FPSO facility for the selected isolatable section along with the given process conditions and failure scenarios.

CONCLUSION

This evaluation study focussed on the vapour cloud explosion effects in the presence of plated and grated process deck in typical FPSO facility. The study was supported by Hazard identification, frequency analysis and explosion analysis. In typical FPSO facility, well fluids and hydrocarbons (liquid/gas) were identified as the major accident hazards with potential severity of a level of '5' in any of the consequence categories (People, Asset, Environment and Reputation). Isolatable section from separation module was identified as a high potential leak scenario.

For the selected failure case, process conditions, atmospheric conditions and characteristics of the plated & grated process deck, the overpressure exceedance frequency for plated process deck level 1 was higher than grated process deck level 1. The significant difference between the exceedance overpressures frequencies of plated and grated process deck shows that the grated process deck is advantageous over plated process deck in reducing the effect of vapour cloud explosion at the main deck of typical FPSO facility. Hence the grated process deck can be selected over plated process deck from vapour cloud explosion perspective.

But from the overall safety perspective, the effect of Fire and Explosion on the typical FPSO facility in presence of plated and grated process deck shall be analyzed in detail using computational fluid dynamic study, for all applicable scenarios, process and atmospheric conditions, and weighed against each other carefully before selection.

The selection of high potential leak scenario can be widely extended to other leak sizes and scenarios for explosion analysis to calculate overpressure exceedance frequency across the typical FPSO facility. The leak scenario from the main deck was also considered. This will give a broader picture of the effectiveness of the presence of grated and plated process deck level 1.

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Intelligent Risk-Based Maintenance Approach for Steam Boilers: Real Case

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ABSTRACT

Maintenance acts as a significant role in smoothening the operations in power plants. Risk and failure are some of the common problems in power plant leading to unexpected outages such as boiler shutdown or tube leakage. The rectification of these problems requires ceasing operations of the boiler which leads to a loss in the revenue annually. Therefore, this work was focused on prioritizing the maintenance activities and optimize the operational duration and cost by implementing risk-based maintenance (RBM) and particle swarm optimization (PSO). Previous literature implores that, RBM is commonly used in oil and gas industries to predict the risk or failure of the equipment. In this work, the RBM method was adopted accordingly to the power plant industries. The methodology is segregated into two main phases. First, the ranking and prioritization maintenance activities were performed using RBM. Then, the optimization of the operational duration and cost were simulated by PSO approached in MATLAB. The main outcome of this research is to act as a reference in adopting the best approaches to improve the power plant performance.

Keywords: Maintenance scheduling, optimization, particle swarm optimization, risk-based maintenance, steam boiler

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INTRODUCTION

Power generation in Malaysia is dominated by two main types of energy source which are thermal power plant and hydropower

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plant. Thermal power plants generate power using conventional steam turbines and steam generators with coal, oil or natural gas as fuels. Thermal plants can be further classified as a steam power plant, open cycle gas turbine generators (gas-fired or diesel-fired), and combined cycle turbine generators (gas-fired or diesel-fired). The selection of coal as fuel is according to a five-fuel policy to reduce heavy dependence on natural gas (Tenaga Nasional Berhad, 2018).

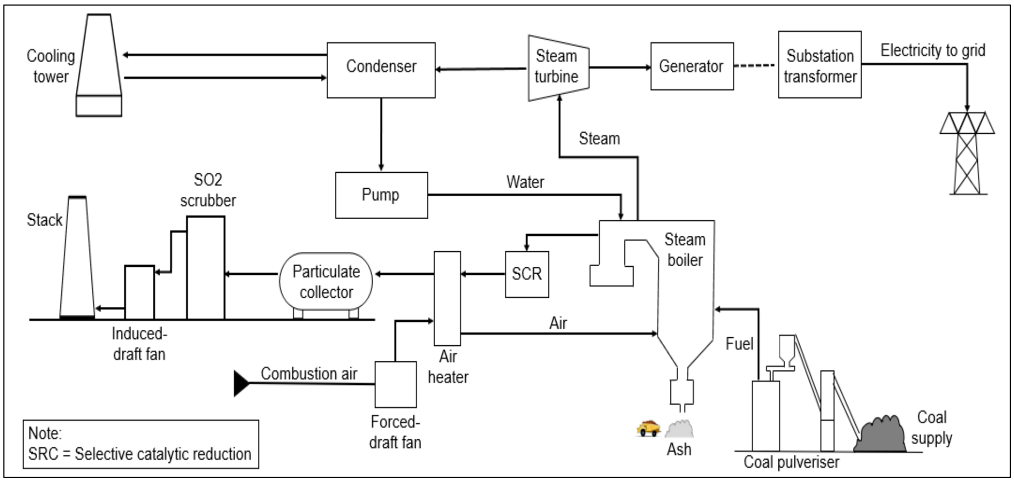

Figure 1. The revised version of the thermal power plant schematic diagram (Kubota, 2015)

In a plant, each major component plays a key role to ensure that the power plant operates efficiently. The components consist of a steam boiler, steam turbine, furnace and chimney (Kubota, 2015). In this work, the steam boiler is identified as the most crucial component due to major outage and the highest incurring maintenance cost. Steam boiler commonly known as the steam generator is shown in Figure 1, which is the most complex industrial component which involved the nonlinear, phase-change and inverse-response performance and also operated as a significant machinery in modelling and simulation challenge (Sunil et al., 2014). Boiler shortage and unexpected shut down incur heavy loss revenue and can further damage other components (Zhakiyev et al., 2017). Therefore, each component must be maintained according to the schedule.

Scheduled maintenance or preventive maintenance is the most common maintenance strategy implemented in industries. Preventive maintenance (PM) is a time-based maintenance method where the maintenance is planned and scheduled to optimize failure during the operation. PM is broadly used specifically for ageing equipment (Borikar et al., 2014; Dachyar et al., 2018). In this work, schedule maintenance for the steam boiler was analyzed to identify the highest expenditure in maintenance cost. The overhaul maintenance process consumes the longest maintenance operational duration which leads to the highest maintenance cost. The overhauling process is a time-consuming operation that includes three phases which are cleaning, repairing and testing. The overhaul is expected to be completed in 35 to 40 days estimated duration (Chandra et al., 2011).

According to Anderson (2015), 80% of preventive maintenance cost is spent on maintenance activities which running within 30 days or less and 30% to 40% of the preventive maintenance cost is spent on unnecessary failure. These are due to the factors such as the inefficient maintenance process, ageing equipment and also redundancy maintenance task which lead to the repetition that takes longer maintenance duration (Ge, 2010; Wang, 2018). To overcome this problem, this work analyzed the Multi-Criteria Decision Making (MCDM) which is a method that is widely adopted to decide on the prioritization maintenance schedule. MCDM consists of Analytical Hierarchy Process (AHP), Failure Mode and Effect Analysis (FMEA), and Risk-Based Maintenance (RBM). RBM is used widely in the oil and gas industry. However, in the previous study, the research works did not cover maintenance scheduling specifically for thermal power plants. Most of the previous studies concentrated on one of the aspects of the risk assessment of such pipes and the possibility of failures in the oil and gas industry. Thus, based on the literature review, this work would be implementing the RBM for maintenance scheduling in the thermal power plant.

Maintenance is crucial to manufacturing operations as wear and tear over time of moving parts is an absolute certainty. In many times the facilities and the production equipment represent the majority of invested capital and deterioration of these equipment increases production cost and reduces the production quality. Preventive maintenance is scheduled to prevent breakdown and equipment deterioration. However, to maximize return on their equipment investment managers attempt to identify the risky equipment required time interval between preventive maintenance action which will balance the cost of breakdowns and equipment deterioration. The risk-based maintenance system identifies critical equipment based on risk evaluation. Overall equipment and component maintenance plans are carried out to reduce the risk of the operation. By pre-scheduling the maintenance activities, RBM approaches the consequences of failures and downtime and reduces it to a minimum level for which the criteria considered are set up financial risks (Sarkar & Behera, 2012; Hameed, 2016).

Based on Khan and Abbasi (1998, 2000), the major challenge for the maintenance engineer is to implement a maintenance strategy based on four criteria which are maximizing the equipment availability and efficiency, controlling the deterioration rate of the equipment, ensuring safe and environment-friendly operation and optimize the total cost of the operation. The only action can be taken is by adopting a structured approach to the study of the equipment. Nowadays, Khan and Haddara (2003) suggested an improvised risk-based inspection and maintenance approach. The new approach was adopted with a specific case study. This method integrates significant risk assessment with proven reliability analysis approaches. The prioritization of the equipment is based on the total risk in terms of economic, safety and environment. Scheduling maintenance is enhanced to optimize the inadequate risk.

Nowadays, the maintenance planning problem is a common problem, especially in the power generation industry. As for Evrencan et al. (2019), the maintenance planning problem was handled by considering risk evaluation to schedule effectively. By implementing Analytical Hierarchy Process (AHP) hybrid with Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), the result then was validated using the RBM model to ensure that the risk is reduced. Besides, Cullum et al. (2018) were implementing RBM to reschedule the maintenance activities for naval vessels and ship. This implementation aimed to reduce the maintenance cost and meeting the availability requirements.

The risk priority number ranking was once introduced in the Failure Mode and Effect Analysis (FMEA) method. However, due to the traditional FMEA, the risk analysis suffered from major weaknesses. Nowadays, RPN ranking had been used widely by the researcher by merging with the RBM method which is more reliable compared to the independent RPN. RPN is engineered to identify the existing and potential risk or failures either in design, process or planning maintenance before they occur, and prevent the undesirable incidents thus protecting the employees from the occupational accidents and diseases by taking the necessary measures (Jamshidi, 2017; Setiawan et al., 2017; Stamatis, 1995).

In recent years, the growth of the evolutionary theory development, such as the Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) have grown into effective optimization tools and implemented widely in power engineering applications. PSO is a mathematical optimization algorithm that was initiated by Kennedy and Eberhart (1995). It has been successfully adopted into problems such as artificial neural network training, function optimization, fuzzy system control, and pattern classification and more (Chu et al., 2006, Samuel & Rajan, 2015). To be highlighted, the main objective of this research was optimizing the maintenance scheduling and form the new list of maintenance activities. Based on the new list of maintenance activities, the operational time and cost would be minimized and the productivity of the worker is increased.

METHOD

The risk-based maintenance (RBM) procedure is a mechanism to plan an effective maintenance scheduling with minimal expected failure of the machine. A simplified RBM procedure is illustrated into Figure 2. The outcome of this RBM method is to enhance the reliability of the equipment and optimizes the total maintenance cost. The equation below is a common problem-solving in the RBM procedure.

$$Risk = Probability\ of\ Failure \times Consequences\ of\ Failure$$

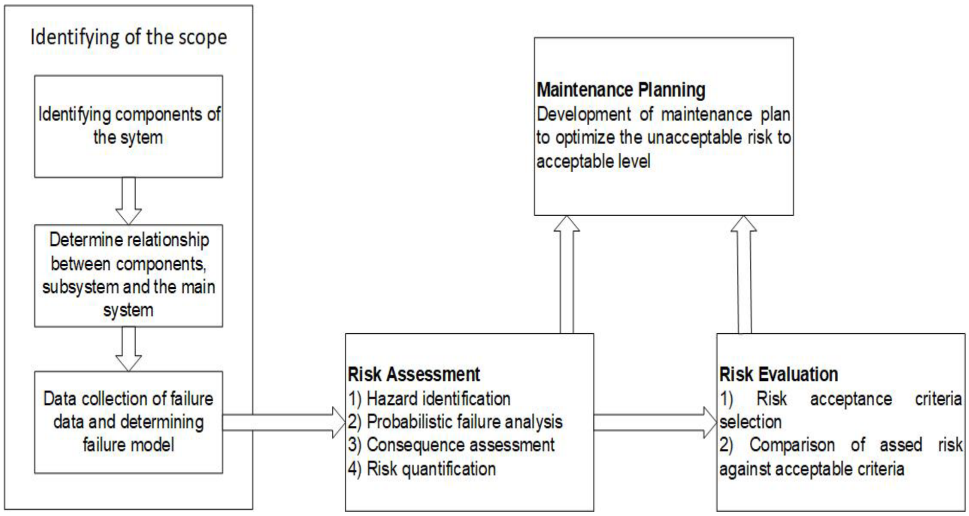

Figure 2. RBM Methodology

Identification of the Scope

The data used in this work was collected from the adopted thermal power plant with a generating capacity of 210MW. Every thermal power plant had similar components as shown in Figure 1. However, the steam boiler is always the key facility in the power plant as it is producing steam to generate electricity. Based on this power plant, the steam boiler consists of six main components which are boiler pressure parts, boiler drum, air preheater, safety valve, heat pressure valves, and coal and oil burner system.

Based on the literature review (Damodar Corporation, 2009), the overhauling process is the most critical maintenance activities in most of the steam boiler power plant. The overhauling process requires the whole system to be shut down in an estimated 35 to 40 days. For this work, the overhaul process for the drum boiler was selected to be implemented in the RBM model (Table 1). To be highlighted, this research only focused on the ranking and prioritization of the maintenance activities according to the risk of failure.

Table 1

Maintenance activities for overhaul boiler drum (Damodar Corporation, 2009)

No	Maintenance activities
M1	Disclosed the boiler drum manholes and accommodate with an exhaust fan to allowed cooling. The contractor will modify the fan accordingly. Cover the downcomer with covers and asbestos cloth.
M2	24 volts power supply connection is required when working inside the drum. (Required transformer from 220V input to be arranged by the contractor).
M3	The cyclone separator in the drum internal is removed for inspection.

Table 1 *(Continued)*

No	Maintenance activities
M4	Wash the welding joints of steam chest, cyclone separator using Teflon brush to avoid the magnetite layer destruction.
M5	The drum internals is inspected.
M6	The DPT of the welding joints of the steam chest is done after cleaning. The contractor is in charge of DPT and will be inspected by a DVC representative.
M7	The drum's phosphate dosing header is taken out and clean it effectively.
M8	Then, re-welding the header in its position.
M9	Removed the CBD isolation v/v bonnet or rip the CBD line to avoid any chocking.
M10	Welding of CBD line and phosphate dozing line shall be carried out by HP welders only. No extra payment will be made for cutting/welding of CBD or phosphate dosing lines.
M11	Wash and blue matching the drum manholes and counter surface. (Material build-up and scrapping to be carried out to complete the matching surface if required)
M12	Gather the drum internals and remove all the left-out materials.
M13	Engineer In-charge inspected. The drum is enclosed after putting a suitable gasket for the drum manhole.
M14	Hot tightening proceeds after boiler light-up at pressures required by the EIC.
M15	The downcomer suspension and drum suspension is checked.

Risk Assessments

Risk assessment is started by identifying the probability of risks from each failure scenario that may occur in the future. The Risk Priority Number (RPN) model is modeled based on the below equation in the Excel file to measure and identify the most critical based on the survey forms that been distributed to the maintenance team.

$$RPN = S\ X\ O\ X\ D$$

Where S is severity where an estimation of how severe the customer will discover the effect of a failure. O is an occurrence where a numerical estimation on the cause of a failure mode will happen within the design phase. D stands for detection where it is an estimation in numerical is made to prevent the cause of failure from occurs before delivery to the customer.

From the value of calculated RPN, the failure mode is ranked individually from high to low risk respectively. The scheduling of the RPN will prioritize the maintenance task to reduce and limit the failure occurrence. To be noted, the calculated RPN is not an absolute value but a respective value. Lastly, it is also able to present the initial state of risk assessment according to the assumption. Based on the predicted maintenance, the maintenance team is assigned to analyze scenarios separately to determine and analyze the impact of the higher risk in RPN, thus it will help to reduce the operational risk of those predicted failure modes.

Risk Evaluations

An adequate risk criterion is studied and determined either the risk of each failure scenario is adequate or not. Failure scenarios that form inadequate risk are used to determine maintenance policies for the components involved. To calculate the RPN, a ranking table for the occurrence, severity, and detection are tabulated as follows.

Table 2
Ranking RPN calculation values for S, O, and D (Setiawan, 2017; Jamshidi, 2017)

Descriptions	RPN value
Occurrence (O)	
Definite (More than 50 times/year)	10
Very possible (10 times/year)	7
Possible (1 times/year)	5
Impossible (1 times/3 year)	3
Almost impossible (1 times/5 year)	1
Severity (S)	
Definite (More than 50 times/year)	10
Very possible (10 times/year)	7
Possible (1 times/year)	5
Impossible (1 times/3 year)	3
Almost impossible (1 times/5 year)	1
Detection (D)	
More than 10 years not detectable	10
Within 5 years	7
Within a year	5
Within half-year	3
Direct detection (e.g. signal to control centre)	1

Maintenance Planning

Failure sub-systems are studied to restructure an optimizing risk maintenance program. The maintenance type and maintenance duration are determined during this phase. In this research, the maintenance interval is used only to reduce the failure probability. When the maintenance interval is modified, the risk failure probability will also be affected. An RPN model is used to prioritize maintenance activities based on the probability and consequences of failure. Consequence analysis involving the total cost of estimation maintenance and the production loss. Following equation is the calculation of the maintenance cost (MC):

$$MC = C_f + D_t \; X \; C_v$$

C_f is the failure fixed cost (e.g. spare parts cost), D_t is the downtime and C_v is the variable cost per hour of shutdown (e.g. manpower cost). Downtime maintenance is the total duration of the plant to be out of service starting from the moment of fails until the moment it is back to operation. While to calculate production loss cost (PLC), the equation is as follow:

$$PLC = D_t \; X \; PL \; X \; SP$$

D_t is the downtime, PL is the production loss in Megawatt, and SP is the generated electricity selling price. The manpower cost is the main cost to be considered in the maintenance cost. The hourly rate depends on the industry. The downtime process is usually related to the forced outage and forced de-rating state. This process is estimated from the historical failure data from the power plant. Due to the lack of data, this research only presents the ranking and prioritization of the maintenance activities by implementing into RPN model (Arunraj & Maiti, 2007; Khan et al., 2011; Mehairjan, 2016).

RESULTS AND DISCUSSION

Rank and Prioritize Maintenance Scheduling using Risk Priority Number (RPN)

Higher accuracy of results can be obtained using RPN method instead of Bayesian Network or Fault Tree Analysis. Based on the previous studies, the RPN method is more reliable for unmeasurable data (Khakzad et al., 2011). For each identified failure mode, the RPN value is calculated in the Excel model. An assessment of these maintenance activities by calculating the RPN value by substituting the ranking value from Table 2 was implemented into equation RPN to optimize the consequence of a specific failure mode. The results are tabulated as shown in Table 3. The results are shown as follows.

$$RPN = 8 \; X \; 10 \; X \; D = 400$$

Table 3
Results of RPN values

Maintenance	RPN value	RPN value (%)
M1	400	40.0
M2	8	0.8
M3	48	4.8
M4	315	31.5
M5	36	3.6
M6	24	2.4
M7	125	12.5
M8	27	2.7
M9	60	6.0
M10	240	24.0
M11	75	7.5
M12	18	1.8
M13	18	1.8
M14	18	1.8
M15	18	1.8

Based on the result obtained, the new maintenance scheduling is corresponding to the risk failure and criticality of each activity. From Figure 3, the results show that M1 (40%) is the most critical with respect to the severity and occurrence, followed by M4 (31.5%), M10 (24.0%), M7 (12.5%), M11 (7.5%), M9 (6.0%), M3 (4.8%), M5 (3.6%), M8 (2.7%), M6 (2.4%), M12 (1.8%), M13 (1.8%), M14 (1.8%), M15 (1.8%), and M2 (0.8%). The new maintenance activities were rearranged descendingly. As for M12 to M15 which produced identical values, it was rearranged based on the S values as it was the most critical compared to O and D values.

The new maintenance activities are verified by comparing the result obtained using the Analytical Hierarchy Process (AHP) method shown in Figure 4. A similar simulation had been simulated using AHP in Excel with the same parameters (severity, occurrence, and detection) and forming a similar ranking. This AHP method is used to verify the new maintenance activities forming by the RBM is effective and reliable. It is clear that the result is engineered according to the adopted thermal power plant and will be different if applied to other operation data.

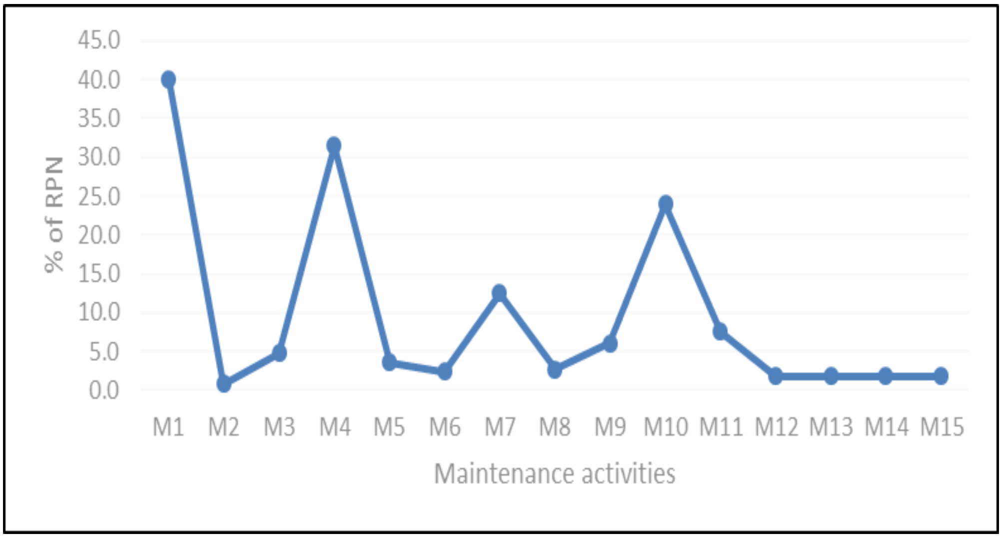

Figure 3. Illustration of ranking and prioritization maintenance activities based on the RPN values

AHP		
840	84.0%	1
20	2.0%	15
100	10.0%	7
700	70.0%	2
80	8.0%	8
50	5.0%	10
300	30.0%	4
60	6.0%	9
200	20.0%	6
600	60.0%	3
242	24.2%	5
42	4.2%	11
42	4.2%	12
42	4.2%	13
42	4.2%	14

Figure 4. Risk evaluation using AHP method as validation

CONCLUSION

This research proposed a procedure in rescheduling the preventive maintenance schedule based on minimizing the risk of failure. This approach was found to increase the safety of the equipment and minimize the maintenance cost. This will contribute to reduce plant shutdowns and ensure smooth and safe operations. In the methodology section, a new maintenance list is formed. The new maintenance scheduling is based on the risk in terms of severity, occurrence, and detection of the failure in maintenance. The new maintenance list is presented as M1 > M4 > M10 > M7 > M11 > M9 > M3 > M5 > M8 > M6 > M12 > M13 > M14> M15 > M2. The advantages of implementing the RBM are the reliability of the systems which is the steam boiler drum is enhance by using effective maintenance activities. Other than that, the RPN calculation is applicable to be used for maintenance activities as it will become possible to evaluate the costs and risks.

The present approach focuses only on the ranking and prioritization of maintenance activities due to the lack of data. However, in future work, the consequence analysis will be added after data collection. The consequence analysis will be analyzed and compared with the value obtained using particle swarm optimization and genetic algorithm. To conclude, by adopting and implementing the RBM modeling, risk failure probability from the maintenance schedule can be optimized and thus producing an effective maintenance scheduling. RBM can be adopted to evaluate the existing maintenance scheduling by using the risk management decision-making process of the systems to achieve the main objective.

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Investigation on the Suitability of Natural Gas Hydrate Formation Prediction Simulation Packages and its Implementation Conditions

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ABSTRACT

In natural gas processing, carbon dioxide is one of the major streams contaminate from the gas reservoir and must be removed, as it reduces the energy content of sales gas. In order to remove huge amounts of carbon dioxide (CO_2), gas hydrate is used to capture CO_2. However, the high formation of hydrate will inhibit clogs in gas pipelines. Hence, this research presents literature on hydrate formation, prediction of methane-carbon dioxide (CH_4-CO_2) gas mixture, by using simulation packages of Aspen Hysys 7.2, K-factor, VMG SIM Ver. 6 and BR & E ProMax 2.0. Peng-Robinson model was used in all simulation packages. Simulation results obtained were then compared with experimental data from previous literature sources. The simulation results showed that the higher the concentration of CO_2 in CH_4-CO_2 gas mixture, the lower the pressure required for CO_2 hydrate to form throughout the predicted temperature range from -20°C to 20°C.

Keywords: Hydrate equilibrium prediction, methane-carbon dioxide gas mixture, Peng-Robinson model

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INTRODUCTION

Offshore facilities are expensive in which wells and flow lines taking up almost 38%

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of offshore project cost. The formation of hydrates frequently leads to the formation of hydrate plugs along the transportation pipelines, posing major injuries and damage of equipment. During natural gas (NG) processing, injection of hydrate inhibitor to prevent hydrate formation requires high inhibition efficiency. This leads to difficulty in monitoring and may generate some economic losses (Bai & Bai, 2005). Therefore, the study of gas hydrate formation is important, in order to improve the technologies of CO_2 sequestration for commercial production, and prevention of pipelines clogging for flow assurance, for instance gas storage and transportation, gas purification, CO_2 separation and sequestration (Biruh & Mukhtar, 2012). Hence, the study of hydrate formation and phase behavior in CH_4-CO_2-NG mixtures is an essential topic in NG processing industries. In this research, the observation on the CO_2 effect on gas hydrate formations, particularly the formation pressure is discussed through the simulation of several packages and the application of thermodynamics model as well as the equation of state in predicting the hydrate formation. Besides that, the accuracy of proposed software packages in this study is analyzed by comparing the predicted and the available experiment data through the hydrate formation curve based on CO_2 composition.

Gas hydrates are crystalline solids composed of gas molecules for example methane caged inside a rigid lattice of water molecules (Kim et al., 2016). The cavities formed by water molecules are ice-like crystalline compound stabilized by inclusions of suitable size gas (guest) molecules, such as CH_4 and CO_2 or some other small molecules. Hydrates usually occur at the gas-water interface or vapour-liquid equilibrium (VLE) (Sloan & Koh, 2008). CH_4 hydrates occur at deep-sea levels and cold regions of water under immense pressure but cool temperatures (Tupsakhare & Castaldi, 2019). The most common hydrate crystal structures are I, II, and H, and they are determined by the molecular size of molecules filling the cages (Sa et al., 2018).

Previous studies have explored significantly on the matter of natural gas hydrate formation due to their loss incurring nature. One such researcher developed a model to that was used to calculate the equilibrium temperature of gas mixtures dissolved in methane gas reliably and compared the results with other computational works (Smith et al., 2015). Another researcher found that small-sized gas particles and the addition of H_2 and N_2 increased methane exploitation efficiency (Xu et al., 2018). A few works have explored on the methane generation in natural gas hydrates via the application of methane-CO_2 replacement (Xu et al., 2015, 2018). Another work explored the effects of the operating pressure on the methane-CO_2 replacement rate and found that the total operating pressure influenced methane-CO_2 replacement rate to a great deal (Xu et al., 2018). One researcher studied the effect of addition kinetic promoters and found that kinetic performance could be improved at room temperature, this significantly increased the feasibility of CO_2

transportation (Zheng et al., 2019a). Another research meanwhile found that addition of kinetic promoters (SDS) at 1000ppm results in increased mechanism and kinetics of the CO_2 hydrate growth (Molokitina et al., 2019). The experimental and operating pressure was identified as one of the key parameters in improving the kinetics of hydrate formation, while at higher temperatures longer process time was observed (Zheng et al., 2019b).

Other works meanwhile have investigated the uses of ammonium chloride as an inhibitor for the formation of methane hydrate. The study also found that ammonium chloride has greater inhibiting properties for the formation of methane hydrate as compared to urea but lesser than methanol (Muromachi, 2019). While most of this study has explored the factors affecting the formation of hydrate, this research provides a different direction of view by studying the aspects of the effect of CO_2 on natural gas hydrate.

The continual growth observed by agglomeration due to the existence of water causes the formation of a solid plug. Furthermore, hydrate formation requires three essential conditions namely: (1) appropriate combination of temperature and pressure, (2) existence of hydrate former and (3) sufficient amount of water. Generally, 5.75 moles of water are required per 1 mole of methane gas to form hydrates (John, 2003). The fulfilment of phase equilibrium for hydrate formation involves: (1) both temperature and pressure of the phases are equal, (2) The chemical potentials of components in each phase are equal and (3) the minimum global Gibbs free energy must be achieved.

These criteria were used as a basis for many models to perform hydrate equilibrium calculations (John, 2003). With the development of simulators (Goodwin et al., 2010), a cubic equation of states that are widely adopted in present-day academia and industry though it was introduced in the 1970s. Equations based on ideal gas model generally incorporate the intermolecular interactions of components (Milo, 2004). In fact, many of the recent Equation of State (EOS) originated from Van der Waals EOS (1873) (as cited in Sloan & Koh, 2008) were devised to improve the efficiency of models. ‘Repulsive forces’ and different ‘attractive’ interactions terms were utilized in order to fit the experimental data.

Peng-Robinson equation of state (PR EOS) (1976) enabled calculation of thermodynamics properties, phase equilibria of pure components and multi-component mixtures applicable in both gaseous and non-aqueous liquids (Goodwin et al., 2010). The basic Peng-Robinson fluid package is appropriate enough to simulate the hydrate formation with multi-component mixtures under VLE condition. The concentration of CO_2 from 0% to 100% in the CH_4-CO_2 gas mixtures was set with 20% step increment for prediction. The water to gas ratio of 5.75 would be held as a constant input during the prediction. The input variable, the temperature in the range of (-20˚C to 20˚C) with 1˚C increment were applied to predict the formation pressure. Smaller temperature increment per 0.2˚C was used to generate nearest upper quadruple point which was predicted by each software packages.

The prediction of the K-factor for hydrate formation condition is based on vapour-solid (vs) phase. K-factor is defined as the distribution of the component between hydrate and gas. The K_{vsi} value for natural gas components was obtained from the K-chart as shown in Figure 1 and Figure 2 (Sloan & Koh, 2008). The K_{vsi} values in Figure 1 and Figure 2 are based on the correlation equation by Sloan and Koh (2008) where $\prod$ is pressure (psia) and is temperature (^{0}F):

$$
\begin{aligned}
ln\ K_{vsi} = {} & A + B.T + C.\Pi + D.T^{-1} + E.\Pi^{-1} + F.\Pi.T + G.T^2 + H.\Pi^2 + I.\Pi.T^{-1} \\
& + J.\ln(\Pi.T^{-1}) + K.\Pi^{-2} + L.T.\Pi^{-1} + M.T^2.\Pi^{-1} + N.\Pi.T^{-2} + O.T.\Pi^{-3} \\
& + Q.T^3 + R.\Pi^3.T^{-2} \\
& + S.T^4
\end{aligned}
$$

From the correlation equation, data for the constants were obtained for CH_4 and CO_2 and summarized in Table 1. The phase equilibrium (hydrate) curves were then plotted, according to simulation results. The simulation results were then analysed and compared with experimental results from various literature sources. Experimental results available for comparison are in vapour-solid-liquid (V-H-Lw) equilibrium ranging from a lower quadruple point, 0˚C (for both pure CH_4 and CO_2 with water system) to the upper quadruple point, 9.8˚C (for pure CO_2 with water system). These points, Q1 and Q2 with line segments (V-H-Lw) are referred to as hydrate formation pressure and temperature boundaries, are indicated in Table 2. Approaches and methods used in each software packages are tabulated as shown in Table 3.

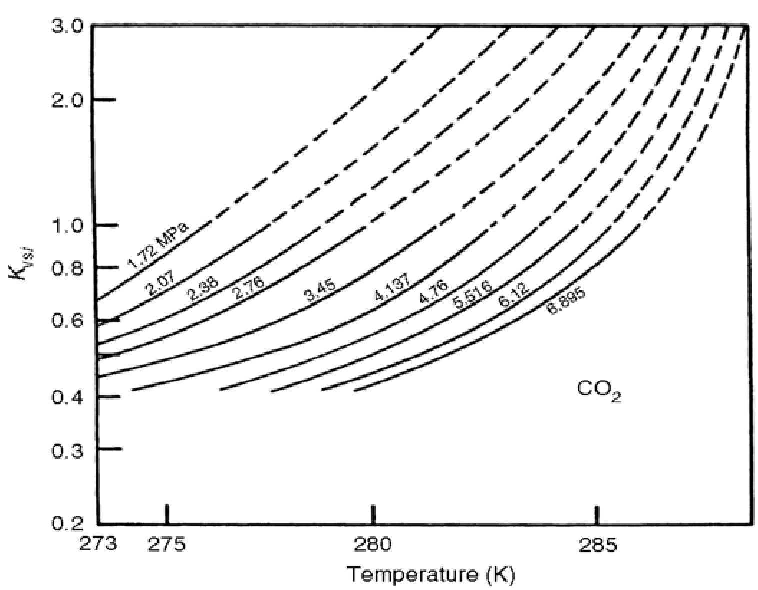

Figure 1. K-chart of carbon dioxide (Sloan & Koh, 2008)

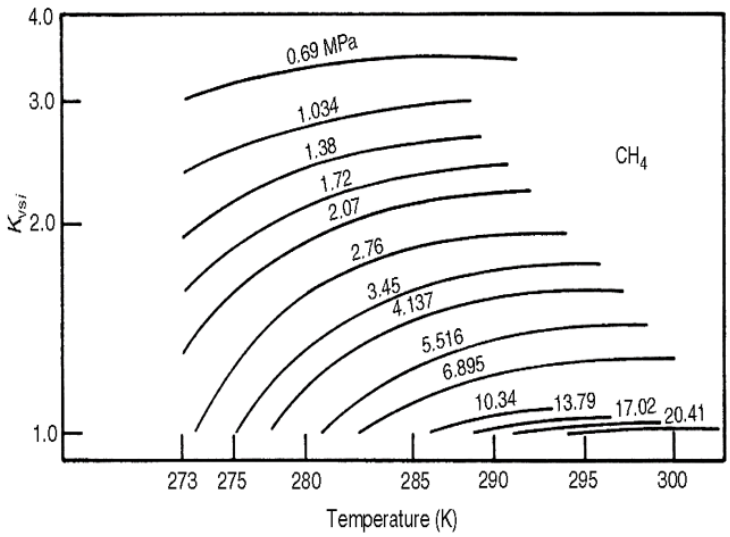

Figure 2. K-chart of methane gas (Sloan & Koh 2008)

Table 1

The guest: Cage ratio for some of the common structure I hydrate former. ζ indicates the cavities occupied by the simple hydrate former

		Molecular diameter/ cavity diameter (guest: cage ratio)	
Guest hydrate former		Hydrate Structure I	
Molecule	Diameter[b] (Å)	5^{12}	$5^{12}6^2$
CH_4	4.36	0.855^{ζ}	0.744^{ζ}
Xe	4.58	0.898^{ζ}	0.782^{ζ}
H_2S	4.58	0.898^{ζ}	0.782^{ζ}
CO_2	5.12	1.00^{ζ}	0.834^{ζ}

Table 2

Hydrate formation phases boundaries for common gas components (Carroll, 2003)

	Q_1: I-L_w-H-V		Q_2: Lw-L_{HC}-V-H	
	Temperature (ºC)	Pressure (MPa)	Temperature (ºC)	Pressure (MPa)
Methane	-0.3	2.563	No Q_2	
Ethane	-0.1	0.530	14.6	3.390
Propane	-0.1	0.172	5.6	0.556
Isobutene	-0.1	0.113	1.8	0.167
Carbon dioxide	-0.1	1.256	9.8	4.499
Hydrogen sulfide	-0.4	0.093	29.4	2.24
Nitrogen	-1.3	14.338	No Q_2	

Table 3
Absolute average error in pressure (% ADDPs) of single gas component + water system for all software packages

		% AADPs			
		Aspen Hysys	K-factor	VMG Sim	BR & E ProMax
pure CH_4 + water system	Temprature range 0-19˚C (n=14)	3.96 %	7.65 %	3.98 %	3.40 %
pure CO_2 + water system	Temprature range: 0-10˚C (n=10)	15.42 %	5.87 %	22.00%	9.59 %

MATERIALS AND METHODS

Hydrate Formation Simulation

A simulation was performed by selecting the thermodynamics property package, in order to calculate the thermodynamics equilibrium. Thermodynamics equilibrium refers to the boundary condition where pressure, temperature and chemical potentials of fluids phases are equal to each other. Hydrate formation which is on the water-gas interface, vapour-liquid equilibrium (VLE), was considered to determine the proper fluid package to be used, due to the mutual insolubility of hydrocarbon and water. Phase changes of liquid at the supercritical region, liquid-liquid equilibrium (LLE), with the consideration of hydrocarbon solubility in water is applicable in Peng-Robinson EOS.

Various independent variables, for example, the concentration of CH_4 and CO_2, water to gas ratio and the temperature range, were selected as inputs to predict the formation pressure. However, the objective of the study was to study the effect of CO_2 on hydrate formation. Hence, the percentage change in the concentration of CO_2 in the ternary system (CO_2-CH_4-H_2O) was used as an approach. The summarized steps involved in all four of simulation software are listed as such: (1) assigning of thermodynamics property packages, for instance, unit conversion to SI unit, (2) setting of gas components (CO_2, CH_4 and H_2O) as ternary system, for instance, manipulating the concentration of components, normalizes the water to gas ratio to mole fraction, (3) inserting conditions into simulation environment, by coupling with operation block column, for instance adding feed stream and phase envelope block, assigning the predicted condition like temperature in range at blocks (4) solving for formation pressure repeatedly or directly from plot, given by +temperature range between -20°C and 20°C.

Water Content Requirement for Hydrate Formation

Hydrate formation usually occurs at gas-water interface, which contains 85% mole of water and 15% mole of gas. This is because the location of the interface requires a very high concentration of host and guest molecules, where cluster growth (nucleation) will start to take place (Sloan & Koh, 2008). According to theoretical formula, 5.75 moles of water require 1 mole of gas for hydrate transformation. The dissociation pressure at the water to gas ratio of 5.75 acts as reference pressure, in order to compare with other ratio value, and to study the contribution of water content on hydrate formation. In this study, water to gas ratios of 1 to 7 were the only manipulated inputs, as they gave the lowest and the highest dissociation pressure respectively (Carroll, 2003).

Evaluation of Phase Composition

Vapour and solid composition of natural gas component, for instance, CO_2 and CH_4, are able to be predicted by using the flash method available in K-Factor. The K-factor flash method calculation steps are listed as such: (1) assigning input of feed percentage concentration, for instance, z_i for CO_2 and CH_4, (2) assigning input of required fixed formation temperature, (3) solving the objective functions iteratively, for instance, setting of Rachford-Rice function equals to zero, taking small step changes of VF during prediction ($0 < VF < 1$), (4) obtaining the results of vapour and solid-phase composition of CO_2 and CH_4.

Phase Diagram and Analysis

A series of Pressure-Temperature diagram, consisting of phase equilibrium curves were generated, based on the simulation results of four different software packages. Formation pressure at a given temperature and percentage concentration of CO_2 impurity were observed. Comparisons were made between the predicted results from the available phase equilibrium diagram and experimental data from Adisasmito et al. (1991). A comparison was made for 0%, 20%, 60% and 100% of CO_2 concentration in the CH_4-CO_2 gas mixture, as shown in Figure 4, Figure 5, Figure 6 and Figure 7, by using the standard error function from Microsoft Office Excel program. Standard error was done by the percentage of error in experimental pressure (y-axis), for an individual (x-axis). The allowable pressure errors were indicated as vertical error bars, as shown in Figure 3, were calculated using Microsoft Office Excel “STEYX” function. Deviation of predicted results at each point was studied, to recommend software accuracies in the gas mixture with a water system.

However, a comparison between predicted results and experimental data were made, by using Absolute Average Deviation (AAD). Both Absolute Average Deviation Pressure (AADP) and Absolute Average Deviation Temperature (AADT) was used to measure the deviations of set points from their average (Azmi et al., 2011). AADP was calculated in percentage for pure gas systems at selected fixed temperatures, with the use of the experimental data from Sloan and Cao (2002) and Sloan and Koh (2008). Meanwhile, both AADP and AADT were calculated in percentage at the upper quadruple point, where Q_2 marks the phase change from CO_2 vapour to liquid (Sloan et al. 2011). The formula for AAD is specified as:

$$\%AAD(P,T) = \frac{1}{n}\Sigma_{i=1}^{n}\frac{|P,T_{predicted} - P,T_{experimental}|}{P,T_{experimental}} \times 100\%$$

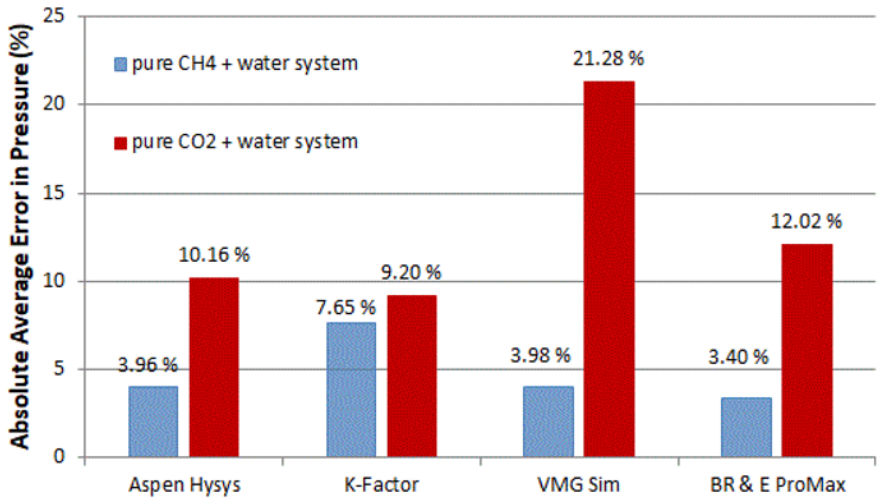

Figure 3. Comparison of % ADDP errors for pure CH_4 and CO_2 system

RESULTS AND DISCUSSION

Figure 4 depicts the comparison between the predicted and experimental data for pure CH_4 + water system. All four software packages predicted the hydrate formation equally well within the pressure error limits (±0.178 MPa) for pure CH_4 system. However, a higher deviation of predicted results was observed due to the pressure difference at higher pressure prediction. This is due to different accuracy of the modified PR-EOS model in most simulation packages at higher pressure prediction.

Figure 5 presents the comparison between predicted and experimental data for 20% CO_2 + water system. According to fitness to all vertical error bars, the pair of Aspen Hysys and BR & E ProMax curves gave a higher overall consistency with experimental data as compared to the other two packages. The pair of VMG Sim and K-factor curves had under-predicted slightly at third experimental data point. Meanwhile, K-factor over-predicted at first experimental data point. Based on the review of the K-factor program, it possessed weaker accuracy for mixture prediction (John, 2003).

Figure 6 shows the comparison between the predicted and experimental data for 60% CO_2 + water system. It was observed that Aspen Hysys, BR & E ProMax and K-factor, had consistently predicted the pressure-temperature (P-T) curves. All the curves were approximately close to the experimental data and within the vertical error limit (±0.261 MPa). VMG Sim was under-predicted except for the first three points due to the inaccuracy of the PR model to fit into the experimental points.

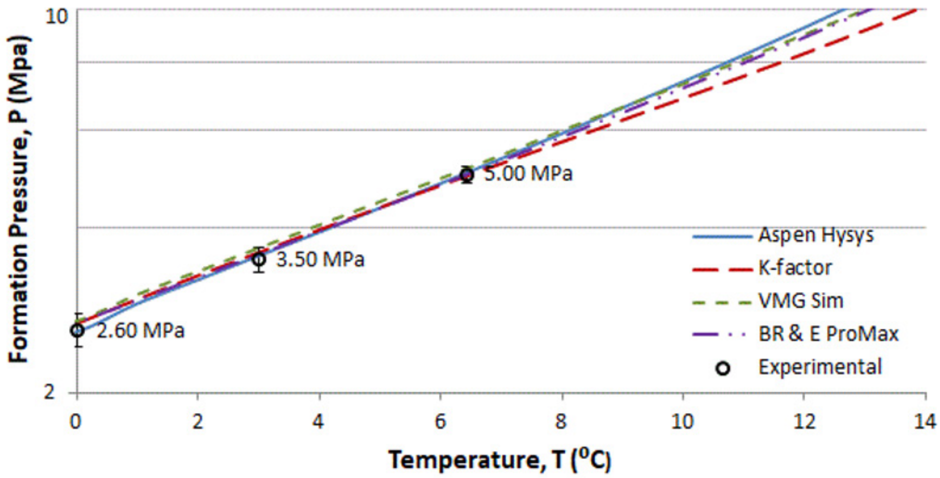

Figure 4. Comparison for pure CH_4 with pressure allowance of ±0.178 MPa

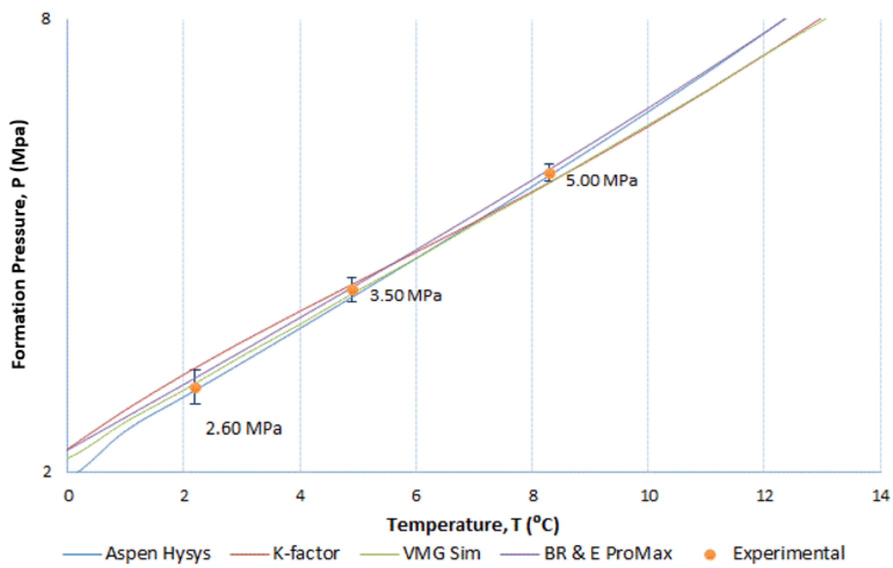

Figure 5. Comparison for 20% CO_2 system with pressure allowance of ± 0.132 MPa

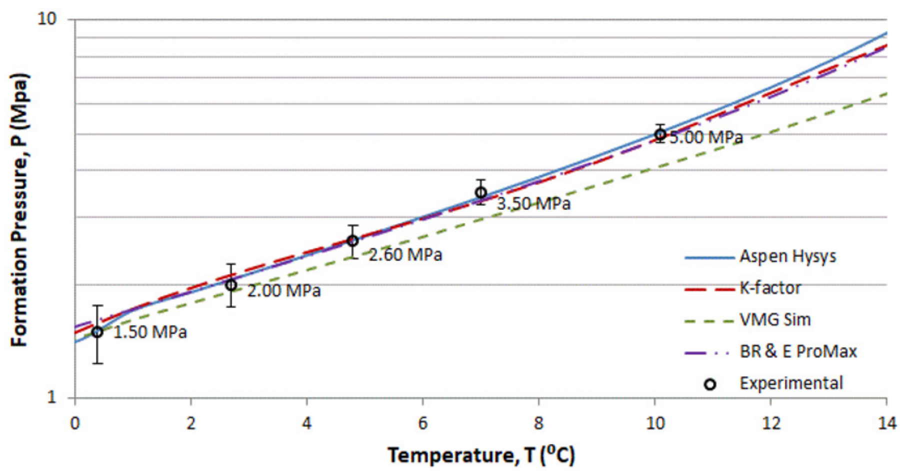

Figure 6. Comparison for 60% CO_2 system with pressure allowance of ±0.261 MPa

Figure 7 displays the comparison between predicted and experimental data for 100% CO_2 + water system. Based on the figure, Aspen Hysys, K-factor, and BR & E ProMax had predicted pressure values consistently at all experimental data. However, BR & E ProMax under-predicted slightly at third and fourth data points. It is observed that VMG Sim did not predict within the vertical error limit for higher % CO_2 concentration hydrate prediction. This may due to the weakness and lower accuracy of modified VMG Sim's PR model to predict the high percentage of CO_2 gas system.

Figure 8 shows the comparison plot of more experimental data with predicted results from 0˚C to 19˚C for pure CH_4 + water system (Cao, 2002). The number of experimental data, (n) used was 14 with all the selected points were the same as the given predicted temperature increment. The measure of pressure deviation of predicted data was calculated as absolute average pressure error represented in Figure 6.

Figure 9 presents the comparison plot of the experimental data with predicted results from 0˚C to 10.4˚C for pure CO_2 + water system (Sloan & Koh, 2008). The number of experimental data, (n) used was 12 with all selected points closed to the given predicted temperature increment. % AADP and % AADT were calculated which included upper quadruple point, Q_2 for pure CO_2 system and represented as a bar chart in Figure 10 and**.** Figure 11. The experimental Q_2 for pure CO_2 system was at 9.8˚C, 4.499MPa (John, 2003). According to the predicted data, Aspen Hysys, BR & E ProMax, and VMG Sim had predicted the upper quadruple point at 9.6˚C with 4.43 MPa, 10.8˚C with 5.23 MPa and 13.8˚C with 4.90 MPa respectively.

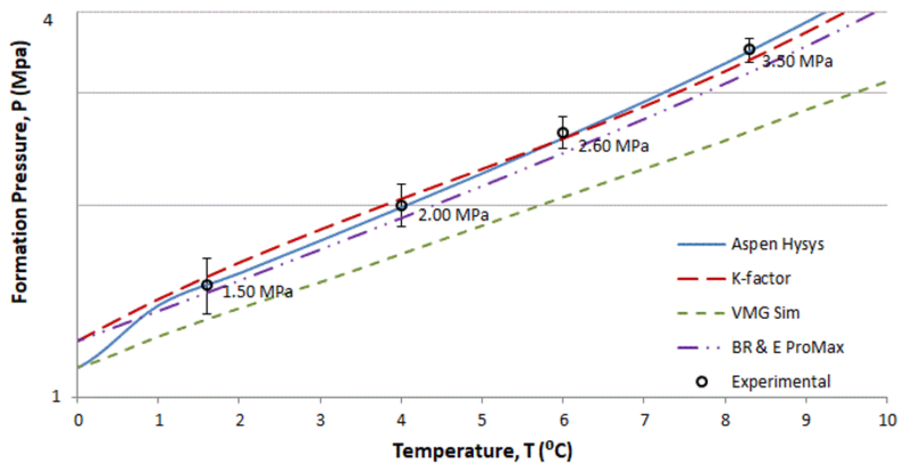

Figure 7. Comparison for pure CO_2 system with pressure allowance of ±0.152 MPa

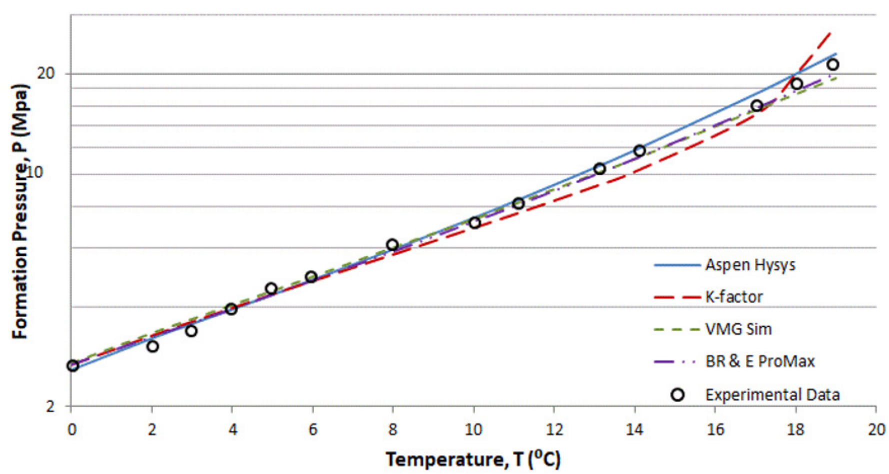

Figure 8. Comparison for pure CH_4 system from 0˚C to 19˚C with n = 14.

Figure 10 represents the comparison of %ADDP in a bar chart for pure CH_4 and CO_2 hydrate prediction. In general, the %AADP produced by all software packages in the pure CH_4 + water system was quite low, except for K-Factor which gave additional 3.3% of deviation error as compared to BR & E ProMax. This is because the predicted result of K-factor for pure CH_4 + water system did not tolerate in a linear form within the experimental data. In ascending order, both BR & E ProMax and Aspen Hysys gave the highest accuracy for pure CH_4 + water system prediction, followed by VMG Sim and lastly the K-Factor. The former 3 packages predicted equally well for pure CH_4 hydrate formation at high pressure.

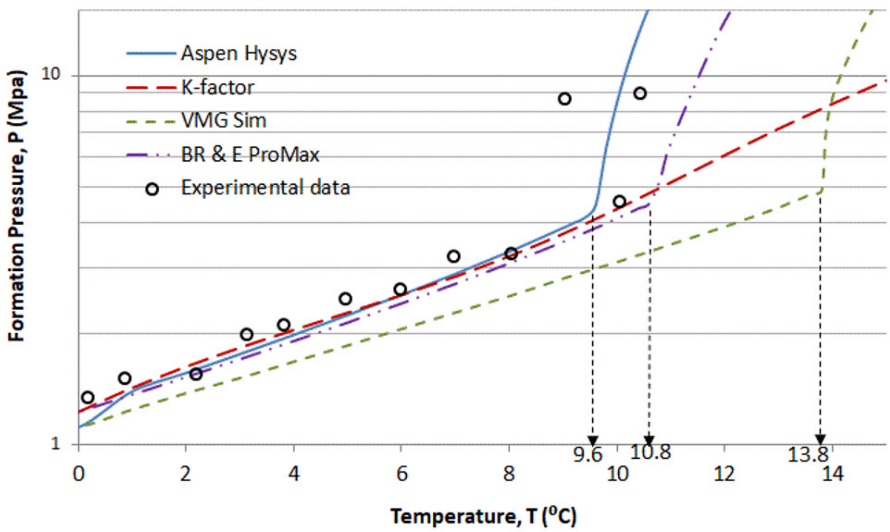

Figure 9. Comparison for pure CO_2 system from 0˚C to 10.4˚C with n = 12

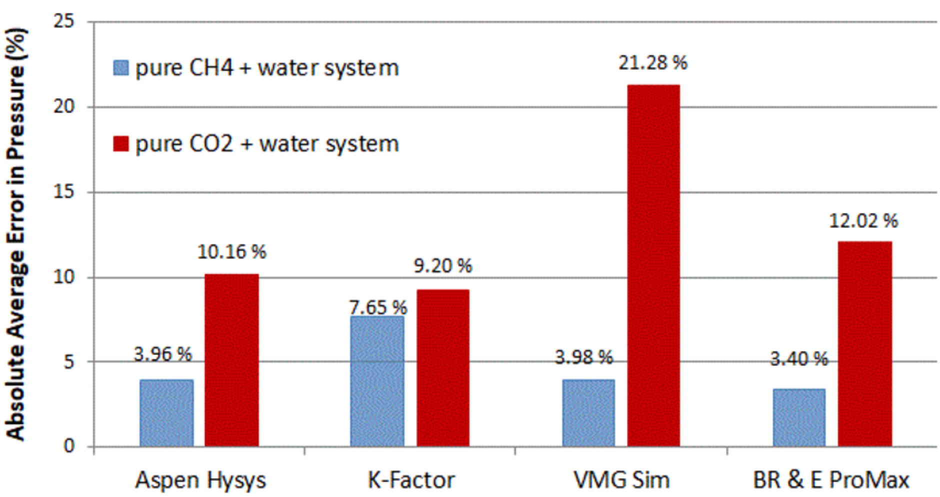

Figure 10. Comparison of % ADDP errors for pure CH_4 and CO_2 system

On the other hand, all simulation packages except the K-factor had predicted the upper-quadruple point in the pure CO_2 + water system. K-Factor's accuracy of hydrate prediction at 10˚C further was a problem. The prediction was just weak at that high-pressure hydrate prediction but its accuracy was still remarkable since it was below 10% AADP. For VMG Sim, its accuracy was getting poorer with increasing CO_2 concentration. It was assumed that the PR model of VMG Sim was not suitable for hydrate prediction with high CO_2 content.

Figure 11 indicated the absolute average deviation of temperature (% AADT) and pressure (% AADP) at upper quadruple point of the pure CO_2 system. Generally, it is concluded that the software accuracies for the pure CO_2 + water system are much affected by the predicted upper quadruple points, Q_2. The suggested accuracy of software in ascending order for pure CO_2 + water system is Aspen Hysys, BR & E ProMax, and VMG Sim.

There was a deviation of pressure and temperature for Q_2 predicted by the 3 simulation packages compared to exact Q_2 at 9.8˚C with 4.49 MPa (Carroll, 2003). The reason may be attributed by the different accuracy of modified PR model to predict CO_2 hydrate formation based on the recognized CO_2 gas properties. Factors such as carbon dioxide gas solubility in water and compressibility of fluid were assumed to contribute some effect to the PR EOS model's accuracy for each simulation packages.

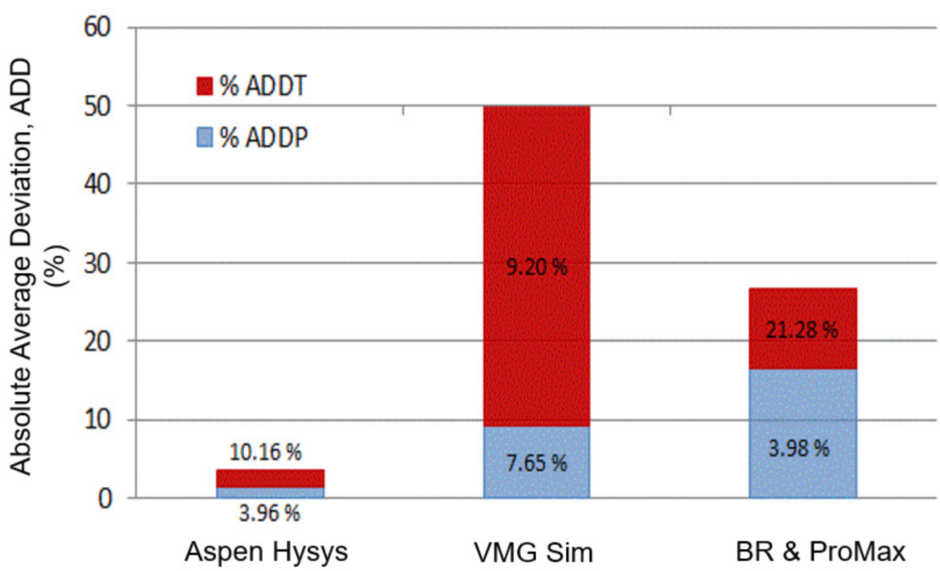

Figure 11. The absolute average deviation of temperature and pressure by % at the upper quadruple point of pure CO_2 system

CONCLUSION

By comparing the hydrate phase curves with the available experimental data, BR & E Pro Max obtained the highest accuracy for hydrate formation prediction in this work. Nevertheless, the hydrate curve below 0˚C remains for further research, since the curve pattern predicted by BR & E Pro Max was different from the other software. K-factor results can be used as a supplement for other advanced simulation software due to its high accuracy from prediction, ranging from 0˚C to 10˚C for CO_2. Besides, K-Factor did not work well at low and high pressure. It could not predict the hydrate formation for liquid, as it tended to extrapolate over the experimental quadruple point for fluid which was still at the vapour phase.

Based on simulation results observation, the higher the CO_2 percentage in the CO_2-CH_4 gas mixture, the lower the pressure for hydrate to form. It is justified that the formation of CO_2 hydrate is favourable at low pressure. This condition is valid throughout the predicted temperature range from -20 to 20˚C, but not for pure CO_2 hydrate. As such, it can be concluded that most of the common gas hydrate prediction software is unable to predict the gas hydrate accurately.

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As Low As Reasonably Practicable (ALARP) Demonstration: A Case Study on Firewater Curtain Application for Liquified Petroleum Gas(LPG) Sphere

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ABSTRACT

As Low As Reasonably Practicable (ALARP) demonstration is a continuous process in ensuring risks are managed in all phases of a project lifecycle (i.e. Assess to Operate phase). However, there is often a misconception that risks reported within the ALARP region are misinterpreted as representing acceptable risk levels or risk levels that are ALARP. It is important that risks reported within the ALARP region of any risk tolerability framework should only be deemed acceptable or tolerable once it has been demonstrated that all reasonably practicable risk reduction measures have been implemented. INPEX has developed a systematic process for ALARP demonstration and this paper discusses the ALARP demonstration for the installation of firewater curtain for the Liquefied Petroleum Gas (LPG) sphere at the LNG regasification terminal. Hazard assessment conducted in the design phase were reviewed based on operating experience and parameters and consequence assessment were re-modelled using Potential Hazard Analysis Software Tool (PHAST). Consequence assessment revealed that for release size 25mm and above, the gas cloud dispersion and radiation distance could exceed the plant distance separation distance of 65m. This research also points out the limitation of consequence modelling using PHAST. Installation of firewater curtain does not provide additional risk reduction outweighing the expenditure required for firewater curtain installation. Existing risk reduction strategy and measures put in place are enough to control the residual risk arising from LPG sphere.

Keywords: ALARP demonstration, firewater curtain, LPG, PHAST

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INTRODUCTION

The ALARP principle recognizes that no industrial activity can be entirely free from risk. The concept of ALARP is now generally adopted as good practice by progressive companies, within a number of potentially high-risk industries, across much of the world. In this respect, INPEX applies the ALARP process as an integral part of its Health, Safety and Environment (HSE) Risk Management (Yonezawa, 2018) and the decision-making process.

The ALARP concept is based on achieving a balance between the costs, difficulty, trouble and time of risk reduction measures and the perceived actual benefits. ALARP requires the identification of potential risk reduction measures and a determination of whether it is ‘reasonably practicable’ to apply them. A systematic process of analysis is required to demonstrate ALARP. The need to perform some type of ALARP analysis is determined from the assessment of risk. The residual and potential risk is assessed, using quantitative or qualitative methods and criteria, to be in one of three broad regions as shown in Figure 1.

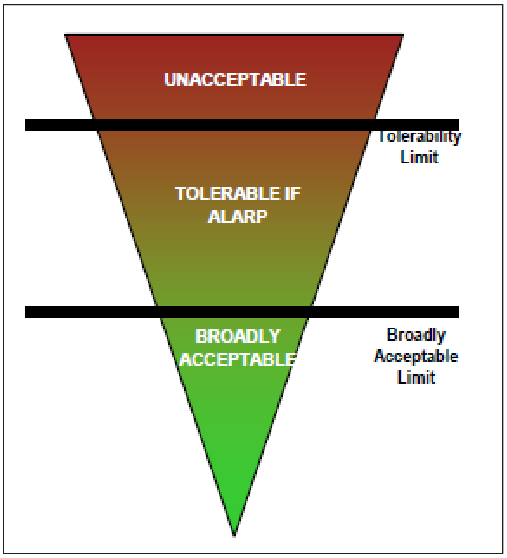

Figure 1. Risk tolerability framework (Yonezawa, 2012)

Risks assessed to be in the High (Unacceptable) band shall be given immediate attention (including, if necessary, suspension of activities or abandoning the associated design or development option) to minimize risk exposure such that the risk is reduced to the “Tolerable” band. Operation in the Intolerable region for a short duration may be considered only if there are no alternatives and approval is given by the INPEX Corporate HSE Committee (Yonezawa, 2018).

Risks assessed to be in the Medium (Tolerable) band shall be analyzed and reduced to levels that are demonstrably ALARP by the consideration of all possible risk reduction measures. Whereas, the Risks assessed to be in the Low (Broadly Acceptable) band do not require detailed working to demonstrate ALARP. The effort to analyze and reduce the risk further shall form part of a continuous improvement program. Where residual risks are determined to be Medium, an ALARP analysis will be required. The closer the risk is to the Intolerable zone the more detailed the ALARP analysis needs to be carried out.

The principles of ALARP apply to risks that are, first and foremost, assessed to fall within tolerable limits. This concept is illustrated in Figure 1. Generally, tolerability limits are typically defined in terms of Individual Risk Per Annum (IRPA). Individual Risk (IR) is calculated by identifying all sources of fatality risk to a given individual deriving from each source and summing these to give overall risk.

IRPA is a measure if the risk incurred by an individual working on an installation. Individual risk is a measure of the likelihood of fatality of an individual during one calendar year, accounting of the time that the individual spends on the installation. The risk to workforce and contractors shall be assessed based on IRPA to the most exposed worker group. Table 1 provides the INPEX workforce, IRPA criteria (Yonezawa, 2012).

Table 1
INPEX workforce, IRPA criteria

	INPEX workforce, IRPA	
Risk criteria	Tolerable limit	1E-03
	Broadly acceptable limit	1E-06

1E-03 refers to the tolerable limit in INPEX. IRPA number above this criterion is deemed to be unacceptable and requires a complete re-design or "no-go" operations. 1E-06 refers to a broadly acceptable limit, which indicates no additional risk reduction measures of ALARP demonstration is required if the IRPA number is lower than 1E-06. For the values in between the risk criteria`s INPEX requires a robust ALARP demonstration.

It is important to note even though ALARP principle promotes safety improvements, it introduces scoping and execution uncertainties with potential impacts on both cost and production especially in the Operate stage of the project lifecycle. Often there are arguments on ways to demonstrate ALARP (i.e. qualitative vs quantitative) and putting too much focus on QRA (Quantitative Risk Assessment) and CBA (Cost Benefit Assessment) may lead to "*Reverse ALARP*". Hence, the successful application of ALARP principles is closely linked to fundamental factors of perception, leadership, ownership and communication. A recent study has shown difference aspects to constructing a legally sound demonstration of ALARP. Keith (2019), concluded that an alternative way to produce a legally sound demonstration of ALARP comprised a Well-Reasoned Argument (WRA) and explained how it should be structured. However, the intention of this research was not to explain the use of WRA, nevertheless to provide details of INPEX approach in ALARP demonstration for a specific case study.

Figure 2 provides the examples of ALARP demonstration topics in each phase of the project lifecycle. It is important to note that, ALARP demonstration does not stop at SUP (Start-up point) but it also continues throughout Operate stage to ensure risks are managed adequately. The intent of this research is to discuss as to how ALARP demonstration for firewater curtain for LPG sphere, is achieved and demonstrated in INPEX.

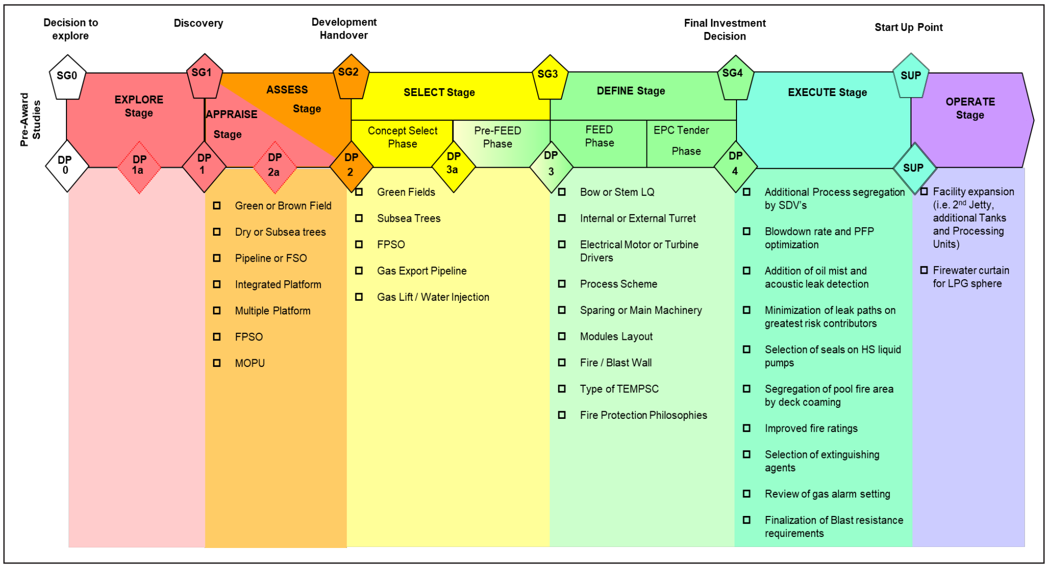

Figure 2. INPEX - ALARP demonstration examples for each phase of project lifecycle

RESEARCH BACKGROUND

The LNG regasification terminal in Japan is owned and operated by INPEX since the end of 2013. During EPC (Engineering, Procurement and Construction), as part of the FSA (Formal Safety Assessment), hazard assessment was conducted by the EPC contractor for LNG regasification terminal recommended the installation of the firewater curtain around the LPG spheres to reduce the escalation risk to the adjacent area, which is owned and operated by an independent power company.

Loss of Containment (LoC) of Hydrocarbon (HC) from LPG sphere is one of the MAE (Major Accident Event) identified for the LNG regasification terminal. A leak from the LPG sphere could cause a fire and explosion, and a threat to personnel and/or the loss of integrity of the facilities. The main safety issue is associated with the potential jet/pool fire and explosion by a LoC of HC which may cause fatal incidents and impact to the facilities. The risk ranking of LoC from LPG sphere is identified as "Tolerable if ALARP' and a specific Bow-Tie has been developed. The Bow-Tie contains associated Hardware, Human barriers and supporting HSE Management System (HSEMS). These barriers are further classified either as prevention or mitigation barriers and system put in place to ensure their effectiveness throughout LNG regasification terminal Operation phase.

In circa 2018, an independent power company commenced the preparation for construction of an independent power company on the land adjacent to the LNG regasification terminal. The closest hazardous installations are the LPG sphere tanks which are approximately 65 m from the site boundary.

An Operational Expenditure (OPEX) meeting was held by the LNG regasification terminal management and the committee approved the installation of the firewater curtain. In addition to the approval, an ALARP Demonstration for the installation of the firewater curtain was performed as part of HSEMS requirements. This paper provides details of the ALARP Demonstration studies that were carried out to fulfill the above requirements of the HSEMS.

METHODS

A step by step approach was undertaken to complete the ALARP demonstration. The methodology was a combination of a physical site survey for verification purposes combined with a desktop review and consequences analysis. The process undertaken were as follows but not limited to:

- Site survey including pictures with necessary details (e.g. actual physical distance from the LPG sphere to the fence and to the boundary of the independent power company plant and the current condition of the flange on the drain line of the LPG sphere tank)
- Review the Engineering Company's report and re-evaluation. This included a review of the Engineering Company's assumptions to ensure the current Operating Status of the LNG regasification terminal and revalidated the results and recommendations. Existing QRA results as part of Operations Safety Case, were also re-assessed.
- Carried out consequence modeling using PHAST on initial modelling cases utilizing the same assumption and criteria as the Engineering Company to replicate the results. However, the modeling was performed using the latest version of PHAST (Version 8.11).
- Additional cases were then completed to meet HSEMS requirements and a comparison between initial work done by the Engineering Company and the current analysis was carried out.
- Based on all inputs undertaken from Step 1 to Step 4, an ALARP Demonstration as per Oil and Gas UK (previously known as UKOOA) and INPEX Guideline (Yonezawa, 2012) was completed.

SITE VISIT RESULTS

Figure 3 shows the site layout including the location of the LPG sphere as well as the open space adjacent to the LNG regasification terminal. This is where the independent power company's power plant, construction will take place. The detailed analysis was also carried out during the site visit to identify all potential leak paths, as part of line-walk verification, as initially identified in Piping and Instrumentation Diagrams (P&IDs).

As shown in Figure 4 and Figure 5, the known leak paths are identified as flanges from LPG sphere. These flanges are noted to be non-leak flanges. Figure 4 shows the configuration of a non-leak flange. The height from the ground is approximately 2m.

In addition to the above, it is also noted that flange located at the downstream of XV (Actuated Valve), is also provided with a deflector as shown in Figure 5. The deflector covers the flange thereby deflecting any potential releases. Noted that, if ignited, the probabilities

Figure 3. INPEX LNG regasification terminal site layout

Figure 4. INPEX LNG regasification terminal - Non-leak flange

that a jet fire directly impinging the LPG sphere will be reduced and chances of a BLEVE (Boiling Liquid Expanding Vapor Explosion) is expected to reduce.

As it can be seen in Figure 6, the height of the bund wall around LPG sphere tank is noted to be 1.65 m. The boundary between LNG regasification terminal and adjacent independent power company's power plant which is yet to be built at the time of writing this research, are separated by embankment. The height of the embankment is approximately 4.7 m, as can be observed from Figure 7. Based on site survey measurements the distance between LPG sphere tank and the adjacent power plant (i.e. independent power company) is noted to be 65m.

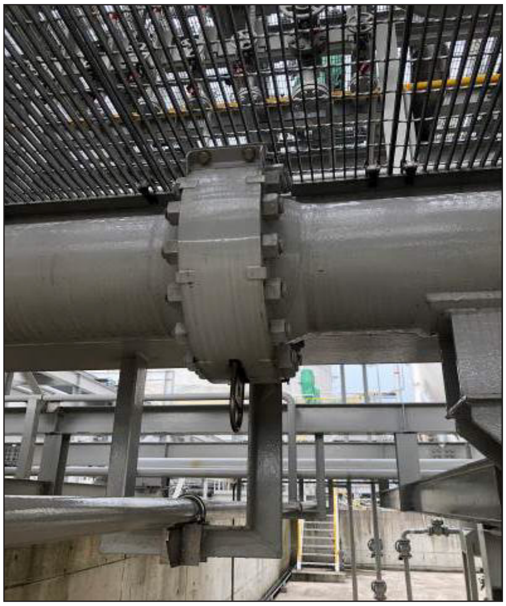

Figure 5. INPEX LNG regasification terminal Deflector on actuated valve

Figure 6. INPEX LNG regasification terminal - bund around LPG sphere

Figure 7. INPEX LNG regasification terminal - embankment between two plants

CONSEQUENCE ASSESSMENT

As described in the previous section, consequence assessment was performed using PHAST and previous studies conducted in the EPC phase were re-assessed based on current operating conditions of the LNG regasification terminal.

In this analysis, the previous FSA has been reviewed and concluded that some parameters and assumptions were not clearly indicated. The details are provided in Table 2. Note also that the previous assessment was conducted in 2010 utilized PHAST Version 6.54.

It is interesting to note that it is indeed Operators responsibility to ensure all FSA's performed during EPC phase are re-checked and re-validated like a 5 yearly HAZOP (Hazard and Operability) performed by a different Oil and Gas Operator.

It is very important for the Operator not to over-rely on consultants' output and it is the Operators responsibility to re-validate the results based on the latest current operating conditions. Therefore, it is important to note that in INPEX, a 5-yearly review of Safety Case(s) are performed to address the shortcomings of FSA(s) performed in the EPC phase.

Note that the consequence analysis was performed by PHAST 8.11 (latest version at the time of writing this research) and with up-to-date operating conditions representing the real operations. Table 2 and Table 3, provide the input parameter used by the EPC Contractor and INPEX respectively.

Table 2
EPC hazard assessment input parameters

Scenario	Flange Leak
PHAST	Ver. 6.54 (EPC) Ver. 8.11 (*INPEX*)
Criteria	
Dispersion	0.5 LFL* (1.0 mol %)
Explosion Pressure	9.8 kPa
Radiation	2.33 kW/m2
LPG Condition (Liquid)	
degC	40
MPaG	1.52
ton	1100
LPG Composition (mol %)	
Ethane	1.55
Propane	96.95
Butane	1.5
Information of Leak location	
Elevation (m)	2
Head (MPa)	0.055 (*Only in EPC input*)

Table 2 *(continue)*

Scenario	Flange Leak	
Distance to Boundary (m)	65	
Leak size (mm)	25	
Flange size	8B (*Note that in latest P&ID, 10B*)	
Leak Direction	Horizontal for dispersion / (*Selected most onerous direction. For Pool fire, vertical is more onerous*)	
Weather Conditions		
Wind velocity (m/s)	3.1	Wind velocity average at 10 m from June to August in 2006
Atmospheric stability	F*	-
Atmospheric Temperature (degC)	23.4	Average temperature from June to August in 2006
Humidity (%)	80	

**LFL – Lower Flammability Limit*
**F – Very stable - Pasquill Stability Class*

Table 3
INPEX input parameters

Scenario	Leak from the Flange at the bottom
PHAST	Ver. 8.11
LPG Condition (Liquid) ※Winter / Summer	
degC	7.0 / 27.5
MPaG	Bubble point
ton	913 / 975
LPG Composition (mol %)	
Ethane	1.55
Propane	96.95
Butane	1.5
Information of Leak location	
Elevation (m)	2
Distance to Boundary (m)	65
Leak size (mm)	5, 25, 50, 75, 100, 267.4
Flange size	(As-built P&ID, 10B = 267.4 mm)
Leak Direction	Horizontal Down on the ground
Weather Conditions	
Wind velocity (m/s)	2 / 5
Atmospheric stability	F / D*
Atmospheric Temperature (degC)	4.4 / 25.0 ※Winter / Summer

Table 3 *(continue)*

Scenario	Leak from the Flange at the bottom
Humidity (%)	87.8 / 85.4 ※Winter / Summer
Wind Direction	Prevailing Wind
Bund Information	
Bund height (m)	1.65
Bund area (m^2)	841
Bund failure modelling	Bund cannot fail (liquid overfill not possible)
Information on Terrain	
Surface roughness length (m)	0.5
Information on Tank ※Winter / Summer	
Tank head (m)	10.8 / 11.9

*D – Neutral - Pasquill Stability Class

CONSEQUENCE RESULTS

The consequence results are provided in Table 4. This includes both comparison of the consequence assessment performed during EPC phase as well as assessments carried out during ALARP demonstration study.

It can be observed that dispersion results are similar for the down on the ground release direction for both cases (i.e. EPC vs INPEX). On the other hand, the jet fire results are also reported to be similar for the horizontal release for both cases (i.e. EPC vs INPEX).

As for a pool fire, INPEX case gives more severe results. This can be explained by the fact that the flame Surface Emissive Power of LPG pool fire has been increased in PHAST between Version 6.54 (used by EPC Contractor) and the latest Version 8.11 used by INPEX.

Amongst other issues observed in EPC consequence assessments are as follows:

- Operating conditions considered are not realistic. (i.e. temperature and pressure do not reflect actual operating condition.)
- No bund has been considered.
- Only one leak size and one weather condition calculated.
- Uncertainties about PHAST parameters not communicated in the study (i.e. surface roughness)
- Uncertainties about actual release elevation considered (i.e. 1m or 2m)

The needs for updating the existing risk profile in operations Safety Case were assessed and the results from consequence analysis concluded that the QRA results was accepted “as is” as no major changes in risk profile were noted.

The Location Specific Individual Risk (LSIR) results are shown in Figure 8. As it can be seen, the LSIR at adjacent power plant is between 1E-04 and 1E-05 per year, which is within the in acceptable risk tolerability of INPEX.

Table 4
Consequence assessment results for 25mm hole size

Cases	Release direction	Flow rate (kg/s)	Dist. (m) to 50% LFL	Jet fire		Pool fire		Comment
				Flame length (m)	Radiation dist. (m) to 2.33 kW/m^2	Pool Diameter (m)	Radiation dist. (m) to 2.33 kW/m^2	-
EPC results	Most onerous between Horizontal and Down impinging on the ground	11.0	116.0	-	78.0	-	127.0	
INPEX	Horizontal	11.6	82.1	34.2	78.5	N/A	N/A	-
	Down on the ground	11.6	122.0	34.2	61.4	41.0	223.0	Results for late pool fire are reported (early pool fire gives less onerous results)
	Horizontal at 1m release elevation	11.6	114.0	34.2	78.3	N/A	N/A	-
	Down on the ground at elevation 1m	11.6	122.0	34.2	61.5	41.0	223.0	Results for late pool fire are reported (early pool fire gives less onerous results)

Figure 8. INPEX LNG regasification terminal - LSIR contours

ALARP DEMONSTRATION

Based on the above site survey, revalidated of existing hazard assessment study and consequence analysis, an ALARP demonstration was undertaken. The ALARP decision context was determined based on UKOOA (now known as Oil and Gas UK) and UK HSE (UKOOA,1999; UKHSE, 2014) as shown in Figure 9. The decision context type was determined to be "A" because the hazard is LPG, a well-known hazard, with no unusual characteristics.

However, due to some uncertainty which exists about the extent of potential damage from accidental releases that require risk analysis, therefore, a "lower A" decision context type was selected which involved consideration of the following means of calibration:

- Codes & standards
- Good practice
- Engineering judgment
- Risk based analysis (Consequence Analysis)

Based on the decision context type concluded for this study (i.e. lower A), 3 options were considered for ALARP demonstration. Table 5, Table 6 and Table 7 provide the advantages and disadvantages of these options. Table 8 provides the discussion summary, means of calibration and option selection.

Option 1 is the base case, which is the installation of firewater curtain with manual activation. Manual activation requires operators' action to activate the firewater system in the event of confirmed fire or gas detection. Manual activation was considered as it had the minimum impact to production as the LNG regasification terminal was currently under operation.

Option 2 is to install firewater curtain with automatic activation by fire and gas detection system. This option would require shutdown of LNG regasification terminal as modification to DCS (Distribution Control System) at CCR (Central Control Room). Noted that, this option was noted to be highest in terms of OPEX compared to Option 1 and Option 3. Option 3 is not to install firewater curtain and maintain/improve the current existing risk reduction measures and improve HSEMS requirements (e.g. people and system).

Table 5
Option 1 - Details

Advantage	Disadvantage
Lower cost than automatic activation Some benefit expected on LPG dilution and fire radiation [Note 1] Note 1: PHAST cannot provide any reduction of benefit concerning gas dilution and fire radiation reduction. Expert judgement and assumptions with regards of reduction should be made to determine the benefits.	Manual activation requiring more time HSE risk during construction (SIMOPS, hot work)

Table 6
Option 2 – Details

Advantage	Disadvantage
Do not require human intervention to activate (fast activation – 2 min) Some benefit expected on gas dilution and fire radiation [Note 1] Note 1: PHAST analysis cannot provide any reduction of benefit concerning gas dilution and fire radiation reduction. Expert judgement and assumptions with regards of reduction should be made to determine the benefits.	High OPEX and impact on production due to shutdown requirements. HSE risk during construction (SIMOPS, hot work)

Table 7
Option 3 – Details

Advantage	Disadvantage
No additional cost	Continuous risk management

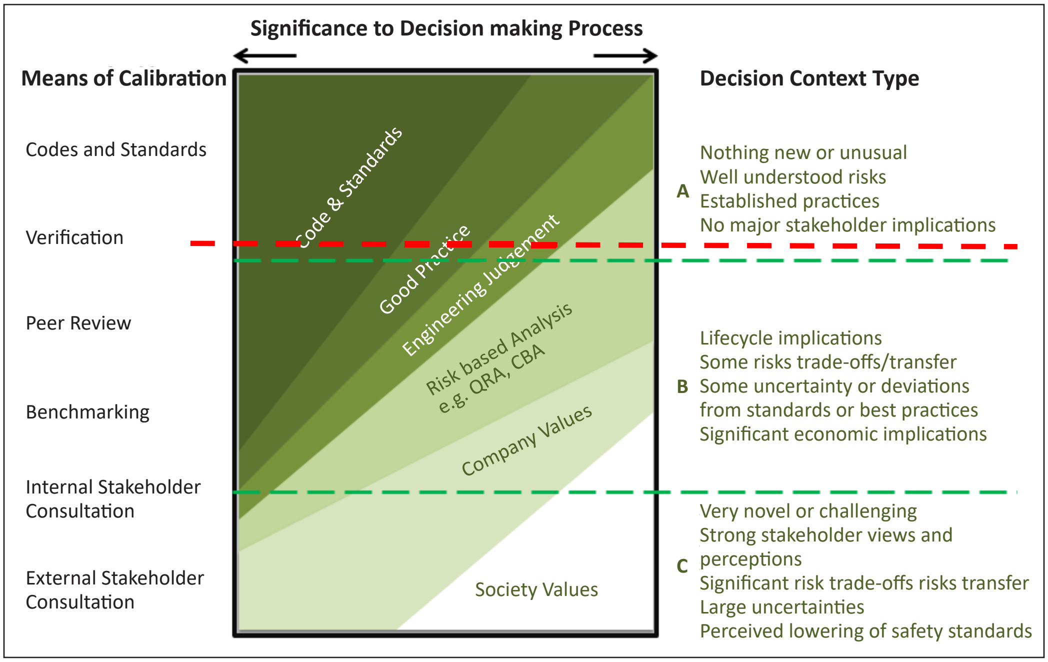

Figure 9. INPEX Corporate HSE - ALARP decision context

Table 8
Discussion summary for means of calibration and option selection

Means of Calibration	Explanation	Preferred Option
Codes & Standards	**<u>National Regulations</u>** Various national regulations were reviewed and no mandatory requirement (except as explained below) for firewater curtain by Japanese National Regulations were observed. Amongst national regulations which were studied in detail are as follows: • Gas Business Act (ガス事業法), e-GOV Japan. (1931) • Fire Service Act (消防法), e-GOV Japan. (2019a) • Regulation on the regulation of dangerous goods -危険物の規制に関する規則”, e-GOV Japan. (2019b) • Act on the Prevention of Disaster in Petroleum Industrial Complexes and Other Petroleum Facilities (石油コンビナート等災害防止法), e-GOV Japan. (2017) • Disaster Assessment Guidelines for Petroleum Industrial Complexes and Other Petroleum Facilities (石油コンビナートの防災アセスメント指針), e-GOV Japan. (2001) Noted that, National Regulation #3 above, mentions that if separation distance is less than 50m the firewater curtain is required. As for this case study, this requirement will not be applicable as the separation distance is more than 65m.	3

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option
	<u>Company Standards</u> Notwithstanding the above, INPEX internal Technical Specifications, INPEX/DEP/SAF/0180 (Hirayama, 2017), states that firewater curtain shall not be used for dilution purposes. **<u>International Standards</u>** On top of National Regulations and Company Standards, International Standards and recommended good practices such as NFPA, Oil and Gas UK, IOGP. were also reviewed. It was observed that no particular requirement addressed in these standards with regards to utilization of firewater curtain for LPG dilution. However, it is interesting to note that the application of firewater curtain is referenced as means to aid escape, evacuation and rescue from fire radiation. Based on the above analysis, it is concluded that the preferred option based on "*Codes and Standards*" is Option 3.	
Good Practice	A review of various industrial LPG related installations in Japan were conducted. The results are as follows: • 23 installations comprising LPG sphere tanks identified (e.g. LNG terminal and refineries) • Amongst these 23 installations, none seemed to have perimeter firewater curtain installed. However, it is important to note that this review was not meant to be an exhaustive review or site survey but the review was made by readily available public information. As such firewater curtain around LPG sphere may still exist but does not appear to be a common practice, in Japan. Based on the above analysis conducted on 23 installations in Japan, it is concluded that the preferred option based on "*Good Practice*", are Options 1, 2 or 3.	1, 2 or 3
Engineering Judgment	The FSA performed by EPC Contractor indicated that firewater curtain can reduce the downwind gas concentration of 50%-90% based on experiments conducted with LNG 30 years ago (Matsuda et al., 1988). However, LPG is heavy gas (LNG light gas), therefore this cannot be used as a direct application. Several other literature survey was carried out and the following was concluded: • Various papers for LNG application. The dilution effects provided by firewater curtain in case of LNG release are well documented • Research conducted by Matsuda et al. (1988), indicated some dilution effect for LPG. However, it should be noted that the research was based on small scale experiment (e.g. LPG leak flow rate of 0.06 kg/s of gas) and not a comparison to scenarios (i.e. large release size with higher release rate) considered in INPEX's consequence assessment. It is not evident if the same dilution effects can be obtained for larger releases. • Research conducted by Qi et al. (2016), indicates that dilution of gas cloud can be expected for heavy gas (i.e. CO_2). However, there are large uncertainties. Physical mechanism by which water curtains can dilute gas is noted as follows: ◦ Absorption by water - Not applicable to LPG as non-polar HC (e.g. not soluble in water)	1, 2 or 3

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option
	- Air turbulence created at the proximity of the water spray enhancing mixing of the gas with air (e.g. applicable to LNG/ LPG) - “Barrier effect” created by the water curtain pushing the gas upward: not applicable for LPG as heavy gas (i.e. however applicable to LNG as light gas) Research conducted by Qi et al. (2016), also indicated the efficiency provided by firewater curtain to dilute gas is dependent on the followings: • Wind speed (e.g. less dilution for higher wind speed) • The ratio of HC leak rate to Water flow rate (e.g. dilution is more effective for small HC leak and high firewater application rate) • Other parameters (spray nozzle type, the distance between leak source and Water Curtain) In conclusion, even though some dilution effect can be expected, this cannot reasonably be quantified and it is expected to be significantly less efficient for LPG compared to LNG, hence it is concluded that the preferred options based on “Engineering Judgement” are Options 1, 2 or 3.	
Risk Based Analysis (Consequence Analysis)	As explained in previous sections, a detailed consequence analysis was carried out using the up-to-date operating parameters and the latest version of PHAST by INPEX. Amongst assumptions which were used for consequence modelling of LPG leak are as follows: • Use of realistic operating and weather conditions (winter and summer) • Range of leak sizes from small leak to full bore rupture • Modelling of Gas Cloud Dispersion, Jet Fire and Pool Fire • Use of latest PHAST Version 8.11 • Use of assumptions and parameters in line with INPEX Standards and Guidelines Noted also some of the existing barriers could not be taken credit in PHAST modelling. This is due to PHAST limitation as PHAST currently cannot predict the effect of bund wall for various consequences. Noted that the bund wall is 1.65 m high and embankment is 4.7 m high. These values are not taken into account, in PHAST modelling. Potential leak paths are identified as flanges located at the bottom of the LPG sphere (i.e. 2 inch, 3 inch and 10 inch). It is also important to note that biggest flange (i.e. 10 inch) within the bund of LPG bunded area are fully welded limiting leak source. Table 8a, 8b and 8c, provides the consequence results for gas cloud dispersion, jet fire radiation and pool fire radiation, respectively.	

Table 8a
Gas cloud dispersion results

Op. Cond.	Leak diam (mm)	Release direction	Flowrate (kg/s)	Gas dispersion			
				Distance (m) to LFL (2F)	Distance (m) to LFL (5D)	Distance (m) to 1/2 LFL (2F)	Distance (m) to 1/2 LFL (5D)
Winter	5	Horizontal	0.3	5.7	4.9	9.0	7.1
		Down on the ground	0.3	10.2	9.5	14.9	14.2

Table 8 *(continue)*

Means of Calibration	Explanation								Preferred Option
	Winter	25	Horizontal	7.4	30.3	24.9	**91.3**	59.3	3
			Down on the ground	7.4	54.6	33.0	**76.5**	45.8	
		50	Horizontal	29.6	**100.5**	**83.4**	**215.1**	**148.1**	
			Down on the ground	29.6	**104.0**	58.2	**138.5**	**87.8**	
		75	Horizontal	66.6	**165.3**	**147.5**	**340.5**	**230.0**	
			Down on the ground	66.6	**159.4**	**84.7**	**207.2**	**123.4**	
		100	Horizontal	118.4	**228.6**	**207.9**	**465.7**	**309.7**	
			Down on the ground	118.4	**214.9**	**109.1**	**274.8**	**156.7**	
		267.4	Horizontal	846.6	**607.9**	**583.6**	**1262.2**	**821.2**	
			Down on the ground	846.6	**617.4**	**266.2**	**780.7**	**369.1**	
	Summer	5	Horizontal	0.4	6.1	5.3	9.9	7.8	
			Down on the ground	0.4	14.2	13.2	20.3	18.7	
		25	Horizontal	9.7	36.9	28.3	**89.7**	**67.3**	
			Down on the ground	9.7	**80.7**	44.2	**109.1**	**68.3**	
		50	Horizontal	38.7	**95.6**	**86.3**	**217.8**	**181.0**	
			Down on the ground	38.7	**155.1**	**81.4**	**200.7**	**118.5**	
		75	Horizontal	87.0	**158.2**	**163.9**	**339.4**	**285.4**	
			Down on the ground	87.0	**233.9**	**116.6**	**297.8**	**165.5**	
		100	Horizontal	154.8	**218.1**	**238.1**	**454.8**	**387.8**	
			Down on the ground	154.8	**313.2**	**151.3**	**395.7**	**211.9**	
		267.4	Horizontal	1106.5	**575.4**	**695.1**	**1109.8**	**1046.9**	
			Down on the ground	1106.5	**875.7**	**389.4**	**1122.3**	**528.6**	

*LFL – Lower Flammability Limit
*1/2 LFL – 50% of Lower Flammability Limit
*F – Very stable - Pasquill Stability Class
*D – Very stable - Pasquill Stability Class

Distances highlighted in bold black fonts are those scenarios which exceed the plant separation distance of 65m.

Pertinent points from the above results are as follows;

- Winter Case:
    - In the most unfavourable condition (leak direction and 2F weather condition) leak with a flow rate in excess of 15 kg/s (typically 36 mm leak) has the potential to result in LFL reaching the site boundary.
    - Large flammable cloud (LFL > 100 m, with potential to reach the main facility) can be experienced for leak in excess of 30 kg/s (50 mm leak).
- Summer case shows a very large difference between horizontal and vertical downward release. Generally, results are more severe compared to winter because of increased pressure in the sphere and higher ambient temperature causing increased LPG flashing and LPG pool vaporization in case of the leak.

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option
	• Time for the flammable gas cloud to reach the site boundary. Typically: □ 5 ~ 15 sec for horizontal release □ 20 ~ 60 sec for vertical downward release • Even assuming 50% dilution provided by Water Curtain (optimistic), large leaks will still have the potential to reach the adjacent facility. Table 8b and 8c provide the results for radiation distances results for jet fire and pool fire respectively.	

Table 8b
Jet fire radiation distance results

Op. Cond.	Leak diam (mm)	Release direction	Flowrate (kg/s)	Jet fire				
				Flame length (m)	Dist. (m) to 5.0 kW/m²	Dist. (m) to 6.3 kW/m²	Dist. (m) to 12.5 kW/m²	Dist. (m) to 37.5 kW/m²
Winter	5	Horizontal	0.3	8.6	13.9	13.1	11.2	8.5
		Down on the ground	0.3	7.6				
	25	Horizontal	7.4	34.5	61.2	58.0	50.1	40.6
		Down on the ground	7.4	30.8				
	50	Horizontal	29.6	62.5	**114.6**	**108.4**	**93.3**	**75.5**
		Down on the ground	29.6	55.9				
	75	Horizontal	66.6	**88.3**	**165.1**	**156.1**	**134.1**	**108.4**
		Down on the ground	66.6	**79.0**				
	100	Horizontal	118.4	**112.8**	**214.0**	**202.2**	**173.4**	**140.0**
		Down on the ground	118.4	**100.9**				
	267.4	Horizontal	846.6	**259.3**	**517.2**	**488.0**	**416.6**	**335.0**
		Down on the ground	846.6	**232.1**				
Summer	5	Horizontal	0.4	9.0	14.5	13.8	11.9	8.9
		Down on the ground	0.4	9.0				
	25	Horizontal	9.7	36.7	63.9	60.7	52.7	43.1
		Down on the ground	9.7	36.7				
	50	Horizontal	38.7	**66.7**	**119.3**	**113.2**	**98.0**	**80.2**
		Down on the ground	38.7	**66.7**				
	75	Horizontal	87.0	**94.5**	**171.7**	**162.8**	**140.8**	**115.0**
		Down on the ground	87.0	**94.5**				
	100	Horizontal	154.8	**120.8**	**222.2**	**210.5**	**181.9**	**148.5**
		Down on the ground	154.8	**120.8**				
	267.4	Horizontal	1106.5	**279.1**	**530.0**	**501.9**	**432.7**	**352.8**
		Down on the ground	1106.5	**279.1**				

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option

Table 8c
Pool fire radiation distance results

Op. Cond.	Leak diam (mm)	Release direction	Flowrate (kg/s)	Pool Fire				
				Pool Diameter (m)	Dist. (m) to 5.0 kW/m2	Dist. (m) to 6.3 kW/m2	Dist. (m) to 12.5 kW/m2	Dist. (m) to 37.5 kW/m2
Winter	5	Horizontal	0.3					
		Down on the ground	0.3	8.8	45.0	40.9	30.6	14.8
	25	Horizontal	7.4					
		Down on the ground	7.4	32.7	**136.1**	**124.4**	**94.8**	58.8
	50	Horizontal	29.6					
		Down on the ground	29.6	32.7	**136.1**	**124.4**	**94.8**	58.8
	75	Horizontal	66.6					
		Down on the ground	66.6	32.7	**136.1**	**124.4**	**94.8**	58.8
	100	Horizontal	118.4					
		Down on the ground	118.4	32.7	**136.1**	**124.4**	**94.8**	58.8
	267.4	Horizontal	846.6					
		Down on the ground	846.6	32.7	**136.1**	**124.4**	**94.8**	58.8
Summer	5	Horizontal	0.4					
		Down on the ground	0.4	8.8	44.4	40.4	30.0	13.9
	25	Horizontal	9.7					
		Down on the ground	9.7	32.7	**133.2**	**121.9**	**93.6**	54.1
	50	Horizontal	38.7					
		Down on the ground	38.7	32.7	**133.2**	**121.9**	**93.6**	54.1
	75	Horizontal	87.0					
		Down on the ground	87.0	32.7	**133.2**	**121.9**	**93.6**	54.1
	100	Horizontal	154.8					
		Down on the ground	154.8	32.7	**133.2**	**121.9**	**93.6**	54.1
	267.4	Horizontal	1106.5					
		Down on the ground	1106.5	32.7	**133.2**	**121.9**	**93.6**	54.1

Distances highlighted in bold black fonts are those scenarios which exceed the plant separation distance of 65m.

As for benefit from the firewater curtain that can be expected to reduce radiation effects are as follows:

- Effective against radiation from pool fire, however the flame height for a full surface bund fire is expected to be more than typical firewater curtain height, therefore firewater curtain will not be fully effective.
- No significant benefit for reduction of effects from large jet fire (i.e. with a flame length extending beyond bund limit)
- No benefit for reduction of overpressure/radiation effects from potential BLEVE

Table 8 *(continue)*

Means of Calibration	Explanation	Preferred Option
	Therefore, it can be concluded that, though some dilution effect can be expected, this cannot reasonably be quantified, and it is expected to be significantly less efficient for larger release cases as can be seen in Table 8a and 8b respectively. As such, it is concluded that the preferred option based on "*Consequence Assessment*" is Option 3.	

It is important to note, Risk (R) is the outcome of Consequences (C) and Probability (P) (R = C x P). In this sense, the installation of a firewater Curtain may be effective in reducing the "*consequences*" (e.g. gas dispersion, radiation) and will need to be quantified or justified technically. As explained in this study, no large effectiveness in terms of "*fire radiation*" and dilution for "*gas dispersion*" can be found or justified to-date.

Hence, even if a QRA was performed, the results would be likely be the same unless various assumptions are taken into consideration. The assumptions are as follows but not limited to:

- Effectiveness of firewater curtain in dilution for LPG gas clouds especially for large release size
- Effectiveness of embankment between two plants
- Response time of firewater curtain activation
- Ignition probabilities
- Frequency of releases
- Success rate of firewater activations

This is also in agreement with the analysis by Keith (2019), which concludes that QRA, PRA (Predictive Risk Assessment) and RAMs (Risk Assessment Matrix) have been comprehensively debunked because they contain multiple errors and constitute a prediction, which has been shown to be little more than guesswork. Hence for these above very reasons, this study only focussed on the consequence analysis as part of the ALARP Demonstration.

JUSTIFICATION FOR OPTIONS CONSIDERED

In view of the various aspects which were considered and explained in the previous section, the installation of a firewater curtain at the perimeter of the LPG sphere was determined not to be necessary. The main arguments to support this recommendation are as follows:

- INPEX Technical Standards do not recommend the use of a firewater curtain for the dilution of LPG releases
- Based on the literature survey that was conducted, there are large uncertainties associated with the dilution effect. In any case, the benefit expected is low for large releases and has the potential to reach the adjacent site even if the firewater curtain was installed.

- Firewater curtain activation time would be more than the time for the gas cloud to reach the adjacent site.
- Benefits on fire radiation are also expected to be limited especially for large releases.

Hence the risk reduction which is provided by the installation of a firewater curtain cannot be justified.

CONCLUSION

Based on the ALARP demonstration performed in this case study the following can be concluded:

- It is important that each Operator take ownership of all FSAs conducted in the EPC phase and re-validate them as part of the Operations Safety Case re-validation exercise.
- All FSA's to be updated based on the latest operating conditions to ensure the realistic HSE Risks determination
- ALARP demonstration decision context to be correctly based on the each scenarios/ options should be considered
- QRA and CBA (Cost Benefit Analysis) are not the only ways to demonstrate ALARP.

It is important to note that the current HSE risk (MAE risk), which has already been identified for the, does not change. Hence the residual risk of the selected option (i.e. no firewater curtain) is as per existing risk ranking (i.e. no change in risk status). Furthermore, it is important to note that all HSE Risks (MAE and Top 10 HSE Risks) are currently being managed by using a centralized HSE Risk Management Software, which is continuously reviewed.

Additional recommendations have been made to further mitigate the risk with other means. Other risk reduction measures, on top of existing current measures which have been proposed, are listed as follows but not limited to:

- A Preventive Maintenance regime (e.g. increased maintenance/inspection on LPG critical systems)
- Emergency Preparedness – Communication line to be established and tested (upon completion of adjacent independent power company's power plant)
- Traffic Light System linked to the GPA (General Plant Alarm) to provide a means of an early warning to the adjacent independent power company's power plant.

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A Novel Denoising Method of Defect Signals based on Ensemble Empirical Mode Decomposition and Energy-based Adaptive Thresholding

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ABSTRACT

In order to ensure the safe operation of oil and gas production systems, real-time online defect detection can play an important role. Among them, the first-hand magnetic eddy current signals can effectively identify the defects existing in the oil and gas pipeline, thereby avoiding serious casualties and economic losses. Aiming at the noise interference problem in signals, this research proposes a comprehensive adaptive noise reduction method based on ensemble empirical mode decomposition (EEMD) method and an energy-based adaptive thresholding method. The detailed steps are as follows: Firstly, a noisy signal is randomly selected in the defect signal database, and then EEMD is carried out to obtain a series of intrinsic mode functions (IMFs). Secondly, the distances measure method and the probability density function are used to identify the high noise IMFs and the low noise IMFs. Thirdly, an energy-based adaptive thresholding method is used to remove the noise of the high noise IMFs. Finally, the signal is reconstructed by combining the low noise IMFs with the high noise IMFs after noise reduction. The result of the proposed noise reduction method is compared with the results of other conventional methods. It is superior to other noise reduction methods in terms of signal-to-noise ratio, mean square error and percent root mean square difference. Therefore, the proposed noise reduction method is efficient and lays a foundation for pattern recognition of pipeline corrosion defects.

Keywords: Adaptive thresholding, ensemble empirical mode decomposition, magnetic eddy current, noise reduction

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INTRODUCTION

At present, signal analysis and processing technology have made great progress, and it has been widely used in petroleum, petrochemical, aerospace, transportation, computer and other industrial fields. Traditional noise reduction methods mainly include Fourier transform, Winer filtering, wavelet transform and so on. The Fourier transform is analyzed by mapping the signal time domain to the frequency domain. It is very practical for stationary signals under the condition that the spectral characteristics of the noise are different from the spectral characteristics of the signal. Wiener Filtering is an improved noise reduction method, but the basic theory is still based on Fourier transform. It is only suitable for stationary linear signals, which is not well suited for engineering signals.

However, the actual signal is usually a non-stationary signal. A wavelet transform method can make the effective components and the noises in the non-stationary signal show different characteristics respectively. Among them, the selection of the wavelet base has a great influence on the noise reduction effect, so the wavelet noise reduction lacks self-adaptability. In order to accurately describe the variation of frequency with time, a better adaptive method of instantaneous frequency analysis is needed. Norden E. Huang proposed a new signal processing method, namely Empirical Mode Decomposition (EMD) (Huang et al., 1998).

In essence, the method can smoothen the complex signal. The result is a gradual decomposition of fluctuations or trends in signals of different scales, resulting in a series of data sequences of different feature scales. On this basis, Flandrin et al. (2004) proposed an idea of EMD-based filter bank, which was an adaptive combination of high-pass, low-pass, band-pass or band-stop filter by selecting the intrinsic mode function of the corresponding order (Flandrin et al., 2004). Wu and Huang (2004), proved that the EMD method had a wavelet-like binary filter characteristic through a large number of experiments. Boudraa and Cexus (2007) used different closed-value methods for filtering and reconstructing each IMF to achieve signal noise reduction.

EMD has the advantage of wavelet transform and solves the problem of wavelet base selection in wavelet transform (Boudraa et al., 2004). In theory, it can be used for any type of signal decomposition. It can convert complex signals into limited order intrinsic mode functions (IMFs). Each order IMF component contains a local characteristic of the original signal on different time scales, and the instantaneous frequency of any point is meaningful (Dybała & Zimroz, 2014). Compared with other methods, the empirical mode decomposition method has a better capability of nonstationary and nonlinear signal processing. Therefore, the EMD method will be studied in depth in this research. However, the EMD method still has some shortcomings, one of which is the modal aliasing problem.

In order to improve the problem of modal aliasing, many researchers have conducted a lot of in-depth research. Tan proposed a multi-resolution EMD method to suppress mode aliasing (Tan et al., 2001). The range of feature scales of each order IMF is defined so that the implied scale components causing mode aliasing are separated from other components. The experimental results show that the method is effective in suppressing mode aliasing, but it sacrifices the time-frequency adaptive property of empirical mode decomposition. Aijun et al. (2011) proposed a method of eliminating mode aliasing by adding high-frequency harmonics and then performing EMD decomposition, which effectively eliminated the mode aliasing phenomenon, but it was difficult to pick the high frequency and amplitude added (Aijun et al., 2011). Based on the shortcomings of the above EMD improvement methods, this research proposes to use EEMD to reduce the noise of magnetic eddy current defect signal. EEMD is an improved EMD algorithm proposed by Norden E. Huang, which effectively solves the mixing phenomenon of EMD. Although EEMD has some problems such as large computation, decomposition times and noise amplitude, the results obtained by EEMD to suppress modal aliasing are still acceptable (Zhang et al., 2010). On this basis, it still needs to solve some problems about how to select high noise IMF components efficiently and reasonably.

Therefore, some scholars proposed to use the correlation coefficient method and Kullback-Leibler (KL) divergence based on information theory to remove the invalid IMF components (Komaty et al., 2013). The threshold selection of the two methods is based on the experience of some signals. The correlation coefficient method has good adaptability and can be used for general faults. The disadvantage is that the discrimination degree is small, the differential effect is not obvious, and the signal near the threshold boundary is prone to misjudgment. The advantage of the KL divergence is that the degree of discrimination is large, and the different effect is obvious. The disadvantage is that the adaptability is poor and the sensitivity is large.

The purpose of this research is to develop an adaptive noise reduction method by using the EEMD method and energy-based adaptive thresholding optimization technology for filtering noise in the eddy current signals. In order to evaluate the noise reduction effect of the proposed method, it is common to use actual signals.

MATERIALS AND METHODS

The noise reduction method proposed in this research is composed of three main parts: EEMD method, IMFs selection, and energy-based adaptive thresholding. Among these approaches, EEMD can decompose the original signal into a set of intrinsic mode functions that reveals the physical connotation of the signal, and effectively suppress the problem of mode aliasing in empirical mode decomposition by means of noise-assisted analysis. IMFs selection is mainly composed of probability density function and distances measure to distinguish the high noise IMFs with low noise IMFs. Probability density function graph can preliminarily find out the similarity between the original signal and each IMF. The distance-based measure can further distinguish high-noise IMF components with low-noise

IMF components. The energy-based adaptive threshold can adaptively set a corresponding threshold according to the nature of each IMF energy. Finally, the final reconstructed signal Z(t) is obtained by combining the denoised high-noise IMF components with the low-noise IMF components (Figure 1).

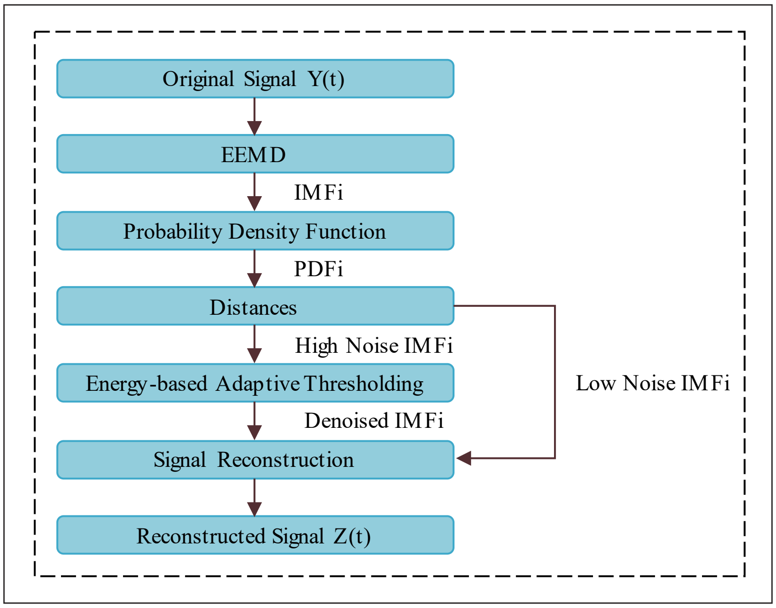

Figure 1. The procedure of the novel noise reduction method

Ensemble Empirical Mode Decomposition

The EMD algorithm can decompose a signal into several IMFs by filtering, and each IMF represents the intrinsic characteristic vibration form of the signal. The residual component reflects the trend of slow change in the signal. By analyzing each IMF, the feature information of the original data can be grasped more accurately and effectively. EMD has the characteristics of a binary filter bank, but this feature is destroyed because of mode aliasing problem. To solve this problem, Huang and Wu (2009) proposed the EEMD method.

The essence of EEMD is to add white noise to the original signal to smooth the abnormal signal and make use of the uniform distribution characteristic of the white noise spectrum to automatically distribute the signals on different time scales to the appropriate reference scales. Meanwhile, the decomposed IMFs will inevitably contain random noise signals. White noise has the characteristic of zero mean value. Multiple averages can make the noise offset each other, which can effectively suppress or even completely eliminate the influence of noise. That is, it is a multiple empirical mode decomposition of superimposed white Gaussian noise. The detailed steps of the EEMD algorithm are as follows:

1. Add a certain signal-to-noise ratio of white noise to the target signal $y(t)$.

$$y_i(t) = y(t) + n_i(t) \tag{1}$$

Where,
$y_i(t)$ is the signal after adding white noise for the *i*th time;
$n_i(t)$ is the white Gaussian noise added for the *i*th time.

2. The EMD decomposition is performed on $y_i(t)$, and the corresponding IMF components and residual component are obtained. The signal is expressed as:

$$y_i(t) = \sum_{j=1}^{n} c_{ij}(t) + r_i(t) \tag{2}$$

Where,
$c_{ij}(t)$ is the *j*th component obtained by the *i*th decomposition.

3. Take the average value of IMF components $c_{ij}(t)$ as the final decomposition result of EEMD. The formula is as follows:

$$c_j(t) = \frac{1}{M}\sum_{i=1}^{M} c_{ij}(t) \tag{3}$$

Where,
$c_j(t)$ is the *j*th component of EEMD, *M* is the total number of EMD.

Moreover, the frequency of added white Gaussian noise in EEMD obeys the following rule:

$$\varepsilon_n = \frac{\varepsilon}{\sqrt{N}} \tag{4}$$

Where,
ε_n is the error between the original signal and the signal resulting from the superposition of the final IMFs. ε is the amplitude of white Gaussian noise. It can be found that with the increase of the total number *N* of IMFs, the result of the final decomposition is closer to the real value.

4. The original signal $y(t)$ can be expressed as follows:

$$y(t) = \sum_{i=1}^{n} c_j(t) + r_n(t) \tag{5}$$

Therefore, as shown in Figure 2, the magnetic eddy current signal of the pipeline is decomposed by EEMD.

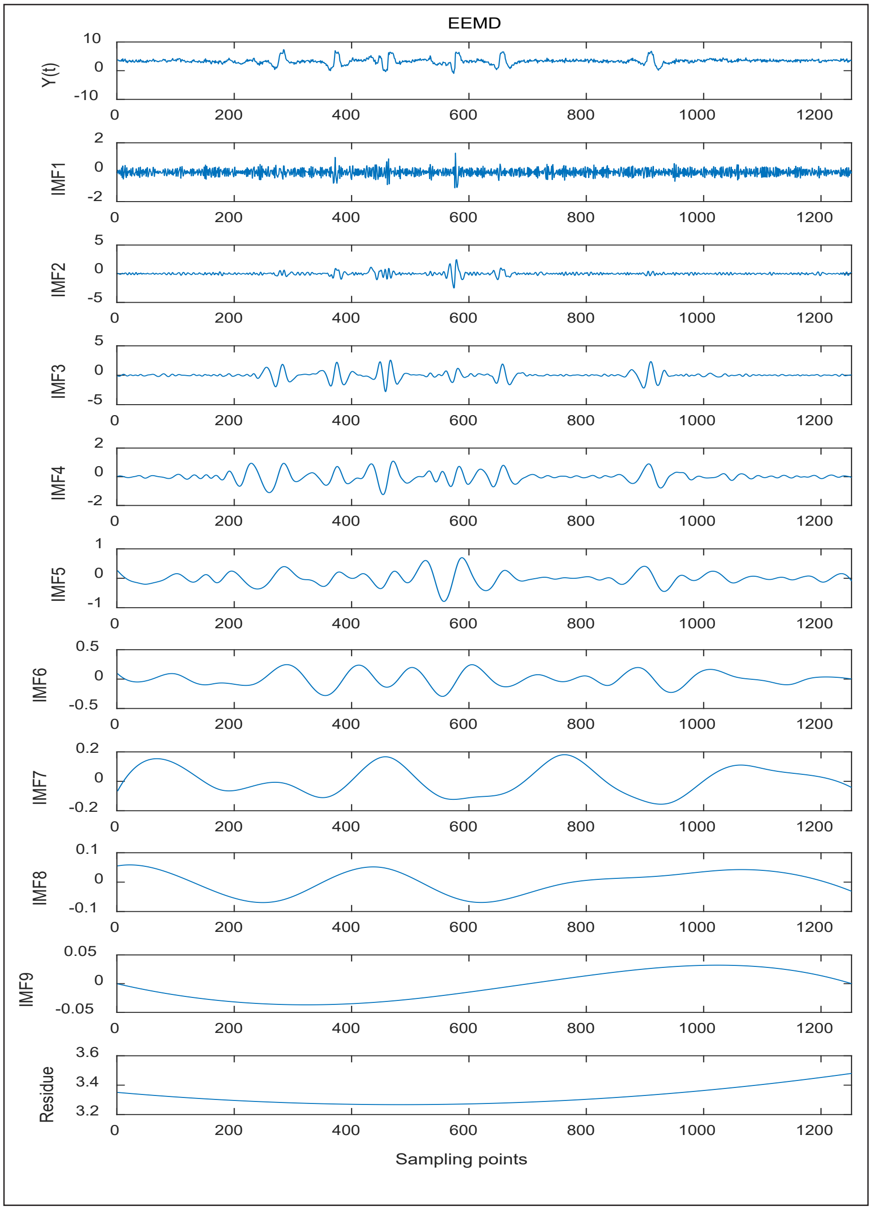

Figure 2. EEMD decomposition of original signal Y(t)

Measures

In the classification algorithm, it is widely used to calculate the distance between two input variables, that is, measurement. In some cases, the results of different measures are quite different from each other. Therefore, it is necessary to choose an appropriate measurement tool according to the characteristics of input data. The measure is composed of the similarity measures and distance measures (Xuecheng, 1992).

If the similarity degree of the two sample points in the similarity measure function is high, the similarity measure value is large. If the sample points are not similar, the similarity measure value is small. In this way, the similarity of sample points can be compared.

In the distance function, each sample point can be regarded as a point in the high-dimensional space, and then a certain distance can be used to represent the similarity between the sample points. The closer sample points are more similar in nature. On the contrary, the greater the distance between sample points, the greater the difference.

Similarity Measures

Correlation Coefficient Method. The correlation coefficient is a statistical indicator to reflect the degree of the correlation between variables (Ye, 2013). The correlation coefficient is calculated by the product difference method, which is also based on the deviation of the two variables and their respective averages. The two deviations are multiplied to reflect the degree of correlation between the two variables.

$$r_i = \frac{\sum_{i=1}^{n}\left(x_i - \overline{x}_i\right)\left(y_i - \overline{y}_i\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \overline{x}_i\right)^2 \sum_{i=1}^{n}\left(y_i - \overline{y}_i\right)^2}} \tag{6}$$

$$\overline{x}_i = \frac{\sum_{i=1}^{n} x_i}{n} \tag{7}$$

$$\overline{y}_i = \frac{\sum_{i=1}^{n} y_i}{n} \tag{8}$$

Where, r_i is the correlation coefficient value between the two vectors, $\overline{x}_i$ and $\overline{y}_i$ are the average values of the two vectors, respectively. In this research, the two vectors represent each IMF component obtained after EEMD decomposition and the original signal.

Angular Similarity Method.

$$S\left(X_i, X_j\right) = \frac{X_i^T X}{\left\|X_i\right\| \cdot \left\|X_j\right\|} \tag{9}$$

The measure of angle cosine reflects the geometric similarity, which is invariable for the rotation and scaling of the coordinate system, but it is not invariable for displacement and general linear transformation (Ji et al., 2014).

Kullback-Leibler Divergence (KLD) Method. An unknown distribution $p(x)$ is assumed to be modelled with an approximate distribution $q(x)$, and $q(x)$ is used to create an encoding system that passes the value of x to the receiver.

$$KLD(p \| q) = -\int p(x) \ln\left[\frac{q(x)}{p(x)}\right] dx \qquad (10)$$

Since $q(x)$ is not the true distribution $p(x)$, the average encoding length will increase compared with the true distribution $p(x)$ for encoding information, the increased information amount is *KLD*, also known as relative entropy (So et al., 2016). Figure 3 shows the three similarity measurement curves of the original signal and each IMF component after the EEMD decomposition.

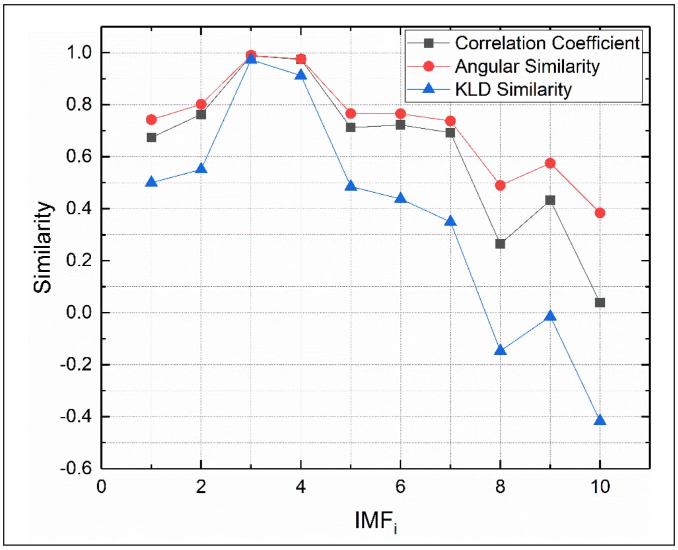

Figure 3. Similarity measures of the original signal and corresponding IMF components

Distance Measures

Euclidean Distance Measure. It is equivalent to the point-to-point distance represented by a vector in a high-dimensional space, which can intuitively represent the similarity between modes. The smaller the distance, the more similar.

$$D(X_i, X_j) = \|X_i - X_j\|_2 \qquad (11)$$

Since the dimensions of each component of the feature vector are inconsistent, it is usually necessary to standardize each component, so that it is independent of the unit. For example, Euclidean distance may produce invalid results for two different indexes of height and weight (Siless et al., 2018).

Manhattan Distance Measure. In Manhattan, someone needs to drive from one intersection to another. The driving distance is not a straight line between two points. The actual driving distance is "Manhattan distance". Manhattan distance is also known as the city block distance (Thakur et al., 2019).

$$dis_{man}\left(x,y\right)=\sum_{i=1}^{n}\left|x_i-y_i\right| \tag{12}$$

The above equation represents the Manhattan distance between two points on an n-dimensional plane.

Chebyshev Distance Measure. If there are two vectors or two points p and q, whose coordinates are p_i and q_i, respectively, then the Chebyshev distance between them is defined as follows:

$$D_{Chebyshev}\left(p,q\right)=\max_i\left|p_i-q_i\right| \tag{13}$$

The above formula is also equal to the extreme value of the following L_p metrics:

$$\lim_{k\to\infty}\left(\sum_{i=1}^{n}\left|p_i-q_i\right|^k\right)^{1/k} \tag{14}$$

So Chebyshev distance is also called the L_∞ measure. From a mathematical point of view, Chebyshev distance is a measure derived from a uniform norm, which is also a kind of super-convex metric (Bhunre et al., 2019). The distance measurement between the original signal and each IMF component is shown in Figure 4.

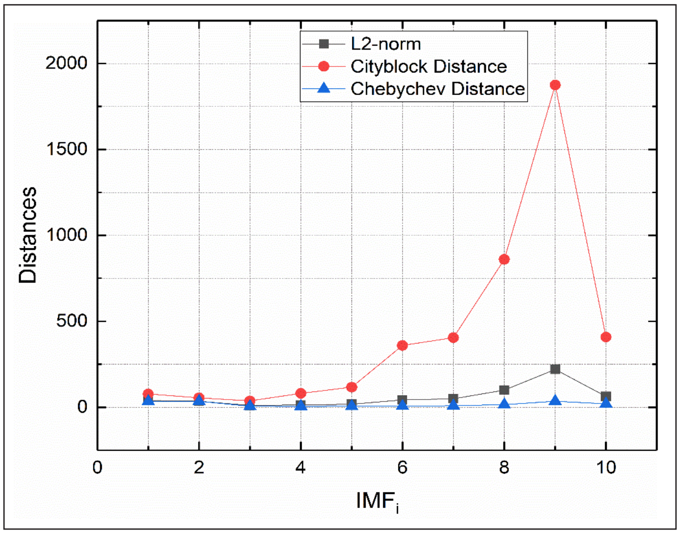

Figure 4. Distance measures of the original signal and corresponding IMF components

Energy-based Adaptive Thresholding

After the EEMD decomposes the noisy signal, the IMF component of each order is obtained. Then, a reasonable threshold is selected for the high-noise IMF component, and the corresponding IMF component is processed by the obtained threshold. Therefore, threshold selection is crucial.

In this research an energy-based adaptive thresholding method inspired by wavelet thresholding is proposed. According to the energy characteristic of each IMF, the method adapts to the special property of each IMF, which breaks the limitation of wavelet fixed threshold, so it can better reduce the noise of the IMF components (Geryes et al., 2019).

The signal $y(t)$ is decomposed by EEMD to obtain IMF components, and some reasonable thresholds are selected for each high-noise IMF component, and these thresholds convert c_i to $\tilde{c}_i$ and then reconstruct the EEMD. The reconstructed signal can be expressed as follows:

$$z(t) = \sum_{i=1}^{M} \tilde{c}_i + \sum_{i=M+1}^{N} c_i + r \tag{15}$$

Where $z(t)$ is the reconstructed signal, $\tilde{c}_i$ is the IMF components requiring threshold processing, and M is the number of IMFs threshold processing. c_i is the unprocessed IMF component, r is the residual component, and N is the total number of IMF components (Kopsinis & McLaughlin, 2009).

The EEMD decomposition is similar to the wavelet transform, and the noise is mainly concentrated in the first component that is decomposed. Thus, in the adaptive threshold noise reduction of EEMD, the estimated noise variance is taken as IMF1. That is, the noise variance is estimated according to the following formula:

$$\sigma = \frac{MAD\left(\left|IMF_1\right|\right)}{0.6745} \tag{16}$$

Where, *MAD* represents the mean absolute deviation, and *IMF1* is the intrinsic mode function of the first layer obtained by EEMD. With respect to the threshold selection, the universal threshold $T=\sigma\sqrt{2\ln N}$ is widely used. However, different IMFs have different energy components, which is clearly inappropriate of the fixed threshold noise reduction for different energy IMFs. The energy formula is as follows:

$$E_k = \frac{1}{N}\left(\sum_{i=1}^{N}\left(IMF_{ki}\right)^2\right) \tag{17}$$

Where E_k is the energy of the kth IMF, and N represents the length of the IMF sequence of each order. It turns out that the noise contained in each IMF component is coloured and has different energies. An improved universal threshold is especially important, as follows:

$$T_k = C\sqrt{E_k 2\ln N} \qquad (18)$$

Where C is a constant. It can usually be determined through experiments, which can be preliminarily selected as σ.

RESULTS AND DISCUSSION

Noise Reduction Test of The Proposed Method

In order to verify the effectiveness of the proposed noise reduction method, a segment of signal in the actual magnetic eddy current signal database was randomly selected for noise reduction. The signal can be described as in Figure 5.

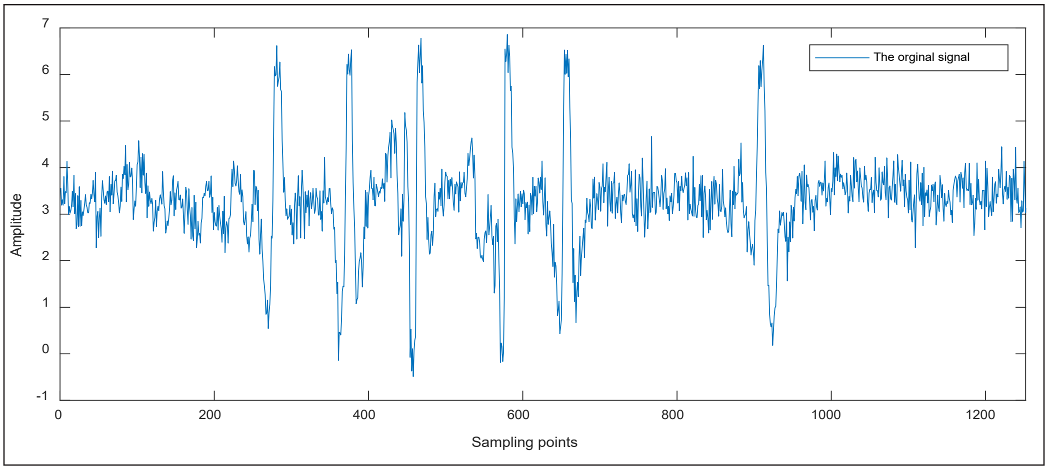

Figure 5. Original defects signal. Signal Y(t) represents an original noisy signal, which includes six irregularly sized corrosion defects.

According to the procedure of the proposed noise reduction method, EEMD decomposition of the noisy signal is carried out to obtain each IMF component (Figure 2). The comparison of probability density function (PDF) of the original signal Y(t) with the corresponding IMFs provides a preliminary and intuitive observation of the similarity between each IMF and the original signal as shown in Figure 6 (Komaty, 2013).

Meanwhile, the similarity measure in Figure 3 shows that the similarity reaches the maximum when IMF=3, and then the similarity gradually decreases. It can be found in Figure 4 that the distance measure increases sharply when IMF=9 and the scale of the probability density function of Figure 6 also confirm the accuracy of the distance measures. Therefore, the number of IMF requiring threshold processing is M=9.

Then, the energy-based adaptive threshold was used to remove the high noise of the selected IMF components. The energy corresponding to each IMF can be obtained from equation 17, so as to obtain the adaptive threshold value. The adaptive threshold can remove the impurity noise of high noise IMFs. According to equation 15, the noise reduction diagram shown in Figure 7 is obtained.

By comparing the signals before and after noise reduction in Figure 5 and Figure 7, it can be found that the proposed noise reduction method can effectively retain the overall shape features of defect signals, laying a foundation for feature extraction and pattern recognition of defect signals later.

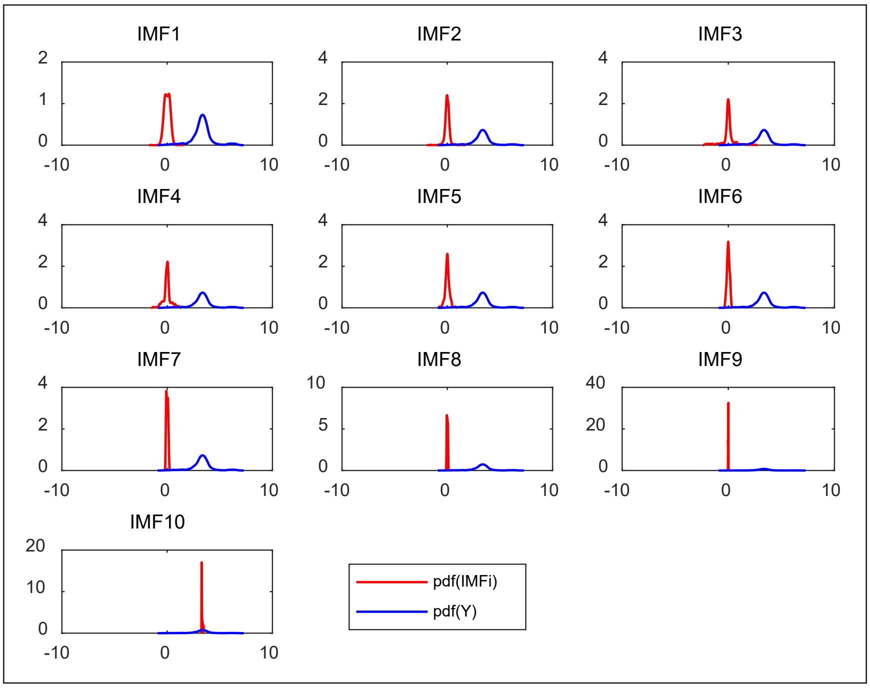

Figure 6. Comparison of PDF of original signal Y(t) and corresponding IMFs

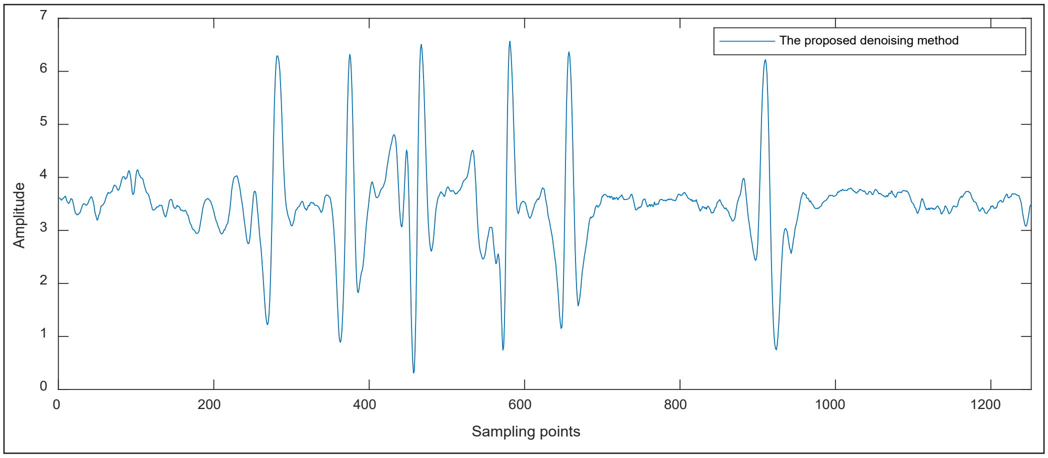

Figure 7. The noise reduction results of the proposed method

Performance Comparison

The proposed noise reduction method was compared with the wavelet soft threshold noise reduction method and wavelet hard threshold noise reduction method. The noise reduction effect of the signal is quantified by signal to noise ratio (SNR), mean square error (MSE) and percent root means square difference (PRD). The expressions of SNR, MSE, and PRD are as follows:

$$SNR = 10\log_{10}\left[\frac{\sum_{j=1}^{N} x^2(j)}{\sum_{j=1}^{N}[x(j)-\hat{x}(j)]^2}\right] \tag{19}$$

$$MSE = \frac{1}{N}\sum_{j=1}^{N}\left[x(j)-\hat{x}(j)\right]^2 \tag{20}$$

$$PRD = 100\sqrt{\frac{\sum_{j=1}^{N}\left(x(j)-\hat{x}(j)\right)^2}{\sum_{j=1}^{N}\hat{x}^2(j)}} \tag{21}$$

Where, $x(j)$ is the amplitude of the original signal at the sampling point j. $\hat{x}(j)$ is the amplitude of the denoised signal at position j. N is the length of the signal.

The noise reduction result of wavelet soft threshold method, wavelet hard threshold method and the proposed denoising method in this research were compared, as shown in Figure 7, Figure 8 and Figure 9 respectively. In addition, the comparison of SNR, MSE and PRD before and after signal noise reduction shows that the proposed denoising method in

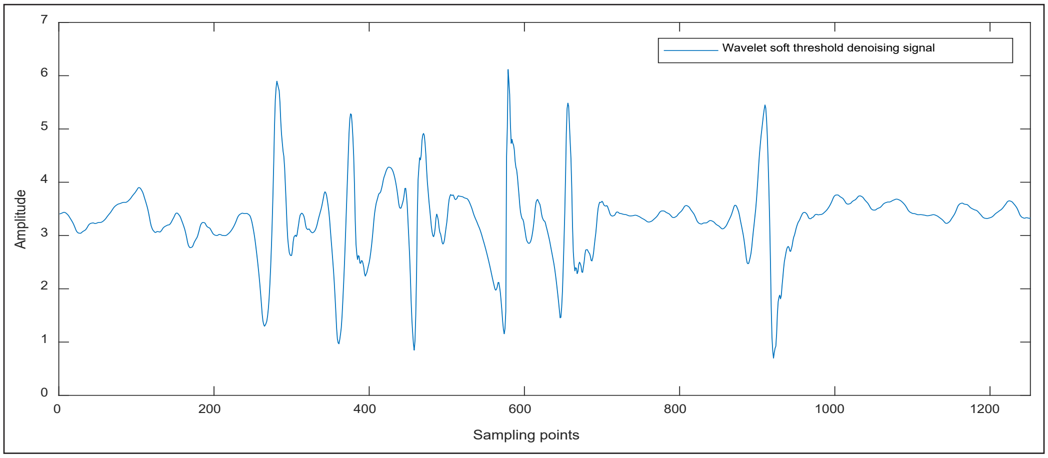

Figure 8. The noise reduction of wavelet soft threshold method

this research can improve the SNR of pipeline magnetic eddy current defect signals and reduce the MSE and PRD of signals as shown in Table 1.

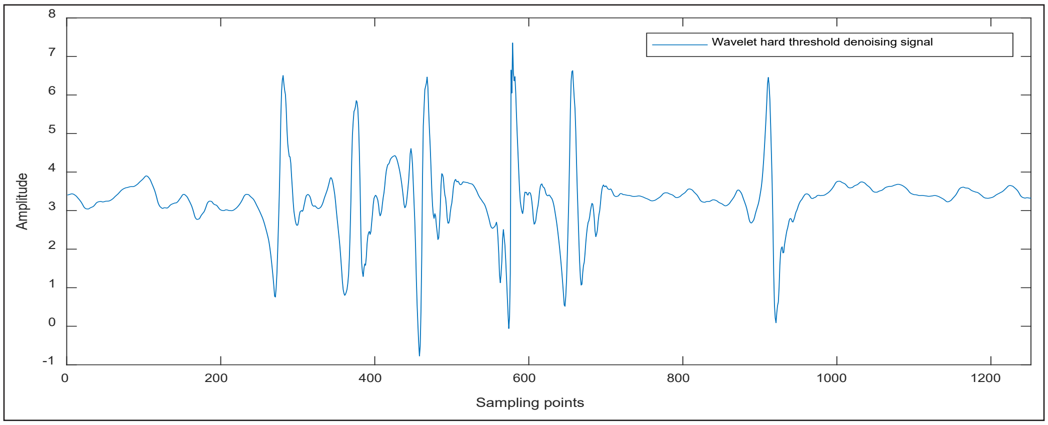

Figure 9. The noise reduction of wavelet hard threshold method

Table 1
SNR, MSE and PRD comparison for noised defect signal

	Wavelet soft threshold method	Wavelet hard threshold method	The proposed method
SNR	15.7443	17.7891	19.1886
MSE	0.3019	0.1932	0.1536
PRD	0.1632	0.1290	0.1098

CONCLUSION

A new adaptive noise reduction method is presented in this research. This method includes EEMD decomposition, PDF visualization comparison, PDF similarity measure comparison, energy-based adaptive thresholding, signal reconstruction. Combined with PDF intuitive comparison and measure analysis of each IMF and the original signal, the boundary value of the high-noise IMF component and low-noise IMF component is more accurately obtained. Among them, the Manhattan distance measure can better identify the boundary than other measures in the measure analysis. At the same time, according to the energy characteristics of each IMF, an adaptive energy-based thresholding method is proposed, and it is superior to wavelet hard threshold denoising method and soft threshold denoising method when it is applied to actual magnetic eddy current signal noise reduction. In fact, the proposed denoising method is also applied to many other magnetic eddy current signals, and the denoising effect is obvious. In addition, the proposed noise reduction method is likely to be used in noise reduction processing of other detection signals, such as the vibration signal of gearbox and compressor.

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Design of Household Products Ingredients wiıth Minimum Safety and Health Risk

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ABSTRACT

In household products, specific chemical ingredients are used to satisfy the desired target properties as required by the consumers. However, some of these ingredients may result in safety risks and adverse health effects. Early consideration of safety and health aspects during product design is vital to minimize the impact on consumers. Safety and health aspects have not been strongly emphasized before in many product design methodologies. Therefore, a systematic methodology is proposed to assess the safety and health effects of the potential ingredients, before they are used in the product formulation. The chemical ingredient candidate may be a novel ingredient or a typical ingredient used in formulated product design. In this work, a computer-aided molecular design (CAMD) technique was used to design the novel ingredient candidates with the integration of safety and health aspects. Then, the safety and health performance of the ingredient candidates were assessed by inherent safety and health sub-indexes. Each safety or health parameter was assigned with a score, based on the degree of the potential hazards. A higher score was given to the ingredients with higher safety risk or more severe health effect, and *vice versa*. The result of the safety and health assessment based on the

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score allocation had contributed to the selection of chemical ingredient. This new approach ensures that the selected ingredient possesses desirable properties as well as low safety and health effects. A case study on surfactant design is presented to illustrate the incorporation of safety and health aspects into product design methodologies.

Keywords: Health, household product design, optimization, risk, safety

INTRODUCTION

Household products are widely and regularly being used in daily activities for cleaning, refreshing, and bleaching. The increase of household chemical usage has resulted in health impact to the consumer. Children around five years old are suffering from respiratory tract irritation due to exposure to household chemicals (Mikes et al., 2019). Dermal exposure to household chemicals such as geraniol has led to skin sensitization (Jongeneel et al., 2018). Health risk assessment on hazardous ingredients contained in cleaning products has been performed for chloroxylenol (Yost et al., 2016), geraniol (Jongeneel et al., 2018) and isothiazolinones (Garcia-Hidalgo et al., 2018). Meanwhile, dermal and inhalation exposure assessments of deodorizing products have been conducted by Kim et al. (2018) and Lee et al. (2018). Current health risk assessments are more focused on assessing the household chemicals in a finished product rather than estimating the health impact during the early stage of product design. If hazardous chemicals can be identified during the early product design stage, it can be replaced with inherently safer chemicals. This type of safety concept is known as inherent safety, which was first introduced in the 1970s by Trevor Kletz (as cited in Srinivasan & Natarajan, 2012). The basic concept of inherent safety and health includes minimization, substitution, moderation and simplification (Crowl & Louvar, 2011). The adoption of inherent safety principles into product design can be made by avoiding the use of hazardous chemicals during product formulation design.

A computer-aided molecular design (CAMD) technique is identified to be a powerful tool to quickly generate and evaluate the vast number of molecules that possess certain desirable functional properties (Liu et al., 2019). It is noted that in most CAMD problems, the main design criteria are the molecular functionalities as represented by the physical and chemical properties. However, these molecules that meet the functional properties may cause safety risks and adverse health effects. Several works have been presented on a molecular design where safety and health properties have been integrated into CAMD. The integration of both safety and health properties into the CAMD framework is developed by assigning each property with a score based on the degree of potential hazards (Ten et al., 2016). The generated molecule with a higher score has a higher hazard level and vice versa. The aspect of safety has been included in designing solvent candidates to be used as bio-oil additives (Mah et al., 2019). CAMD has also been used to identify alternative solvents to extract residual oil from palm pressed fibre with the consideration of safety aspect

(Ooi et al., 2019). Limited CAMD works have been reported on the design of household products ingredients with safety and health aspects as target properties. Furthermore, the design of chemical candidates has incorporated limited aspects of safety and health as it is restricted to the availability of property prediction model. More environmental-related property models have been established by Hukkerikar et al. (2012a) in comparison to safety and health properties.

The safety and health aspects have not been emphasized before in many of CAMD problems, especially for household products. The design of novel chemical ingredients must be optimized not only in terms of functional properties but also their safety and health performance. In addition, there is a lack of a systematic safety and health assessments methodology that can be integrated during the early stage of product design. The safety and health performance of the generated molecule by CAMD (novel ingredient) and the typical ingredient used in product formulation must be assessed to ensure that the selected chemical ingredients meet the functional criteria as well as safe to consume. In this work, the safety and health properties are incorporated into CAMD technique coupling with safety and health assessments through an index-based methodology. This new approach has highlighted the safety and health aspects during the early stage of product design.

MATERIALS AND METHODS

Design of Novel Ingredients

The molecular design problem began with the identification of product functionality properties. These product functionality properties were matched in physical and chemical properties. Such properties are known as target properties (V_p), which must fall within the specified upper bounds (v_p^U) and lower bounds (v_p^L) to ensure that the molecules function and behave in the desired characteristics. This constraint is shown in Equation (1) following the CAMD approach.

$$v_p^L \leq V_p \leq v_p^U \qquad \forall p \in P \tag{1}$$

where p represents the target property and V_p is for target property value.

The target properties were then calculated through the property prediction models following the selected groups of building blocks. An established approach known as group contribution method (GCM) was used to estimate the target physical and chemical properties of a molecule. The target property can be estimated by summing up the frequency of each selected group in the molecule multiplied by its contribution (Marrero & Gani, 2001) as shown in Equation (2).

$$f(X) = \sum N_i C_i \tag{2}$$

where *f (X)* is the function of the target property *X*, C_i is the contribution of the first-order group that occurs N_i times. The first-order groups comprise a large set of simple and basic molecular groups that cover a wide range of organic compounds including CH3, CH2, CH, CHO and OH.

In the optimization model, the single-objective optimization problem was solved where only one target property was selected as an objective function. The remaining target properties would act as property constraints to be fulfilled. The target properties and its GCM equation models are shown in Supplementary Table 1 in Appendix. The physical and chemical properties considered were molecular weight (M_w), melting point (T_m) and boiling point (T_b). The safety property is represented by the value of flammability which is based on the value of flashpoint, Fp and boiling point, $T_{b.}$ Meanwhile, health properties including toxicity (LD_{50}) and permissible exposure limit (PEL) are considered. The property model of PEL represents the chronic type of toxicity from the dermal and inhalation route with the basis of 8 hours daily exposure time. The optimal molecules were then evaluated based on their safety and health performance by the application of product ingredient safety index (PISI). With this, only molecules that are inherently safer and healthier as well as meeting the desired target properties are selected for product formulation design.

Selection of Typical Ingredients

The selection of typical ingredients has been discussed by Zhang et al. (2017) where chemical ingredient databases and rule-based methods were applied. The chemical ingredient databases can be obtained from National Institute of Standards and Technology (NIST) Chemistry WebBook and Integrated Computer Aided System (ICAS) database. Besides, the rule-based methods have been used to select the chemical ingredient as presented in the design of inkjet ink (Tam et al., 2016) and cream and paste (Wibowo & Ng, 2001). However, not all the typical chemical ingredients possess the properties that are needed for the product. Therefore, a novel chemical ingredient can be designed.

Safety and Health Assessments by Applying Product Ingredient Safety Index (PISI)

The chemical ingredient candidates (novel and typical ingredients) are evaluated based on their safety and health performances by the application of Product Ingredient Safety Index (PISI). It is applied to estimate the potential hazards at the early stage of product design, which is after the generation of ingredient candidates. In PISI, a score is assigned to distinguish among the low, medium and high degree of safety and health effects of the ingredients. A higher number of score indicates a higher degree of the severity of the hazards and vice versa. The lowest score is “zero” to indicate that the ingredient does not affect the particular safety or health property. The score of 1 represents low safety and health effects and a score of 2 for medium effects. The high scores of 3 and 4 are assigned to indicate the high degree of safety and health effects. In this work, it was proposed that ingredient with a low degree of effects (score of 2 and below) was selected for the design of product formulation.

There are seven sub-indexes presented in PISI including flammability, toxicity, PEL, eye, skin, inhalation and ingestion exposures. The existing inherent safety and health indexes are modified and applied to assess the level of severity of safety and health effects caused by the ingredient candidates. The scores assigned to the sub-indexes are shown in supplementary materials (Supplementary Table 2 to Supplementary Table 8). Flammability is based on the flashpoint and boiling point where it was assessed following the established rating system by the National Fire Protection Association (National Fire Protection Association, 2020). The acute oral toxicity, LD_{50} was assessed to estimate the potential of the chemical ingredient to cause acute health effect. Since the group contribution model for LD_{50} (acute oral toxicity) is available, it is included as toxicity sub-index. Meanwhile, the exposure limit is represented by the data on PEL for chronic type toxicity. Hazard classification developed by Globally Harmonised System of Classification and Labelling of Chemicals (United Nations, 2013) provides the hazard indication corresponding to the level of danger by using precautionary statements and hazard codes. The GHS classification of a chemical substance is available in material safety data sheets (MSDS), chemical safety data sheets (CSDS) and chemistry database provided by the National Institute of Health (NIH) via PubChem search engine. The allocation of scores for the eye, skin, inhalation and ingestion exposures are based on the severity level of the health hazard effects. The higher the severity of the effect, the higher the score is allocated. The workflow of the safety and health assessments of the novel and typical ingredients is shown in Figure 1.

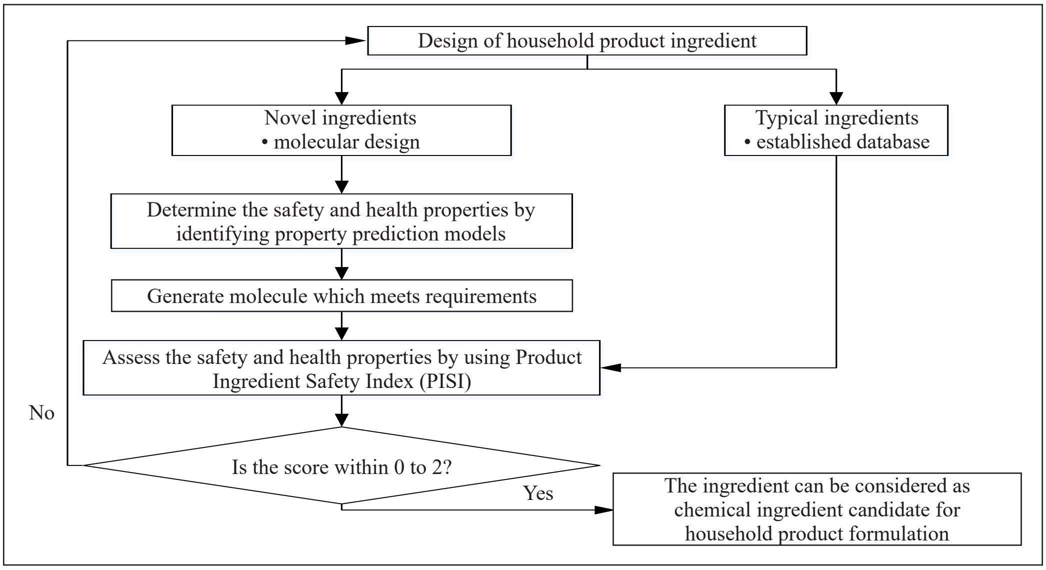


Figure 1. Work-flow diagram of household product ingredient design

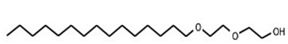
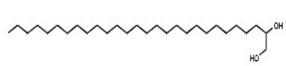
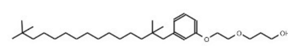
RESULTS AND DISCUSSION

The safety and health assessments by the application of PISI for two case studies on a novel and typical ingredients used in surfactant design are presented. Surfactant is an active ingredient used in household cleaning products. The surfactant must not only possess high cleaning performance but also able to protect the consumers' skin and has low toxicity (Mattei et al., 2013).

Design of Novel Ingredients

The novel ingredients were designed by selecting the following groups of molecular blocks such as CH_3, CH_2, CH, OH, CH_2O, aCO, aCH and aCC. The objective was to design a non-ionic surfactant with minimum toxicity potential. Hence, single-objective optimization was used in CAMD technique where acute oral toxicity, LD_{50} was chosen as an objective function. The optimal surfactant molecule was screened out and generated by CAMD. There were three non-ionic surfactants obtained, which were linear alkyl ethoxylate (surfactant 1), alkanediol (surfactant 2) and phenol ethoxylate (surfactant 3). The molecular structure and the target properties are shown in Table 1. All properties are determined using the property prediction model as shown in Supplementary Table 1.

Table 1
Properties of novel ingredients

Properties	Surfactant 1	Surfactant 2	Surfactant 3
Molecule	$C_{19}H_{40}O_3$	$C_{28}H_{58}O_2$	$C_{30}H_{54}O_3$
Molecular structure			
Mw (g/mol)	316.53	426.77	462.76
Fp (°C)	248.03	370.86	343.33
T_m (°C)	61.08	112.70	120.45
T_b (°C)	377.80	462.72	452.88
LD_{50} (mg/kg)	145.13	235.47	57.55
PEL (ppm)	6.04	5.16	0.12

The allocation of scores for the three generated surfactant molecules shown in Table 2 is based on the safety and health sub-indexes presented in PISI. All the molecules obtained a score of 1 for flammability sub-index indicating that the molecules possessed low flammability potential. Meanwhile, the three surfactant molecules also received a similar score of 2 for toxicity potential. For PEL, surfactant 3 received a high score of 4, indicating that it has a higher potential of health hazard in comparison to surfactant 1 and surfactant 2 that received a score of 3. However, all the novel surfactant molecules can be considered as a highly hazardous ingredient concerning PEL. Thus, it can be decided that no generated surfactant molecule can be selected as the ingredient candidates for household product formulation.

Table 2
Scores of novel ingredients

Properties	Surfactant 1	Surfactant 2	Surfactant 3
Flammability	1	1	1
LD_{50}	2	2	2
PEL	3	3	4

Selection of Typical Ingredients

The typical ingredient candidates of surfactants are taken from the detergent formulation established by Zhang et al. (2017) and Seider et al. (2017). The physical and chemical properties of the typical ingredients including the flash point and boiling point are shown in Table 3. The health hazard potential is represented by referring to the hazard classification of four exposure routes of eye, skin, inhalation and ingestion (United Nations, 2013).

Table 3
Properties of typical ingredients

Properties	Alcohol ethoxylate	Alkyl N-methyl glucamide	Nonoxynol-9
Fp (°C)	77.2	110	197
T_b (°C)	225.6	300	250
LD_{50} (mg/kg)	2850	500	1400
PEL (ppm)	Not available	Not available	Not available
Eye	H318	H318	H319
Skin	No effect	No effect	H315
Inhalation	No effect	No effect	No effect
Ingestion	H302	No effect	H302

The scores of the typical surfactant candidates are given based on the safety and health sub-indexes in PISI as shown in Table 4. The alcohol ethoxylate obtained a high score of 3 for eye exposure hazard and score of 2 for flammability potential. For alkyl N-methyl glucamide, no high scores were obtained indicating a low safety and health hazard potential. Furthermore, nonoxynol-9 received a high score of 3 for eye exposure, while a score of 2 for skin exposure. According to Mattei et al. (2014), the usage of non-ionic surfactant is known to be much gentler on skin compared to other types of surfactant. However, nonoxynol-9 has the potential to cause skin irritation as shown by the hazard statement, H315 in Table 3. For alkyl N-methyl glucamide, the low score of 1 is received for flammability and score of 2 for eye exposure. As a whole, alcohol ethoxylate and nonoxynol-9 possessed a high degree of severity of eye exposure. It is worth to note that alkyl N-methyl glucamide is found to be safer and healthier compared to the other two surfactant candidates since it only received scores of 2 and below. Hence, alkyl N-methyl glucamide can be considered as surfactant candidates in the product formulation.

Table 4
Scores of typical ingredients

Properties	Alcohol ethoxylate	Alkyl N-methyl glucamide	Nonoxynol-9
Fp	2	1	1
T_b	0	0	0
LD_{50}	0	2	1
Eye	3	2	3
Skin	0	0	2
Inhalation	0	0	0
Ingestion	1	0	1

The design of surfactant presented by Liu et al. (2019) and Seider et al. (2017) had highlighted the environmental toxicity where LC_{50} property was optimized. It is noted that the safety and health effects of the surfactant had not been considered. However, in this work, two steps of safety and health aspects had been taken into consideration. Firstly, the safety and health aspects had been incorporated into the product design. Secondly, the safety and health performance of the ingredient candidates was assessed by using PISI. The safety and health performance of the generated novel ingredients was assessed by considering its flammability, LD_{50} and PEL. Thus, the score assigned to the novel ingredient is referring to the sub-indexes presented in Supplementary Table 2, Supplementary Table 3 and Supplementary Table 4. The eye, skin, inhalation and ingestion sub-indexes are not applicable since no data on hazard classification by GHS are available for novel ingredients. On the other hand, the safety and health performance of the typical ingredient candidates can be assessed based on all sub-indexes presented in PISI because the safety and health properties required can be obtained. The ingredient with a low score (score of 2 and below) can be considered as safe and can be selected as feasible surfactant candidate for household product formulation.

CONCLUSION

The proposed methodology is capable of helping users on decision making to consider the selection of safer and healthier ingredient. Based on the result of the safety and health assessment by PISI, the ingredients with high safety and health hazard can be identified. Eliminating high safety risk and adverse health effects ingredients at the early stage of design may avoid changes made after the product is developed. Further study can be carried out to take into account the concentration of the ingredients in the product formulation as it is decided during the later stages of product design. After the concentration of the ingredients has been decided, it is suggested that the ingredient candidates are to be analyzed further. For instance, a toxicology test might be considered during laboratory experiments to validate the proposed methodology. However, the safety and health assessment of the chemical ingredient by the application of PISI is sufficient as an initial tool to screen the highly hazardous ingredient.

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APPENDIX

Supplementary Table 1
List of target properties

Property	Group contribution method
Molecular weight, Mw (g/mol)	$Mw = \sum_i N_i Mw_i$
Normal melting point, T_m (°C) (Hukkerikar et al., 2012b)	$\exp\left(\frac{T_m}{T_{mo}}\right) = \sum_i (N_i T_{mi})$ $T_{mo} = 143.5706K$
Normal boiling point, T_b (°C) (Hukkerikar et al., 2012b)	$\exp\left(\frac{T_b}{T_{bo}}\right) = \sum_i (N_i T_{bi})$ $T_{bo} = 244.5165K$
Flash point, F_p (°C) (Hukkerikar et al., 2012b)	$F_p - F_{po} = \sum_i (N_i F_{pi})$ F_{po}=170.7058K
Toxicity, LD_{50} (mol/kg) (Hukkerikar et al., 2012a)	$-\log LD_{50} - A_{LD50} - B_{LD50} M_w = \sum_i N_i LD_{50i}$ A_{LD50} =1.9372 B_{LD50} = 0.0016
Permissible exposure limit, PEL (mol/m^3) (Hukkerikar et al., 2012a)	$-\log(PEL) = \sum_i N_i PEL_i$

Supplementary Table 2
Flammability sub-index

Hazard indicator	Score information	Score
Flash point, (F_p) (National Fire Protection Association, 2020)	Non-flammable	0
	$F_p \geq 93.4$°C	1
	$F_p < 93.4$°C	2
	$F_p < 37.8$°C	3
	$F_p < 22.8$°C and $T_b < 37.8$°C	4

Supplementary Table 3
Toxicity sub-index

Hazard indicator	Score information	Score
Toxicity (LD_{50}) (mg/kg) (Heikkila, 1999)	$LD_{50} > 2000$	0
	$500 < LD_{50} \leq 2000$	1
	$50 < LD_{50} \leq 500$	2
	$5 < LD_{50} \leq 50$	3
	$LD_{50} \leq 5$	4

Supplementary Table 4
Exposure limit sub-index

Hazard indicator	Score information	Score
Permissable exposure limit (PEL) (Vapour, ppm) (Heikkila, 1999)	PEL > 1000	0
	PEL ≤ 1000	1
	PEL ≤ 100	2
	PEL ≤ 10	3
	PEL ≤ 1	4

Supplementary Table 5
Eye contact sub-index

Hazard indicator	Score information	Score
Acute effect (United Nations, 2013)	No effect	0
	H320: Cause eye irritation	1
	H319: Cause serious eye irritation	2
	H318: Cause serious eye damage	3

Supplementary Table 6
Skin exposure sub-index

Hazard indicator	Score information	Score
Acute effect (United Nations, 2013)	No effect	0
	H312: Harmful in contact with skin	1
	H311: Toxic in contact with skin	2
	H310: Fatal in contact with skin	3
Skin corrosion / irritation	H316: Cause mild skin irritation	1
	H315: Cause skin irritation	2
	H314: Cause severe skin burns	3
Skin sensitization	H317: May cause an allergic skin reaction	3

Supplementary Table 7
Inhalation exposure sub-index

Hazard indicator	Score information	Score
Acute effect (United Nations, 2013)	No effect	0
	H332: Harmful if inhaled	1
	H331: Toxic if inhaled	2
	H330: Fatal if inhaled	3
Respiratory irritation	H335: May cause respiratory irritation	2
Respiratory sensitization	H334: May cause allergy or asthma symptoms or breathing difficulties if inhaled	3

Supplementary Table 8
Ingestion exposure sub-index

Hazard indicator	Score information	Score
Acute effect (United Nations, 2013)	No effect	0
	H302: Harmful if swallowed	1
	H301: Toxic if swallowed	2
	H300: Fatal if swallowed H304: May be fatal if swallowed and enter airways	3

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Composite Repairs Integrity Assessment: An Overview of Inspection Techniques

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ABSTRACT

Composite repairs have been increasingly applied for maintenance and rehabilitation of piping, pipelines and vessels in the oil and gas industry, thus there is a growing need to monitor their in-service integrity, repair lifetime extension and prevent loss of containment of the product. There are many challenges of inspecting composite repairs including accessibility, inhomogeneous and anisotropic structure of composites, probability of detection, lack of adequate standards and diversity of composite materials amongst others. The current practice for inspection and monitoring of composites repair on oil and gas piping and pipelines is usually conducted based on International Standards Organisation (ISO) 24817 whereby visual inspection is generally performed to observe any irregularities on the surface like discolouration, cracks, chalking and blistering. This will usually be followed through with a coin tap test and Barcol hardness testing. Upon any findings of anomalies, further investigation is then performed using advance non-destructive testing (NDT) inspection technique to determine the integrity of the wrap, depending on the type and severity of defects. ISO 24817 has stated the general techniques that can be used to inspect the composites overwrap repairs including Ultrasound Technique, Radiography and Acoustic Emission. However, Petroliam Nasional Berhad (PETRONAS) has performed a series of assessments on various inspection techniques to seek suitable inspection methods for the composite wrap system, composites/substrate interface and/or substrate. A total of 10 NDT techniques had been evaluated thus far including Laser

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Shearography, X-Ray, Microwave technique, Dynamic Response Spectroscopy (DRS), Acoustic Emission (AE), Computed Radiography (CRT), Pulse Eddy Current, Metal Magnetic Memory (MMM). This research summarises an overview of the effectiveness of the evaluated techniques and findings of the evaluation.

Keywords: Composite repairs, in-service integrity, NDT techniques

INTRODUCTION

PETRONAS has utilized composite repairs on piping, pipeline and equipment for the past 20 years. These composite repairs provide an effective and economical solution for extension of operational life, prevention of loss of containment and sustain the integrity of the assets. Composite repairs have the ability to strengthen as well as providing corrosion protection to the assets without disrupting the operation. The composite repair involves the application of an overwrap to a damaged or defective area(s) in order to strengthen or reinforce the defect area to restore the integrity of assets. The general guidance and requirements for qualification, design and applications of composite repairs are provided in ISO 24817 (2006) and ASME (2018).

There are two common types of composite repairs, the overwrap and preformed sleeve type. Under this assessment, the NDT techniques are evaluated on samples applied using ProAssure® composite overwrap repair system. This composite overwrap repair consists of composite laminate fibres (e-glass fibre) and a thermosetting epoxy resin that is chemically cured. The composite is manufactured under controlled conditions with the ratio of glass to resin accurately controlled and monitored.

All repairs have to be designed and applied under a specified, controlled process so that under the design conditions, there is a high degree of confidence that the repair will maintain its integrity over the design lifetime. However, there is a growing need to monitor their in-service integrity for repair lifetime extension and to better manage any loss of containment of the product. Nevertheless, inspecting composite repairs have many challenges including accessibility, inhomogeneous and anisotropic structure of composites, probability of detection, lack of adequate standards and diversity of composite materials amongst others.

Composite repairs inspection is part of overall integrity management activities that are required to be performed to ensure repairs are fit for purpose throughout its designed repair lifetime. To supplement this composite repair system, there is an increasing need for assurance that these repairs remain in good condition throughout its repair lifetime, and in certain cases, remain fit for use beyond its original repair lifetime. This approach will provide an opportunity for cost-saving of avoiding shutting down the equipment to allow for removal and replacement of composite repair with another permanent installation. In order to achieve this, identifying suitable tools to inspect and determine the condition of the composite repairs, are pivotal. Currently, whilst there are many inspection methods claimed to be able to perform an inspection on composites/composite repairs, the truth of the matter is, only a small percentage of techniques are actually suitable, and able to perform the inspection. Inspection methods used on composite repairs in other industries such as aerospace, marine and wind energy, include shearography, ultrasonics, infrared, thermography, and these are amongst the techniques that can also be considered for use in the oil and gas industry.

In order to identify suitable inspection techniques, PETRONAS has evaluated various potential non-destructive technique (NDT) from various technology providers. The objectives of the evaluation are to:

- Evaluate various inspection techniques for composites overwrap repairs.
- Demonstrate the applicability of the NDT technique for on-site inspection.
- Develop the allowable defects and acceptance criteria for the composite repairs system.
- Summarise advantages/disadvantages and restrictions for each NDT technique that have been tested and assessed with recommendations and way forward.

Current Practice

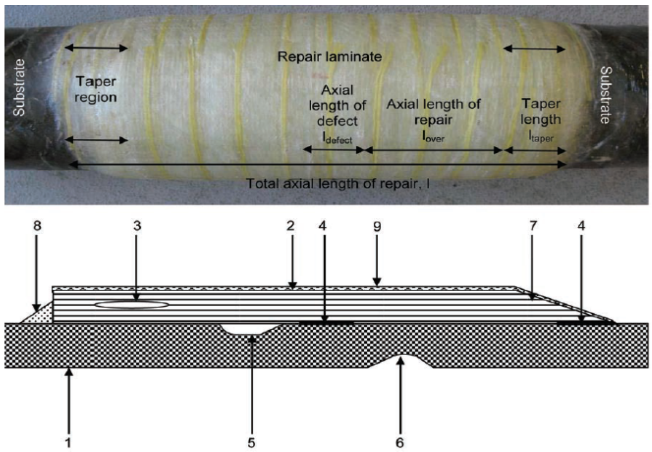
The current practice for inspection and monitoring of composites repair on oil and gas piping, pipelines and vessels is usually conducted based on ISO 24817 standard (2006) whereby visual inspection is generally performed to observe any irregularities on the composite repair surface like discolouration, cracks, chalking and blistering. This will usually be followed through with a coin tap test to detect any possible delamination/voids in composite and Barcol hardness testing to verify the curing of composite repairs.

The methods mentioned above serve as initial inspection tools to provide an indication of the condition of the repair. Any findings observed during these inspections would render the application of other non-destructive testing techniques to determine the integrity of the wrap, depending on the type and severity of defects.

Advanced NDT inspection techniques may be applied immediately after the repair system application as a baseline measurement or during the repair design lifetime. The NDT techniques are aimed to inspect both the substrate and composites repair system, to demonstrate the overall integrity of the repair system. Ideally, the NDT techniques are aimed to perform the followings:

- inspection of the repair laminate;
- inspection of the bond between the repair laminate and the substrate; and
- inspection of the substrate underneath the repair laminate.

The basic structure of a repair system in this context is considered in Figure 1.



1 Substrate, pipe wall
2 Repair laminate
3 Internal laminate defect
4 Interface delamination de-bond
5 External defect (with filler)
6 Internal defet
7 Taper of laminate (extends beyond overlay lover)
8 Adhesive fillet
9 Resin rich surface layer

Figure 1. Schematic of the composite repair system and typical location of defects (ISO 24817 (2006))

INTEGRITY MONITORING OF COMPOSITE REPAIR SYSTEM

There is a growing need to monitor their in-service integrity of composite repair system to better manage and prevent any loss of product containment during the design lifetime of the repair system. However, inspecting composite repairs have many challenges such as accessibility, lack of adequate standards and availability of suitable tools for the industry. Current standards which are ISO 24817 & ASME PCC 2 provide general inspection requirements for overwrap i.e. frequency, size of defects & acceptance criteria. Thus, it needs further establishment to address the gaps and provide more details information on inspection requirements and integrity management of composite repair system. There are four critical elements to be established for the overall integrity of composite repair systems:

- Pre-application requirements (site survey, risk assessment and design)
- During application requirements (quality of material, surface preparation and qualified applicators)
- Post-application requirements (hardness test, visual inspection and baseline record)
- Operational integrity management (inspection and monitoring program)

Each element plays important roles in quality assurance of the repair system. The composite repairs inspection falls under operational integrity management throughout repair lifetime. For effective overall integrity management of composite repair system, each operator should establish clear roles and responsibility, and procedure in managing the integrity of composite. There should also be a nominated individual who will coordinate the repair application and in-service monitoring.

It should also be ensured that all required quality assurance (QA) documentation, test and inspection records are available and established including use of any NDT techniques for monitoring. The accuracy of inspection method and technology readiness for the NDT tools are significant to ensure integrity management of composite repair system is fully implemented.

With these challenges, the way forward is to assess which technologies are suitable, hence an in-house scheme of the experiment set up to achieve this objective, addressing the gaps in ensuring the suitable inspection tools are selected.

EVALUATION METHODS

ISO 24817 (2006) provides very general information on NDT techniques that can be used to inspect the composites overwrap repairs including Ultrasonic Test (UT), Radiographic Test (RT) and Acoustic Emission (AE). However, these techniques have not been validated for use in PETRONAS to inspect the integrity of the composite repairs. In view of this situation, PETRONAS has taken an initiative to perform a series of assessments on various NDT techniques that are available in the market which has potential to be endorsed as standard tools for inspection of composite repairs in PETRONAS.

Various technology providers were approached to seek for any suitable inspection methods for the composite repairs, composites/substrate interface and/or substrate. These technology providers would then propose a potential solution based on the technologies that they either own or operate under a license. Once the technology is deemed suitable or viable by PETRONAS, they are then requested to perform a live demonstration, witnessed by various representatives from PETRONAS.

Evaluation Process

For the evaluation process, the following steps were taken:

- Review of current practices and standards for inspection and monitoring of composite repair system
- Engagement with various parties of inspection companies'/service providers.
- Technology presentation
- Technology demonstration on test spool
- Evaluation of techniques

A total of 10 NDT techniques has been evaluated, and amongst the technologies that were assessed include:

- Laser Shearography
- X-Ray
- Microwave
- Dynamic Response Spectroscopy (DRS)
- Acoustic Emission (AE)
- Backscatter Computed Thermography (BCT)
- Electromagnetic Acoustic Transducer (EMAT)

- Computed Radiography (CRT)
- Pulsed Eddy Current
- Metal Magnetic Memory

However, three NDT technologies, Acoustic Emission Technology (AET), Backscatter Computed Thermography (BCT) and Electromagnetic Acoustic Transducer (EMAT) were not evaluated further during technology demonstration phase due to the unavailability of the equipment and /or principal for the demonstration purposes.

Technology Demonstrations

The demonstration was aimed to detect the embedded defects as well as to detect the interface and substrate. A test spool had been prepared and wrapped with few layers of composite overwrap repair system and embedded with simulated defects for blind detection by various NDT techniques. The test spool as shown in Figure 2, is constructed using a 10” API X65 pipe, with a few layers of composite overwrap repair. The simulated defects include disbandment, delamination, and void.

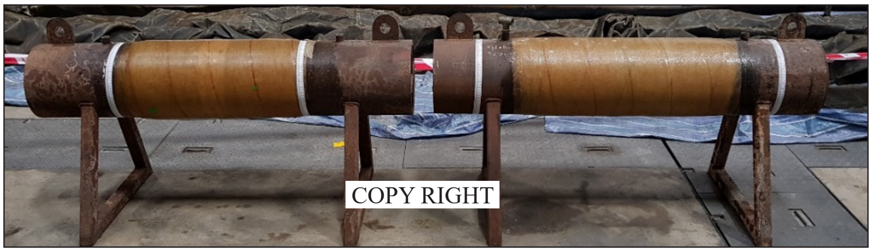


Figure 2. Test spool (Courtesy of PETRONAS Research Sdn Bhd)

A total of seven inspection techniques were demonstrated including the followings:

- Laser Shearography
- X-Ray
- Microwave
- Dynamic Response Spectroscopy
- Computed Radiography (CRT)
- Pulsed Eddy Current
- Magnetic Metal Memory

Separate sessions were arranged for each technology providers to perform their live demonstration, and evaluation was based on several criteria including time taken to perform, weight, ease of set-up, as well as other key criteria described in Table 1.

RESULTS AND DISCUSSION

The evaluation summary findings revealed mixed results.

Table 1
Evaluation summary and results

NDT Methods	On-line Inspection	Easy set-up	Portable	Detect defect	Measure defect	Classify defect	Repeatable
Laser Shearography	√	√	√	√	X	√	√
X-Ray	√	√	√	X	X	X	√
DRS	√	√	√	√	X	X	√
Microwave	√	√	√	√	X	√	√
CRT	√	√	√	√	√	X	√
MMM	√	√	√	X	X	X	√
Pulsed Eddy Current	√	√	√	√	X	X	√

The criteria in Table 1 were selected to ensure that the tools would be suitable for application in the oil and gas environment, and these would include on-line inspection during operation thus avoiding shutdown, easy to set up and portable, functions to detect/measure/classify the defects and can be repeatable for inspection at various locations. The ability of a tool to classify the defects is the probability that a feature is correctly identified by the tool, this includes the type of anomalies that are to be detected, identified, and sized by the tools shall be clearly indicated.

The evaluation showed that some techniques such as Laser Shearography, DRS, CRT, Eddy Current and Microwave techniques are able to detect the presence of a defect in the composite wrap, but the only shearography is able to classify the types of defects present in the overwrap. Whilst CRT is demonstrated to able to detect both the presence of defects in composite wrapping and substrate interface and measure the thickness of the substrate, it is not able to classify the types of defects present. Eddy Current technique, on the other hand, is only able to measure the thickness of the substrate. X-Tray technique is the only

Table 2
Summary of observations

Category	Criteria	Method
Category I	Able to detect the presence of defect in the composite repairs	i. Laser Shearography ii. Computed Radiography Testing (CRT) iii. Dynamic Respond Spectroscopy (DRS) iv. Microwave
Category 2	Able to detect the presence of defects in both composite repairs and substrate interface	i. CRT[1] ii. DRS
Category 3	Able to inspect the condition of the substrate	i. CRT ii. DRS
Category 4	Able to measure substrate thickness	i. Eddy current ii. CRT
Category 5	Unable to detect the presence of the defect	X-Ray

Note: 1. Limited to 10-inch pipe diameter technique which was unable to detect any defects in composites overwrap and substrate due to the low resolution.

Based on the evaluation and demonstration of various NDT technique conducted for composite repairs, the observations are summarized in Table 2.

CONCLUSION

Some technologies have shown the ability to inspect the composites repairs while some are observed to have additional advantages and are readily deployable. The way forward will include future technology refinement of the potential techniques to achieve technology readiness level (TRL) to meet PETRONAS requirements. As part of monitoring the performance and effectiveness of selected inspection tools, it is important that the NDT company provides information on the performance of anomaly detection, sizing and other measurement capabilities of their tool based on their in-house testing and collective of on-site verification. In conclusion, it is shown that each NDT technique evaluated has its own advantages and disadvantages, and the selection of which technique to use will be based on the repair condition, criticality, component to be assessed and accessibility.

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Management of Change System with Integrated Risk Analysis for Temporary and Emergency Cases

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ABSTRACT

The potential of a major accident may significantly increase when change is unprepared especially in a temporary and emergency change. An unplanned change may lead to the emergence of new hazards which eventually lead towards severe impact on human, property, environment and business reputation. Management of Change (MOC) with integrated risk analysis is an important Process Safety Management (PSM) elements involving planning and controlling risks and hazards that come with the proposed change. However, lacking systematic technique for easy adoption of this element has delayed its application in plant. Corresponding to these weaknesses, an integrated MOC management system focusing on the temporary and emergency change is presented in this study. Results of this study comprise MOC process framework and MOC management system (MOCMS) which act as a guidance and documentation inventory tool. Implementation of this technique and system at the selected plant as a case study is examined and discussed. The system is beneficial to industries to manage underlying risks in a temporary and emergency change which ease the tracking of MOC case inventory to improve risk controls in changes.

Keywords: Emergency change, management of change (MOC), process safety management (PSM), temporary change

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INTRODUCTION

Nowadays, highly hazardous industries grow rapidly due to the increasing demand towards petroleum made products. Technologies and manufacturing process in these industries are getting complex to improve productivity in order to meet the market demand, aiming to remain competitive. Potential of disastrous events may significantly increase following the growing complexity and expansion of operation process. In the business world, the successful enterprise should have the ability in managing and exploiting changes effectively, turning the unpredictable situation into business opportunities. Therefore, enterprise requires an effective Management of Change (MOC) system to survive in this ever-changing world. MOC possesses an advantage not only applicable to process safety but also in terms of business perspective. MOC system covers planning and proposing of tactical control actions on potential risk (Kontogiannis et al., 2017; Kuivupalo et al., 2015). Managing the change is challenging as it requires quick disseminate of related knowledge and information to address the hazards. Reporting and reviewing task may be complicated as more paperwork is required. Moreover, applying changes on operation process is complex procedures and relatively challenging which requires assessing the need for improvements and training of personnel, to meet potential challenges and so on. Period of change required varies according to the situation. It may come as permanent, temporary or only during an emergency.

The temporary change is the change required for a specific duration up to several months meanwhile emergency change is required when the situation goes beyond control from the safety perspective and has been declared as an emergency in emergency response procedure (Centre for Chemical Process Safety, 1995). Bypassing process or maintenance repair are the common temporary or emergency changes which appear in the process plant (Harrison, 2012). Looking back on a few previous major industry tragedies such as Flixborough in 1974, Bhopal in 1984 and many more, these incidents mainly occurred due to unplanned temporary MOC (Bowonder, 1987). Example of temporary change is well portrayed from the Flixborough incident. There was a temporary change on the reactor to complete maintenance of corrosion. This temporary change was not well controlled and contributed to the happening of the explosion (Siong et al., 2017). MOC is the element which is worth for the employer to pay attention to. This can be seen from the statistics presented by previous studies where 19% of process safety accidents occurred due to poor MOC program (Siong et al., 2017; Ye et al., 2012). Approximately 80% of major accidents traced showed MOC failure as the root cause. In every 1000 work tasks, there would be 5-10% of tasks requiring MOC with 5 to 10 changes are high risk (Gambetti et al., 2013).

Importance of MOC was discovered by many international organizations in recent years. There were several standards and regulations established such as ISO 45001 and Process Safety Management (PSM) regulation which included MOC as one of the 14 elements. US Occupational Safety and Health Administration (OSHA) established the PSM standards in February 1992 entitled "Process Safety Management of Highly Hazardous Chemicals, 29 CFR 1910.119". It is one of the common standards referred in PSM implementation and practice. 29 CFR 1910.119 incorporated a total of 14 elements to manage all aspects in industry to cover almost every aspect of safety management (OSHA, 2013). PSM improves safety performance proactively at developed country such as U.S as well as developing country (Anwar et al., 2019). MOC is an interdependent element where several elements work together to provide sufficient evidence for the decision-making phase. MOC is interrelated with at least 10 elements in PSM including Process Hazard Analysis, Process Safety Information, Mechanical Integrity, Employee Participation, Incident Investigation, Compliance Audit, Pre-Startup Safety Review, Contractor, Training and Operating Procedure (Aziz et al., 2016).

MOC process requires long lead time due to several factors. A meeting should be conducted with the affected departments and specialist to address the control measure on the potential risk in the change. Documents related to process hazard analysis (PHA), process safety information (PSI) and other elements are required to review and evaluate the change. Lastly, documentation for all related work task and risk assessment is required for both temporary and permanent changes. Unfortunately, current MOC approaches are having limitation in time constraint and urgency to resume operation which contributes to failure. This is obviously time consuming to perform all the steps especially for temporary and emergency MOC changes (Gambetti, 2013). As a result, simplification on risk assessment and the absence of updating operating procedure were elements that were neglected in MOC due to urgency (Siong et al., 2017). There exists a major weakness on MOC effectiveness in current practice which is poor documentation where tracking of MOC cases are building up the number of incomplete MOC cases, which may eventually turn incomplete temporary changes into a potential hazard on the premise (Chosnek, 2010).

Despite having established PSM standard, a method for integrated management of organizational and technical changes was introduced by Gerbec (2017). Following the concept, an integrated MOC model shall consider the issues of technical/technological changes, the complexity of impacts or risk and how the change influences all levels of employee in an organization. Even though its implementation would drive a major improvement in process plant safety, lack of a systematic technique for easy adoption of this standard had delayed its application in plant. Therefore, this study presents an integrated MOC risk analysis system focusing on temporary and emergency cases in order to minimize the limitation in time prediction, prioritization of risk, record logging and storage into a more convenient yet less burdensome way.

METHODS

Figure 1 shows the overall flow of this research study. MOC Framework in this study is an extension of the Gerbec (2017) framework and risk assessment research. Following the concept of Gerbec (2017) model, an integrated MOC model should consider the issues of technical/technological changes, the complexity of impacts or risk and how the change influences all levels of employee in an organization (Gerbec, 2017). Data and information collection on temporary and emergency change are performed by visiting two highly hazardous plants. Issues and current practice adopted in managing temporary and emergency changes are gathered from the above literature reviews, and through sharing session with the safety practitioners of the selected plants. An integrated system in managing both changes is needed which considers all issues identified through the data collection process.

On the other hand, another purpose of this study is to prevent ignorance or complacency towards risk behind short term changes. An integrated yet time-saving risk analysis is relatively critical in managing both types of changes. Improvement and modification are made on the proposed risk assessment checklist where risk rating is added into the adopted risk assessment checklist to highlight the risk prioritization and decision making.

Managing and updating of information manually are burdensome and challenging in the current technological era (Bakar et al., 2017). There is a need to implement technological aid to overcome the current MOC weakness in terms of workload and efficiency on information management. A well-developed and integrated management system would help in the data inventory and tracking of important information. Microsoft Access software was utilized to develop a MOC management process to achieve the objective of improving information management.

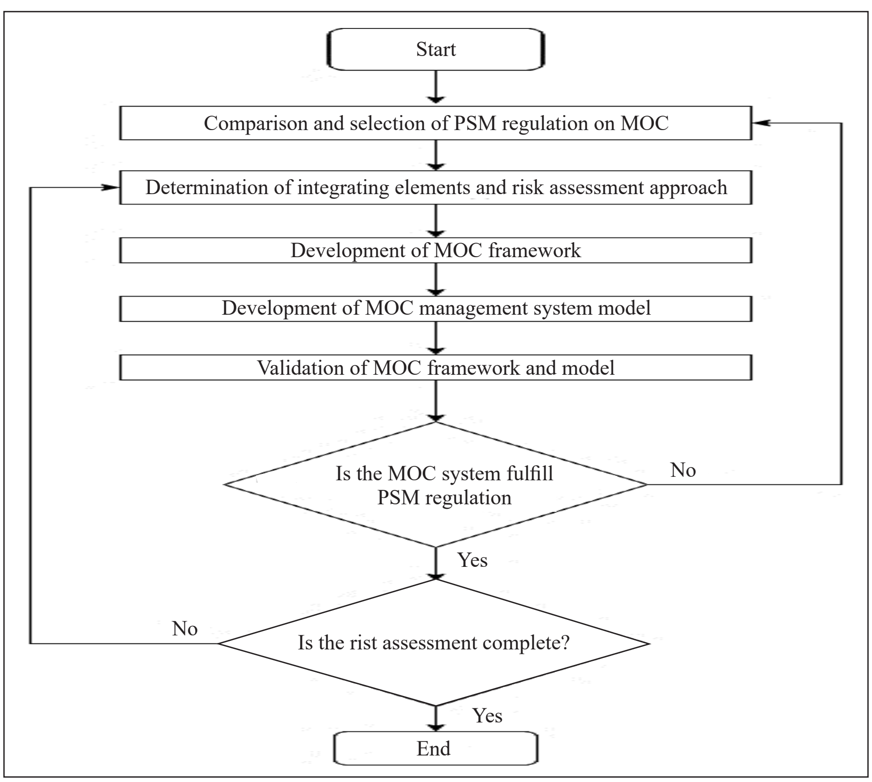

Figure 1. Overall process flow

Developed framework and MOCMS model were pilots tested at two plants in Malaysia. This pilot test was conducted to ensure the feasibility and efficiency of the developed result in real-life practice. This section displayed the functionality of the model in the real MOC case in the industry. Developed results and software were piloted on three MOC cases. Model performance efficiency survey was conducted involving focus group to obtain feedback and suggestion on the model.

Determination of Standard, Integrating Elements and Development of Framework

Process Safety Management (PSM) standard 29 CFR 1910.119 was referred as the basis of MOC framework development and to meet all the requirements as stated in the regulation. Critical elements and assessment which should be covered under MOC were studied through the literature review and standards. The risk assessment checklist by Gerbec (2017) had been embedded throughout the framework. The developed method consisted of two major nature of change; temporary and emergency. The Other five aspects that were covered under MOC were included for an efficient approach; technical basis for the proposed change; impact on safety and health brought by the change; modification to the operating procedure; necessary time period for the change; authorization requirements for the proposed change.

Computer Database Prototype System

The implementation of this technique was assisted by a computer database system in managing and communication the MOC cases. MOC management system (MOCMS) was developed to demonstrate the proposed framework using Microsoft Office Access and Excel environment. The system had been designed to allow for capturing documented data at specific evidence location either in the paper form within files, in computer databases or using a computer-aided design system.

Validation via Case Studies

The developed system was tested at the selected unit of process plants in Malaysia. A total of three MOC cases had been conducted to see the feasibility of the system in real-life practice.

RESULTS AND DISCUSSION

The Framework of Temporary, Urgent and Emergency MOCs

Temporary, urgent and emergency MOC frameworks developed in this study are shown in Figure 2, Figure 3 and Figure 4 respectively. Both changes were developed with similar action items but differed in terms of work flowchart due to time constraint in both natures

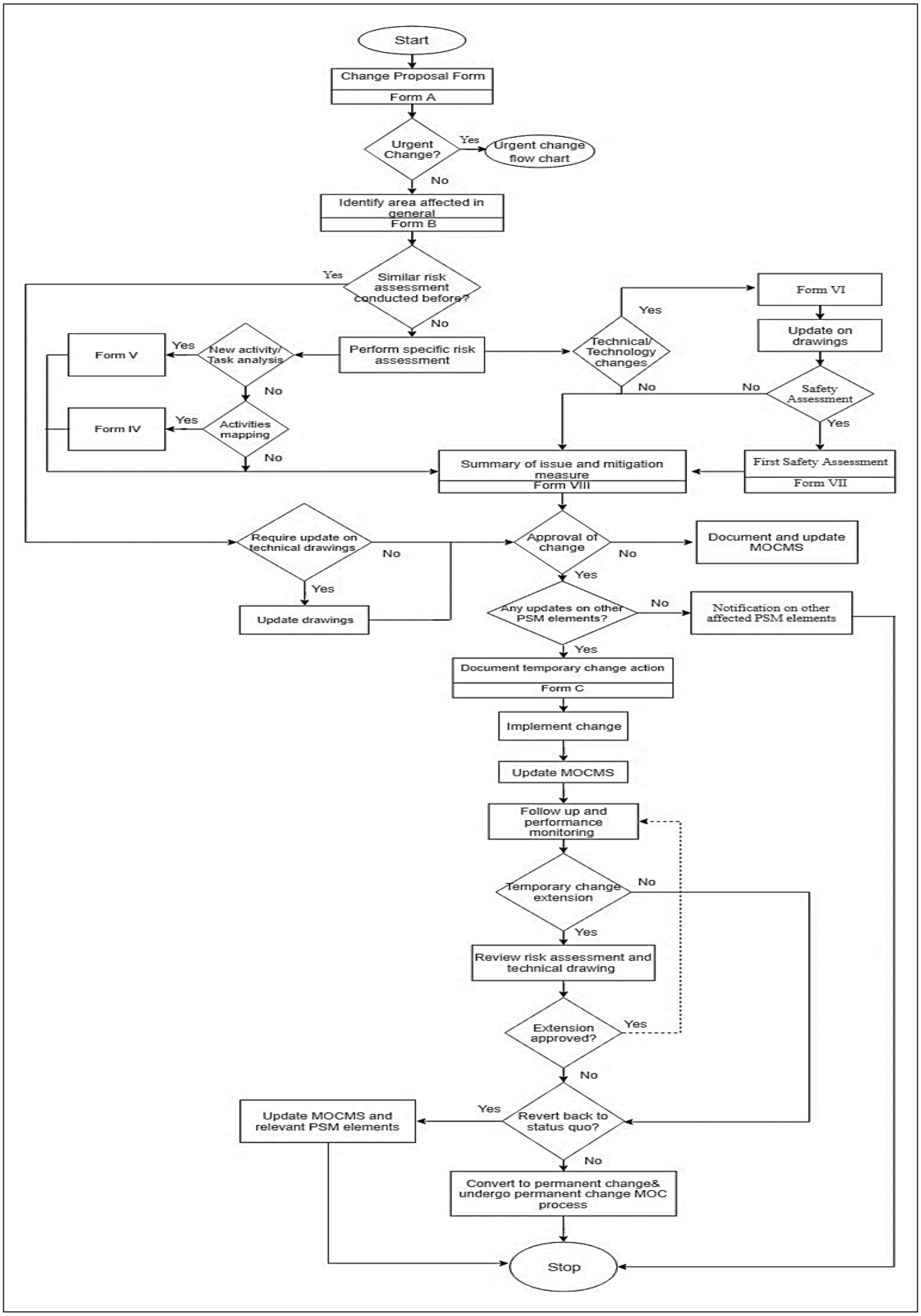

Figure 2. Temporary change framework

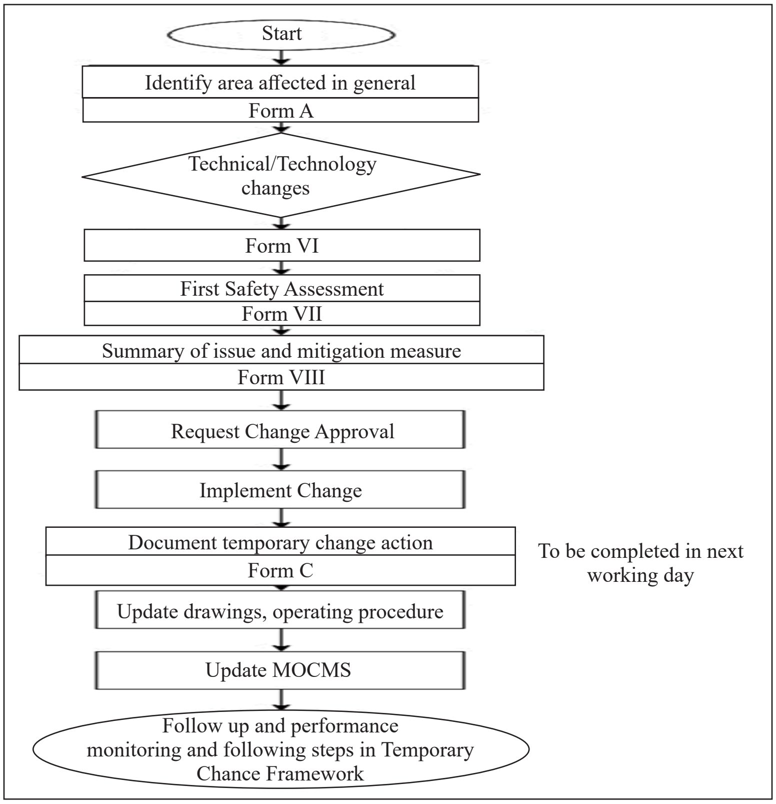

Figure 3. Urgent change framework

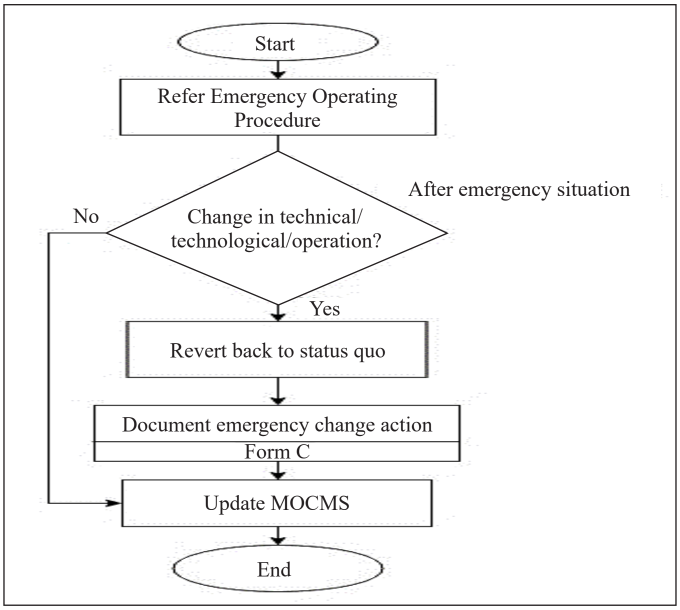

Figure 4. Emergency change framework

of change. Under temporary changes, there is a common temporary change and urgent change which shall be implemented within days or in a day. Besides, the emergency is different from the urgent change where urgent change may be implemented for a period of time whereas emergency change will only be required to perform during the emergency to prevent further destruction and devastating consequences.

Temporary Change. Temporary change framework (Figure 2) begins with identifying whether the proposed change is an urgent or normal temporary change. Changes which are planned to be implemented for 3 months and below can be considered as temporary changes. The urgent change can proceed to urgent change framework which is discussed in the next section. Non-urgent change undergoes general risk assessment checklist to identify the areas affected by the proposed, e.g. organizational or technical and technological aspect. Change that affects the organizational context in temporary change is proposed to perform simple task analysis and activities mapping between new and old job task whereas technical context comes with technological area risk assessment checklist. It will then proceed to specific risk assessment for the affected area. Every area affected by the change comes along with a proposed risk assessment checklist. Upon completion of the risk assessment, summary of risk and mitigation measure is be completed to highlight the risk prioritization and change approval. The implemented change will then update other related PSM elements including process safety information, mechanical integrity, operating procedures and so on.

Next, documentation comes in place where all forms and risk assessment checklist are stored in MOCMS. Follow up and performance monitoring on the implemented change is compulsory to be conducted throughout the implementation period. Follow up schedule can be decided based on the period of temporary change. In the case of the temporary change extension request, risk assessment and technical drawing will be a major consideration in this context. Approved extension of change is followed up to the validity of extension. Conversion of change back to the status quo will again update the MOCMS and relevant PSM elements. Any change approved to be converted to the permanent change will undergo permanent MOC process.

Urgent Change. Urgent change is one of the temporary changes which possess time restriction in planning and preparation work. Any proposed change which can be implemented within one to two days can be considered as an urgent change. There is a higher tendency which leads to neglection of MOC due to the urgent nature of the proposed change. In the developed framework, it is a simplified process of normal temporary change but possesses a similar compulsory risk analysis process as shown in Figure 3. It is proposed to overcome the time constraint by limiting the risk analysis to be completed within a day by using the proposed risk analysis checklist and forms by Gerbec (2017). Information inventory and update of any related documentation can be performed the next working day after changes have been implemented.

Emergency Change. Emergency Change is an essential step of response in an emergency especially in the case of life saving, prevent further damage to the environment, property and process line. In an emergency, the emergency operating procedure will be the priority in response. In the developed framework as shown in Figure 4, changes made during the emergency are recorded for future review which can help in decision making and improvement in terms of emergency change procedure and emergency response procedure. Documentation framework in emergency change repeats the temporary change framework (Figure 2). Any changes during an emergency will revert to the status quo to resume operation after the emergency. In this case, the status quo can be the original setting or process according to the design specification. User will fill only Form C, as a summary of change action taken during an emergency.

Risk Assessment

Risk assessment checklist and related MOC forms were adopted from the work of Gerbec (2017) with a new improvement on his work to fit into this study. Improvised risk assessment checklist on technical and technological changes covered on the process, process conditions, inspections and maintenance as well as technical documentation aspects. The improvised risk assessment proposed on additional PHA risk rating to aid in risk prioritization and decision making (Galante et al., 2014). The concept of this risk assessment checklist is proposed to be a quick alternative of complete risk assessment for short term and emergency changes when other hazard analysis and risk assessment such as Hazard and Operability Study (HAZOP), Hazard Identification Studies (HAZID) require a large amount of time and group of expertise for the brainstorming session.

MOC Management System (MOCMS)

MOC Management System (MOCMS) comprises one dashboard, a data inventory form, nine tables, three queries and nine reports. This database is aimed at increasing the control over data inventory and tracking of information. It acts as active guidance merged with MOC framework throughout overall MOC process where the user may access all related forms and risk assessment checklist stored in the system in the early stage of change proposal and risk assessment. The system established is able to store all the vital information in MOC by storing it separately according to the type of risk assessment followed by a general MOC case and summary table storage. Next, MOCMS is acting as a data inventory system where the user may store all information and risk assessment checklist related to the change on one specific form. Meanwhile, in the later stage of the framework, MOCMS will function as tracking tools to follow up and evaluation on change extension steps on open temporary MOC cases.

Case Study

To demonstrate the developed concept, three case studies had been conducted at the selected unit of the real plant. Since the plant is handling a flammable gas at a high pressure condition, it is compulsory by management that the unit is subjected to MOC program. Referring to Figure 5, end users may access data entry interface from the dashboard. This interface is designed for data input for all types of risk assessment and general information of MOC cases, summary and follow up action of the specific case.

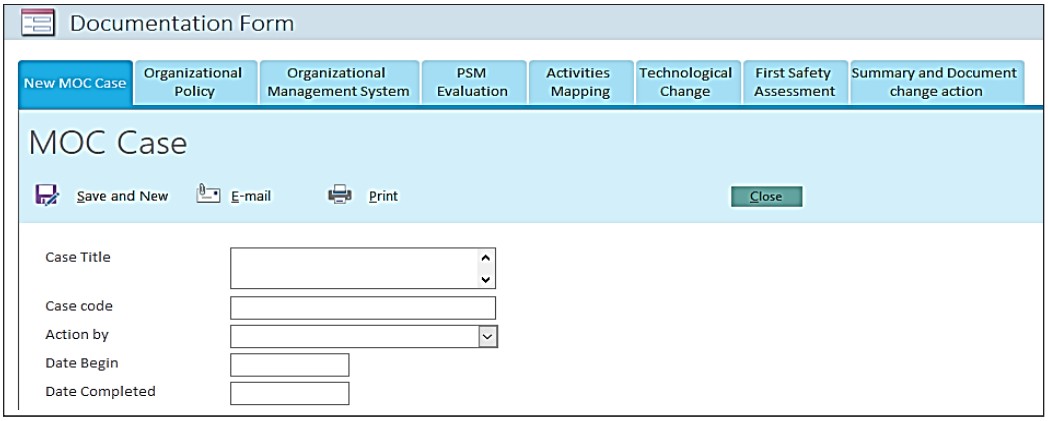

Figure 5. Documentation form interface in MOCMS

All data input will be interlinked to the MOC case information inserted from the first tab as shown in Figure 6. The interface of overall MOC cases in the system also designed to store data related to case code, the responsible person on approval and execution, date begin and due date, as well as storage of related documentation. There are several features designed to minimize the identified current issue in MOC. Time motion-based study is minimized by allocating time begun and time completed for every risk assessment. This feature aims to help in recording the period required to perform every risk assessment which can be used as a reference to predict the overall time required from the change proposal to approval. This is believed to be significant in solving the current issue of time constraint in MOC (Koivupalo et al., 2015). Furthermore, a feature which addresses the type of change, whether is permanent, temporary or emergency, would help end users to easily track on the previous type of change cases and related risk assessment conducted. Temporary cases may often be the loop of an organization in accident occurrence, as risk assessment are often simplified or merely absent due to the implementation period. Therefore, this feature is convenient for end users in tracking back similar temporary cases and related risk assessment. Apart from that, there is another additional feature which enables the user to track the open task of MOC which is yet to meet to due date established. There is a status input which enables the MOC team to select whether the task is "Completed", "Pending" or "Incomplete". In addition, an open task query is designed to track on MOC cases which hold on the status of "Pending" or "Incomplete".

Apart from that, the technical and technological risk analysis checklist had been used on one of the existing temporary change cases during plant turnaround period, as shown in Figure 7. It shows that the risk assessment checklist is able to cover related items in the technical and technological area. The document is linked to the technical risk assessment interface on pilot test case is shown in Figure 8. This interface has the items of "Time begin" and "Time completed". This feature is made available in all risk assessment interface which aims to record the period required for every single risk assessment. This is believed to improve the prediction on time required for a complete MOC cycle and eventually helps to overcome the practice of time-motion based study in a previous MOC approach.

Next, Figure 9 shows the filled organizational change risk assessment checklist which was conducted on the changing of job position of selected personnel. Activities mapping risk analysis was conducted to analyze the hidden risk of the changing of work nature and job position. The result of activities mapping risk analysis of the specific organizational change. Based on case studies activities mapping aids in predicting any newly arose safety

01_MOC

Case Title	Case code	Change approve	Approved b	Action by	Date Begir	Date Complete	Type of change	Area affected	Status	Form A	📎	Form B	📎	External file stora
Changing of position: Selected personnel	OMOC-2019-01	☑			1/21/2019	1/22/2019	Permanent	Organizational	Complete	☐	📎(0)	☑	📎(1)	https://drive.google.com/open?id=10KgEwBWGGaTpf4H-UORZOoxqFplq_F58
Improvement on battery limit area	CRF- 2016-D-M-011	☑			8/8/2016	10/31/2019	Temporary	Technological	Complete	☑	📎(1)	☑	📎(1)	https://drive.google.com/open?id=1kcq_7NedrXvDQpraPM3h8pt7-I-YpjLi
New-Improvement on battery limit area	NEW-CFR-2016-D-M-011	☑			1/21/2019		Temporary	Technological	Pending	☑	📎(1)	☑	📎(1)	https://drive.google.com/open?id=1kcq_7NedrXvDQpraPM3h8pt7-I-YpjLi

Figure 6. Overall MOC case interface on pilot test case

ID, (sub)Component & audit question		Impacted (require MOC)	What is impacted?	Kind of impact?	Possible consequences?"	Possible mitigations?"	Probability	Severity	Risk rating	Is mitigated impacts adequate?"
A	PROCESSES									
A.4	Temporary procedural changes	Yes	Startup & shutdown	Plant operation	Unknown hazard arised	To include step in procedure	D	4	LOW	YES
C.4	Periodic equipment maintenance	Yes	Update maintenance schedule	Maintenance acitvity	Reduce valve reliability if maintenance not conducted following updated schedule	Include in MOC work procedure for updates, folow up action by specific personnel	D	4	LOW	YES
C.5	Alarm, safety and security systems testing									

Figure 7. Technical and technological change risk assessment checklist on pilot study

and health hazards, in addition of workload in new job task, evaluation of the adequacy of control measures and so on.

Figure 10 shows one of the queries developed in MOCMS which helps to track the list of temporary MOC cases. As shown in Figure 10, the query is designed to track temporary

07_Technological Change Assessment

ID	Case Title	Case code	Action by	Approved by	Status	Date Begin	Due Date	Date Complete	Time begin	Time completed	📎	External evidence location
1	Improvement on battery limit area	CRF- 2016-D-M-011			Complete	10/8/2018		1/9/2018			(1)	https://drive.google.com/open?d=1eD4jW9p53yhWmKcFN4HF0XBCY-1WvKQT
2	New- Improvement on battery limit area	NEW-CFR-2016-D-M-011			Pending	1/21/2019		1/22/2019	1430	1600	(1)	https://drive.google.com/open?d=1wbjiBAJOdUVd-gbc8M1LheDZXLe8w-2V

ID, (sub)Component & audit question		Impacted (require MOC)	What is impacted?	Kind of impact?	Possible consequences?"	Possible mitigations?"	Probability	Severity	Risk rating	Is mitigated impacts adequate?"
A	**PROCESSES**									
A.4	Temporary procedural changes	Yes	Startup & shutdown	Plant operation	Unknown hazard arised	To include step in procedure	D	4	LOW	YES
C.4	Periodic equipment maintenance	Yes	Update maintenance schedule	Maintenance acitvity	Reduce valve reliability if maintenance not conducted following updated schedule	Include in MOC work procedure for updates, folow up action by specific personnel	D	4	LOW	YES
C.5	Alarm, safety and security systems testing									

Figure 8. Technological risk assessment interface on pilot test case

	OLD ROLE ACTIVITIES										NEW ROLE ACTIVITIES								COMPARISON [b]		
				Involves [a]								Any new role issues?									
No	Appointed activities	Can it be eliminated?	Req. hours per week	Response to deviations	Assuring plant integrity	Assuring plant availability	Managing HSE procedures	Manages essential knowledge and expertise	Subject of change?	Significant risk?	Appointed activities	Req. hours per week	Significant HSE hazards?	High workload, fatigue?	Competence issues?	Communication issues?	Team work issues?	Motivation issues?	Old role control measures that were applied?	Additional measures needed, or any comments?	Will controls be adequate?
1	Deliver training program	No	15	Med	Med	High	Med	High	Med	Med	Management of shift, personnel, operation schedule	25	NA	No	Compatible education background but lack of related work experiences	No	No	No	Management training provided upon change of job position		Yes
2	Develop module	No	40	Low	Med	Low	Low	High	Low	Low	Taking sample for quality checking	10	Involves with process equipment, chemicals	No	No	No	No	No	Onsite chemical handling training		Yes
3	Schedule training program	No	4	Med	Low	Low	Low	Low	Low	Low	Participate in plant shutdown & startup	30	Involves with process equipment, chemicals	Maybe	No	No	No	No	Onsite chemical handling training		Yes
4	Evaluate training effectiveness	No	5	Low	Low	Low	Low	Low	Low	Low											

Figure 9. Activities mapping of pilot test organizational change case

Temporary MOC case

Type of change	Case Title	Case code	Date Begin	Date Completed	Action by	Area affected
Temporary	New- Improvement on battery limit area	NEW-CFR-2016-D-M-011	1/21/2019			Technological
Temporary	Improvement on battery limit area	CRF- 2016-D-M-011	8/8/2016	10/31/2019		Technological

Figure 10. Temporary change query in MOC

MOC case which displays all the vital information of temporary MOC cases with “Due date” and “Remarks”. This query helps end user to easily track on the temporary case which will meet the due date. This is to improve the management of overdue temporary change. There are two queries designed to track on the open task and emergency change cases.

CONCLUSION

Three frameworks were established addressing common temporary change, urgent change and emergency change with respective critical action items and risk assessment. A MOCMS is established which stores all related risk assessment forms, change proposal, which also acts as a storage database for related documents. Pilot tests had been conducted to validate the framework and management system developed to determine the reliability and applicability in the real life operation process. It can be concluded that this system is able to ease the burden of documentation and yet proposes a new approach in MOC management. Tracking of open MOC task in the temporary and emergency case is additional features in the system. Time begin and completed field in the system is established to enhance the time prediction in performing every risk assessment and period required for a whole MOC process

In a nutshell, this study introduces a system to improve risk analysis and tracking of open MOC cases especially towards temporary and emergency changes. The framework developed in this study is aligned with the international standard on all the important criteria to be covered in a MOC process. Implementation of this system can serve as a database, guidelines and tracking tool in MOC.

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Classification of Faults in Oil and Gas Pipelines using Support Vector Machines

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ABSTRACT

Leaks and breakdowns of pipelines can lead to catastrophic failures and cause economical losses worldwide. Currently, condition monitoring has become a challenging process because of various reasons such as fluctuating external conditions, natural hazards. Pipelines are installed in severe conditions and are subjected to degradation mainly due to corrosion and metal loss. This study attempted to classify different types of metal loss faults using historical inspection data of oil and gas fields. For this purpose, Support Vector Machines (SVM) were employed to classify and predict various types of metal loss faults which were affecting the life condition of a crude oil pipeline. The historical inspection data was acquired from a crude oil pipeline located in Sudan. Different types of SVM models were trained and quadratic SVM type was selected for the present study due to its high prediction accuracy. The performance evaluation of the proposed SVM model was done using the confusion matrix. The developed SVM model provides promising results with a prediction accuracy of 93.0%. As a result, the fault detection rate (FDR) for all faults is found to be 90.4%, while the misclassification rate (MR) is 9.6%. The prediction of metal loss fault type may help in condition assessment and maintenance schedule to take prior actions for the better life of pipeline which reduces the degradation rate of a pipeline.

Keywords: Classification, metal loss, oil and gas, pipeline, prediction, support vector machines

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INTRODUCTION

Pipelines are being inspected in various ways such as intelligent pigging, Magnetic flux leakage (MFL) detection techniques, ultrasonic techniques, on a timely basis since decades. Among all methods, smart pigs are widely used by pipeline industries due to their better performance and pinpoint information of faults (Isa & Rajkumar, 2009). Many features like metal loss anomalies, weld anomalies can be detected using these smart pigs which are affecting the life of a pipeline majorly. The rate of metal loss of a pipeline is typically interrelated with external and internal features (Cosham et al., 2007; Nešić, 2007). The metal loss may be of any type like pitting, general, biologically influenced and stray currents (Vanaei et al., 2017). However, it is difficult to know which type of metal loss is majorly affecting the life of the pipeline (Kishawy & Gabbar, 2010). Many attempts were made to predict different types of leakages and faults of a pipeline since decades (Breton et al., 2010; Mandal et al., 2012; Qu et al, 2010; Sun et al., 2014; Vanaei et al., 2017).

The health monitoring systems is crucial to reduce the risk and consequences of failure (Ahsan et al., 2019). Therefore, the reliability analysis of pipeline was carried out with corrosion defects by Teixeira et al. (2008) in which corrosion resulted as one of the major defects which were affecting the pipeline condition. Gloria et al. (2009) introduced a magnetic sensor that predicted the internal defects of corrosion for the inspection process and also had more advantages than MFL The detection of pipeline leakages and pre-warning monitoring using SVM techniques was presented by Qu et al. (2010). Some researchers developed statistical models that could predict the life condition of pipelines using inspection data from oil and gas fields by means of different machine learning techniques like artificial neural networks, regression analysis, Bayesian networks (Basha & Rao, 2018; El-Abbasy et al., 2014; Li et al., 2016; Sacluti et al., 1999). However, of all machine learning techniques, SVM is used in the present work because of its popularity in classifying different types of faults in a pipeline.

An illustration of an oil and gas pipeline undergoing a pig inspection located in a severe environmental condition is shown in Figure 1 (Vanaei et al., 2017). The intelligent pigs are generally used to detect and recognize abnormalities like pressure flow differences, pits, dents, wall thinning, and cracks.

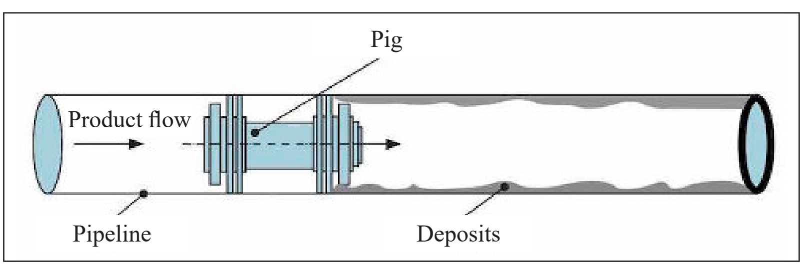

Figure 1. Corroded pipeline in a severe environment

The usage of Support vector machines (SVM) is continuously increasing due to their generalization ability and observed performance for the classification problems. SVM's have a unique architecture that predicts the classification of data in which the hyperplane separates the data of two or more categories. The detailed representation of optimal hyperplane is shown in Figure 2. The vectors that are located closest to the margins of a hyperplane are termed as support vectors. The hyperplane separating two types of metal loss anomalies is termed as optimal separating hyperplane as shown in Figure 2. The generalization control can be attained by maximizing the margin, which corresponds to the minimization of the weight vector (Gunn, 1998). SVM is an innovative learning technique that shows greater performance related to other machine learning techniques, which is derived from the statistical learning concept (Qu et al., 2010). The main contribution of the current work is to classify the types of metal loss anomalies using historical inspection data using SVM technique. The proposed model may help in predicting the type of metal loss defects affecting the life condition of an oil and gas pipeline.

METHODS

Data Acquisition

The historical inspection data was acquired from the crude oil industry located in Sudan. The pipeline section was prolonged to a length of 241.2 km. The pipeline was commissioned in the year 2006 and the inspection of a crude oil pipeline was done in the years 2009 and 2015 (Shaik et al., 2019). The historical data was collected and used in the present study. The recorded metal loss features were identified and selected for the development of the SVM model. Five types of metal loss features were recorded all over the pipeline during the inspection time such as pitting, general, circumferential grooving, axial grooving and circumferential slotting. It was found that the pitting type of metal loss was most reoccurring as compared to other metal loss types.

Since the available data was large, only a small portion of the data set was used for training SVM models to deal with computational memory requirements. To develop the SVM model, the parameters such as length, width, depth, pressure, wall thickness, weld girth are considered as predictors whereas metal loss type is considered as a response. Different types of SVM models were investigated for their accuracies in predicting the fault. Later, the best accurate SVM model type was opted for the prediction of metal loss defects for unseen data. The performance of the selected SVM model was analysed by means of correctness rate in prediction for fault type. The detailed methodology of the selected SVM type is given in the next section.

SVM Approach

SVMs can manage linear, modest, classification tasks as well as complex non-linear classification problems. The basic principle or idea behind SVM is presented in Figure 2, where the hyperplane is separating two classes of data so that the margin is maximized. In other words, the more is the margin, the best will be the classification of data. The formulation or the decision rule that is involved for a point to lie in a hyperplane can be given by the Equation (1) for a data $(x_i,y_i)^n{}_{i=1}$.

$$w.x_i + b = 0 \quad , \qquad \text{for } y_i = 0 \tag{1}$$

where, w is the weight of vector, x_i is a point and b is the bias.

For an optimization constrained problem, an optimal hyperplane can be attained as a solution by means of Equation (2) when the data sets are linearly separable (Vapnik, 2000).

$$\text{Minimize } \frac{1}{2}\|w\|^2 \tag{2}$$

Subjected to $y_i\ [w.x_i + b] - 1 \geq 0,\ i = 1, 2, \cdot \cdot k$

Nevertheless, the acquired data was overlapping, hence a soft constrained condition using a soft variable ε_i was used as given in Equation (3), Yan (2015).

$$y_i\,[w.x_i + b] - 1 + \varepsilon_i \geq 0,\ i = 1, 2, \cdot \cdot k \tag{3}$$

Where ε_i is soft variable

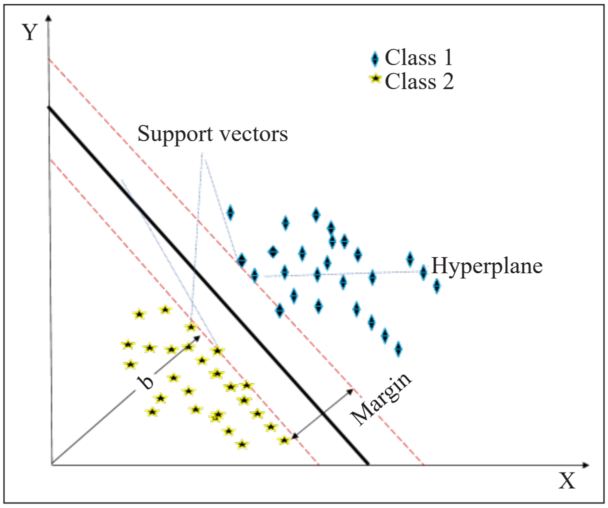

Figure 2. Optimal hyperplane architecture

The structure risk minimization principle was applied to the classification case and the SVM model was trained based on the Equations (4) and Equation (5), Yan (2015).

$$\text{Minimize } \frac{1}{2}\|w\|^2 + C\sum_{i=1}^{k}\varepsilon_i \qquad (4)$$

$$\text{Subjected to } y_i\,[w.x_i + b] - 1 + \varepsilon_i \geq 0,\ \varepsilon_i \geq 0,\ i = 1, 2, \cdot\cdot k \qquad (5)$$

where, C is the disciplinal parameter

Proposed SVM Model Training

The historical inspection data was used to develop SVM models for the prediction of metal loss of different types. Five types of metal loss were identified such as pitting, circumferential grooving, general, circumferential slotting and axial grooving which are affecting the crude oil pipeline in the available data. These metal loss anomalies were given as response while the variables length, width, depth, wall thickness, pressure and weld girth were given as inputs during the training stage for all types of SVM models. The SVM models were trained based on supervised classification principles by means of Equation (4) and Equation (5).

After the data acquisition process, a small portion of five metal loss types data sets were used for training different types of SVM models namely (i) linear SVM, (ii) quadratic SVM, (iii) cubic SVM, (iv) Fine Gaussian SVM, (v) Medium Gaussian SVM, (vi) Coarse Gaussian SVM. Classification toolbox in MATLAB® 2018 for the training of the SVM

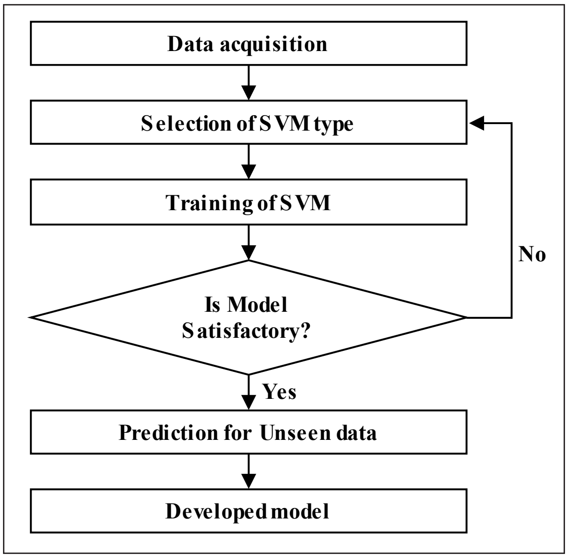

Figure 3. SVM approach

model. Later, the accuracy of all these models was compared. The best accurate SVM type was chosen for the prediction of unseen data. The workflow of the SVM approach is given in Figure 3.

Performance Evaluation Indices

The classification performance of proposed SVM had been evaluated using confusion matrix and various performance indices such as Accuracy, Recall, Precision and F1 Score were defined in Equation (6), Equation (7), Equation (8) and Equation (9), Taqvi et al. (2018). It is noted that the performance evaluation of a developed classification model is a compulsory step in model selection. Once the classification model has developed, the performance of the developed model has been evaluated. It is usually incorporated using predefined performance measure indices. These terms are defined as:

Accuracy: It is a ratio of correctly predicted samples to the total samples

$$Accuracy = \frac{TP + TN}{TP + FP + TN + FN} \tag{6}$$

Precision: It is the ratio of correctly predicted positive samples to the total predicted positive samples. The high precision from a classifier relates to the low false positive rate.

$$Precision\,(P) = \frac{TP}{TP + FP} \tag{7}$$

Recall: It is also known as sensitivity. It is the ratio of correctly predicted positive samples to all observations in the actual class.

$$Recall\,(R) = \frac{TP}{TP + FN} \tag{8}$$

F1 score: F1 score is the weighted average of precision and recall. Therefore, this score takes both false positives and false negatives into account.

$$F1 = 2 \times \frac{P \times R}{P + R} \tag{9}$$

Whereas, TN = True Negative, TP = True Positive, FP = False Positive and FN = False Negative

RESULTS AND DISCUSSION

The crude oil pipeline historical data was used to train all types of SVM models. The models were trained based on supervised classification principles using Equation (4) and Equation (5). The accuracies of all trained SVM models were then calculated and are presented in Table 1. The finest model in terms of accuracy among all models was quadratic SVM, with an accuracy of 87.4%. The proposed Quadratic SVM classified three (03) faults such as general, circumferential slotting and axial grooving most accurate (100% accuracy) among five (05) types of faults. The other two faults such as pitting and circumferential grooving were not found to be so accurate, the accuracies of true and false classification can be seen in the confusion matrix as shown in Figure 4. Notably, it is estimated that some pin locations of a crude oil pipeline were corroded due to more than one type of class, but one type of class was reported in the inspection data. The same SVM model was employed for further predictions on unseen data.

Table 1
Training prediction accuracy for each SVM type

SVM Type	Prediction Accuracy
Linear	84.5%
Quadratic	87.4%
Cubic	78.9%
Fine Gaussian	65.3%
Medium Gaussian	76.8%
Coarse Gaussian	78.5%

True class	Circum. Slotting	Axial Grooving	Circum. Grooving	General	Pitting	TP Rate	FN rate
Circum. Slotting	100%					100%	
Axial Grooving		100%				100%	
Circum. Grooving	5%		84%	5%	5%	84%	16%
General				100%		100%	
Pitting	11%		11%	11%	68%	68%	32%

Predicted class

Figure 4. Confusion Matrix of Quadratic SVM for training data

The trained quadratic SVM model had been applied to unseen data for the prediction and results found to be satisfactory. The trained SVM model was tested using a new dataset that has not been used in the training stage and allowed for the prediction of fault. Later, the prediction was made for the data irrespective of fault type, and results were found to be 93.0% accurate. Among these predictions, pitting fault type was least accurate which may be due to the occurrence of more than one fault type at the same pin location of a pipeline. The accuracies of all predictions of faulty type for unseen data are presented in Figure 5.

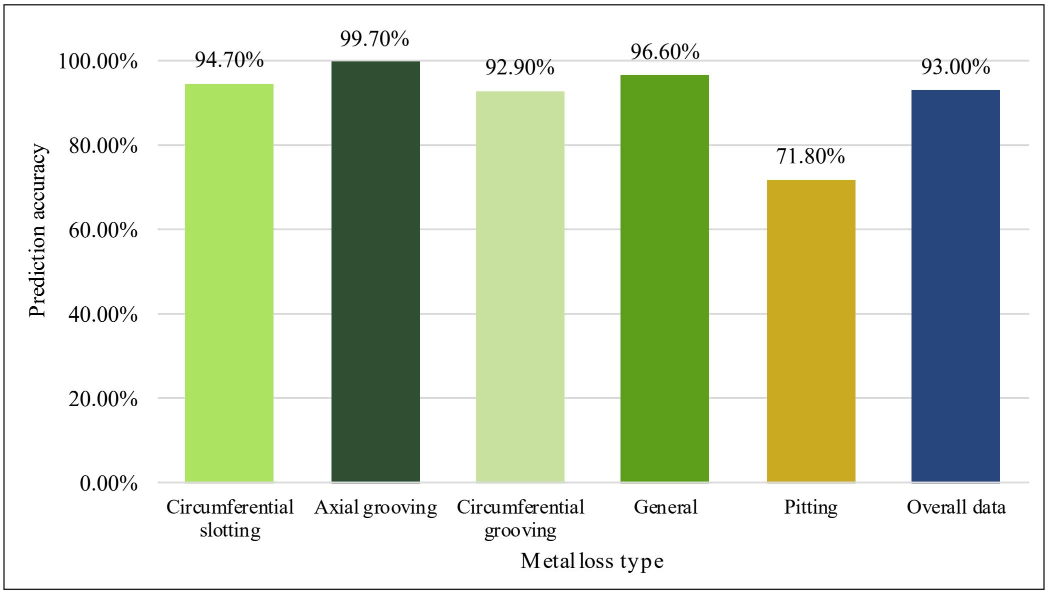

Figure 5. Accuracy predictions of metal loss type

Performance Evaluation

The classification performance of the developed SVM model had been evaluated using a confusion matrix as shown in Table 2. It can be observed that SVM had correctly classified axial grooving fault with the accuracy and F1 score of 100%. Similar results were obtained for type general, circumferential slotting and circumferential grooving fault with accuracies of 98%, 97.88% and 90.62%, F1 scores of 98.04%, 97.92% and 89.96 respectively. A very low classification accuracy can be observed in pitting fault as it has been 33% misclassified in other fault classes. As a result, the fault detection rate (FDR) for all faults was found to be 90.4%, while the misclassification rate (MR) was 9.6%. These results can also be compared with the previous study by (Taqvi et al., 2018) in which distillation column fault were classified using SVM. The FDR was found to 99.7% which is comparable with the current study. The high FDR is the previous study is due to the large number of faults used for the training of classifier.

Table 2
Classification performance

Type Of Fault	Accuracy	Recall	Precision	F1 Score
Circumferential Slotting	97.88	100	95.90	97.92
Axial Grooving	100	100	100	100
Circumferential Grooving	90.62	84	96.8	89.96
General	98.00	100	96.2	98.04
Pitting	83.37	68	98.2	80.35

Pareto Analysis

The data had been analysed by utilizing Pareto analysis to observe the most affecting fault type using historical data. The historical data that contained a type of metal loss was counted and arranged in descending order such that the most occuring type of metal loss on top. The cummulative percentage of fault type had been calculated and presented in Table 3. Figure 6 shows that pitting fault type has the highest impact according to the 80/20 rule as denoted by the dotted line. The Pareto analysis shows that the pitting fault type was majorly occuring when compared to other faults (metal loss) types. Therefore, it can be concluded that the pipeline under consideration in this study is most affected by pitting type of metal loss. The pitting fault type is highly affecting the pipeline and causing major deterioration due to harsh environmental conditions around the pipeline. Vanaei et al. (2017) described pitting corrosion to be the most observed metal loss in the transmission pipeline causing severe, localized deterioration to the surface area of the pipeline (Vanaei et al., 2017). Pitting corrosion can be caused due to several reasons that include: pipe material defects, penetration by chemicals, damage protective passive film or improper material used in the

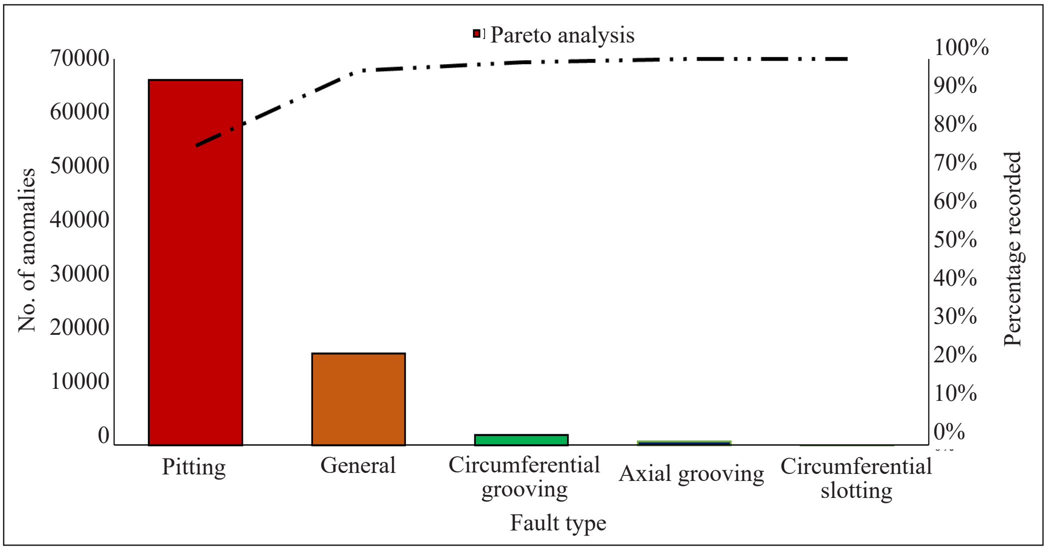

Figure 6. Pareto analysis

pipeline. To overcome this metal loss type, necessary actions like repair, a cathodic coating is done for better reliability of pipeline and smooth operation. Failure analysis for pitting corrosion for pipelines installed in Iran is done by Mansoori et al. (2017) which founds pitting mechanism to be the cause of failure in the pipeline. Necessary actions like repair, cathodic coating need to be done to avoid these issues for better reliability of pipelines and smooth operation.

Table 3
Contribution effect of individual type

Type of fault	Contribution (%)
Pitting	77.47869
Circumferential Grooving	2.197173
General	19.49041
Axial Grooving	0.810346
Circumferential Slotting	0.022217

CONCLUSION

This study presented an SVM based approach to classify various faults in crude oil pipeline based on historical inspection data. The data was utilized to develop an accurate SVM model for the classification purpose. The accuracy rates of all SVM models such as Linear SVM, Quadratic SVM, Cubic SVM, Fine Gaussian SVM, Medium Gaussian SVM and Coarse Gaussian SVM were calculated and presented. The quadratic SVM type was found to be more appropriate for this available data in terms of classifying the metal loss type and was selected for further predictions. The results were found to be satisfactory with an overall prediction rate of 93.0%. It was found that the data used for prediction was not classified as two faults at a single point which might be the cause of deviation in predictions. Furthermore, it was revealed that the pipeline under consideration was mostly affected by pitting type of metal loss with 77.47 % share in total recorded failures. The proposed approach may help the oil and gas or other pipeline industries in condition assessment and maintenance schedule, which can decrease the product losses, increase the life span of a pipeline and minimize the risk associated with failure.

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Statistical Analysis of Malaysian Timber's Combustion Data from Cone Calorimeter Test

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ABSTRACT

The information on the combustion properties of local timber is crucial in Malaysia as the archival material related to this subject matter is found to be very limited in scope and incomplete. The heat release rate (HRR) is the most precious variable of combustion properties as it provides the key to understand and quantify the hazard in fires. Thus, this work is to verify the reliability of the HRR obtained from cone calorimeter tests conducted upon six Malaysian wood species: *Shorea laevis, Vatica rassak, Koompassia malaccensis, Heritiera, Shorea parvifolia* and *Cratoxylum arborescens*. The single factor one-way analysis of variance (ANOVA) was used to investigate statistically significant differences between the means of the HRR dataset of each species during the combustion tests at three different heat fluxes. Later, the confidence interval estimation was occupied to determine the range around the HRR dataset, where the means of the data was likely to be found. The intraclass correlation coefficient (ICC) test was also implemented to assess the reliability of the heat release rate data obtained from the cone calorimeter test. From the surveillance, the P-values of all the six species were higher than $\alpha = 0.05$, insinuating that the difference between the means of the dataset was not statistically significant. The confidence interval values consisting of the upper bound and lower bound limits indicate that the certainty that these ranges contain the true mean of the heat release rate dataset is 95%. Finally, the

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fact that heat release data received from the cone calorimeter test were highly reliable to statistically calculate the variation in measurements taken by a single instrument under the same condition confirmed by the ICC's values of 0.82 to 0.99 that reflect good to excellent correlations.

Keywords: ANOVA, combustion, cone calorimeter test, heat release rate, Malaysian timber

INTRODUCTION

Malaysia has always been known for its wood-based furniture, owing to its natural resources. Due to its qualities, Malaysian timbers are highly favoured for use as materials for furniture such as sofa, dining table and cabinet. As a result, Malaysia ranked amongst the top 10 largest exporters of furniture in the world and the country exports around 80% of its furniture production. In January 2019, Malaysia's largest export of major timber product is wooden furniture, portrayed the United States of America (USA) as the largest importer, followed by Japan and Australia (Malaysian Timber Industry Board, 2019). Under the National Timber Industry Policy, the furniture industry is targeted to contribute RM 12 billion in exports by 2020 (Ministry of Plantation Industry and Commodities Malaysia, 2009). With large markets in the USA, Japan and Australia, Malaysia is seen to have a strong position in the global furniture industry. This situation is supported by the tremendous growth in exports to the United Kingdom (UK), the United Arab Emirates (UAE), Saudi Arabia, Philippines and Russia. In expanding the export wing, Malaysia is now eyeing countries like Algeria, Greece, Puerto Rico and Libya as prospects for the new furniture market.

In the tropical rainforest of Malaysia, there are more than 3,000 species of trees categorized as hardwood, medium hardwood, light hardwood and softwood, which are categorized according to their density. These timbers are of high quality and ranged from very durable to durable wood (Tewarson, 1980). With varying physical texture, fabulous colour, and good manufacturing properties encouraged continuing world demand for Malaysian timber and timber-based furniture. However, timber is always considered as combustible material and the usage as furniture may notably add to the fire loading in the compartment and promote the spread of flame and speed up the outbreak of flashover.

When timber heated up to 500°C, the cellulose, hemicellulose, and lignin decomposed to unstable gases, tar (levoglucosan), and carbonaceous char (Lowden & Hull, 2013). The decomposition of timber follows a pattern which is considered as the mechanism of superposition of the individual components; starting with the decomposition of hemicellulose at 180°C-350°C, followed by the decomposition of cellulose at 275°C-350°C, and lastly the decomposition of lignin at 250°C-500°C (Kim et al., 2006). In a simple explanation, as a porous material, timber gets burned when exposed to high heat fluxes and goes through pyrolysis. It is a process where the high temperature exhibited by the firing trigger the timber components to decompose to a mixture of volatiles, tar, and highly reactive carbonaceous char. The timber experiences two oxidation phases in burning; (1) The gas-phase oxidation of the volatiles and tar, which produces flaming combustion; and (2) The solid-phase oxidation of the remaining char, which produces glowing or smouldering combustion. The smoke released from timber contains harmful gases, and the compositions influenced by combustion condition, the pattern of decomposition, ventilation, temperature, heat exposures, the oxygen and moisture present, the species of timber, any treatments or finishes that may apply and fuel chemical nature (Neviaser & Gann, 2004; Quintiere, 1982; Rasbash & Drysdale, 1982; Tewarson, 1980).

Generally, the works regarding timber fire study stands on the timber's primary reaction towards burning, which involves three stages of heat action (Tsatsoulas et al., 2009); preliminary (flameless) stage; main (flame) stage; and final (flameless) stage. The preliminary stage involves the dehydration and the release of liquid and volatile compounds while heating the timber to its decomposition temperature. The main flame stage includes the ignition of thermal decomposition products, flame spread by combustible gases, and an increase in heat release and mass-loss rates, which is the active process of decomposition. The final stage includes the slow burning of the residue and ashing of the remaining matter. However, this stage is not often reached (Tsatsoulas et al., 2009). There are numbers of research work done in different aspect of the reaction to fire of timber. Terrei et al. (2018) had set up an experimental tool attached to the cone calorimeter to study the process involved during the autoignition as this phenomenon was still in the grey area. Hou et al. (2017) investigated the combustion performance using cone calorimeter for three types of wood–aluminium composites and found that the peak HRR, average HRR, total heat release, and mean mass loss rate (MLR) of wood–aluminium composites with 1.6-mm-thick aluminium alloy sheet on the surface were decreased to 70.18%, 48.71%, 24.27%, and 80.60%, respectively. Rantuch et al. (2017) analyzed the possibility of floating flooring to ignite due to different densities of external heat flux using cone calorimeter to calculate the critical heat flux and concluded higher values had been calculated for the test conditions without the igniter (9.5 $kW.m^{-2}$ – 23.6 $kW.m^{-2}$) than for the conditions with the igniter (23.6 $kW.m^{-2}$ do 34.7 $kW.m^{-2}$). The effects of density, gas permeability, ring width, grain orientation, and heat flux, on the charring rate of six Chinese wood using cone calorimeter, had been studied by Wen et al. (2015) and led to the finding that density, gas permeability, and heat flux, but not the grain orientation, significantly affected the charring rate. Fateh et al. (2016) conducted an experiment using cone calorimeter to measure the yields of the gaseous emissions released during combustion of Maritime pine needles (*Pinus pinaster*) and the result showed that carbon dioxide and water were the main emissions during the experiments including about 5% of the carbon released as carbon monoxide and hydrocarbon at whatever the value of external heat flux selected. Khalfi et al. (2004)

determined that dense samples of wood waste furniture burned considerably better than the fibrous type with higher maximum HRR and a lower CO/CO_2 ratio in fire test using an open calorimeter.

The fire properties of heat release rate and time to ignition are known as essentials parameters for the performance-based fire safety engineering design (Babraukas & Peacock, 1992). Even though many works executed on the reaction to fire of timber, the archival material related to the Malaysian timber is found to be very limited in scope and incomplete (Wong, 1995). For instance, the records of the strength and physical properties of local timber are available (Lee et al., 1979; Tahir et al., 1996), but there is only a few information on the fire properties. To date, some studies (Marsono & Balasbaneh, 2015; Mohamed & Abdullah, 2014; Ratnasingam et al., 2016) conducted to rectify the issues and challenges of using local timber in Malaysia, but none conducted on the fire properties. There is a decreasing interest in using local timber for being the structure used in household furniture since timber considered as combustible material that may accumulate fuels in building fire. As timber produces heat, toxic gas, and smoke when burned, the products have adverse effects on the safety of occupants and at the same time, the fire may cause property losses. Therefore, there is an urge for knowledge on the combustion properties of Malaysian timber species particularly for the benefit of fire engineers for fire simulation modelling purposes. Thus, this work is to verify the reliability of the HRR obtained from the cone calorimeter tests using statistical analysis upon six species of local timber which are selected based on its application as indoor and outdoor furniture in Malaysia.

METHODS

Samples Preparation

Specimens of six timber species used in this work, *Shorea laevis, Vatica rassak, Koompassia malaccensis, Heritiera, Shorea parvifolia* and *Cratoxylum arborescens*. All specimens were prepared to be in the dimension of 100 mm × 100 mm × 30 mm squares. The solid timbers were untreated and kiln dried. Prior testing, the specimens were oven-dried at 70°C for 24 hours and kept in 50% relative humidity (Simpson, 1982).

Experimental Program

A standard cone calorimeter performed the experimental tests (Figure 1) built to comply with ISO5660-1:2002. The cone calorimeter used was a Fire Testing Technology (FTT) iCone Plus Calorimeter, manufactured in 2015 and upgraded in 2018. The data collection and calculations deployed the FTT Conecalc v6.5 software. The cone calorimeter is a fire testing tool deployed the principle of oxygen depletion based on the principle that the heat release per unit mass of oxygen consumed has a value of 13.1 MJ/kg. It is utilized by many researchers in the fire engineering field to get data of combustion properties for a material tested and used as input to models when predicting the fire conduct of that material (Babrauskas & Peacock, 1992). The principle idea of this equipment is to get the source of fuel's surface radiated under constant heat flux to ignition and then burned (Figure 2).

Figure 1. Cone calorimeter

Figure 2. Timber surface radiated to get burned

In this study, the cone calorimeter tests were conducted at three different constant incident heat fluxes: 35, 50, and 65 kW/m^2. The selection of the irradiances was based on the factor that it represented a possible range of incident heat fluxes to be counted in developing fire (Tsatsoulas et al., 2009). At each incident irradiance, the specimens were heated for 30 minutes. The test specimens were wrapped with 0.0 – 0.05 mm thick aluminium foil except for the top side and placed in a retainer frame/holder, resulting only 0.0088 m^2 of specimen surface area exposed to the radiant source. All specimens were imposed on the heat fluxes at horizontal orientation along with the pilot ignitor parallel to the grain and the cylindrical heater located 25 mm from the top surface of the specimens. Before the spark igniter was placed above the sample surface, and the actual burning test was started, baseline data was collected for 60 seconds. The experimental data was then measured from this baseline. The length of time required to create a steady flame state was recorded through visual observation. The test was triplicated for all species of timber, as shown in Table 1. Replication was needed as it is the repetition of an experimental condition so that the variability associated with the phenomenon such as random error of the analytical method could be estimated. The descriptive analysis was calculated to bring out the necessary valuable information of the data series. While the P-value for each set of replications was determined using the single factor ANOVA of Excel and the interpretation of the key results are detailed in the following section.

Table 1
The hardwood species for cone calorimeter tests

Species	Categories of hardwood	Heat flux	No. of tests
Shorea laevis	Heavy hardwood	35, 50, 65 kW/m^2	9
Vatica rassak	Heavy hardwood	35, 50, 65 kW/m^2	9
Koompassia malaccensis	Medium hardwood	35, 50, 65 kW/m^2	9
Heritiera	Medium hardwood	35, 50, 65 kW/m^2	9
Shorea parvifolia	Light hardwood	35, 50, 65 kW/m^2	9
Cratoxylum arborescens	Light hardwood	35, 50, 65 kW/m^2	9

RESULTS AND DISCUSSION

Differences Between Group Means

The variation of heat release rate to time for six Malaysian timber is as shown in Figure 3. From the observation, the shape of curves divulged the way untreated timber releases the heat in the combustion is alike in terms of the process that comprehends three stages (Kim et al., 2006). However, the values of heat released are different from one sample to another of the same species as it depends on many factors, such as the moisture content and density. The curves of each sample are found to be identical. The statistical analysis of single factor ANOVA used to analyse the data of heat release rate from the six species of Malaysian timber and the P-value for each species is as portrayed in Table 2. The P-value for all the timber species tested is higher than $\alpha = 0.05$, which means that the difference between the means of samples is not statistically significant. In this work, there must be no significant difference between the means to assure the consistency of the data obtained from the replications of the combustion test.

Table 2
The P-value of HRR for Malaysian timber under different heat fluxes

Category	Species	Heat Flux (kW/m^2)	HRR measurement's data count	P-value	
Heavy Hardwood - Density range: 800 – 1,120 kg/m^3	*Shorea laevis*	35	50	0.44	Differences between the means are statistically not significant
		50	50	0.76	
		65	50	0.07	
	Vatica rassak	35	50	0.17	
		50	50	0.77	
		65	50	0.92	
Medium hardwood - Density range: 720 – 880 kg/m^3	*Koompassia malaccensis*	35	50	0.15	
		50	50	0.42	
		65	50	0.15	
	Heritiera	35	50	0.19	
		50	50	0.94	
		65	50	0.09	

Table 2 (*continue*)

Category	Species	Heat Flux (kW/m^2)	HRR measurement's data count	P-value	
Light hardwood - Density range: 400 – 720 kg/m^3	*Shorea parvifolia*	35	50	0.18	Differences between the means are statistically not significant
		50	50	0.28	
		65	50	0.73	
	Cratoxylum arborescens	35	50	0.59	
		50	50	0.20	
		65	50	0.21	

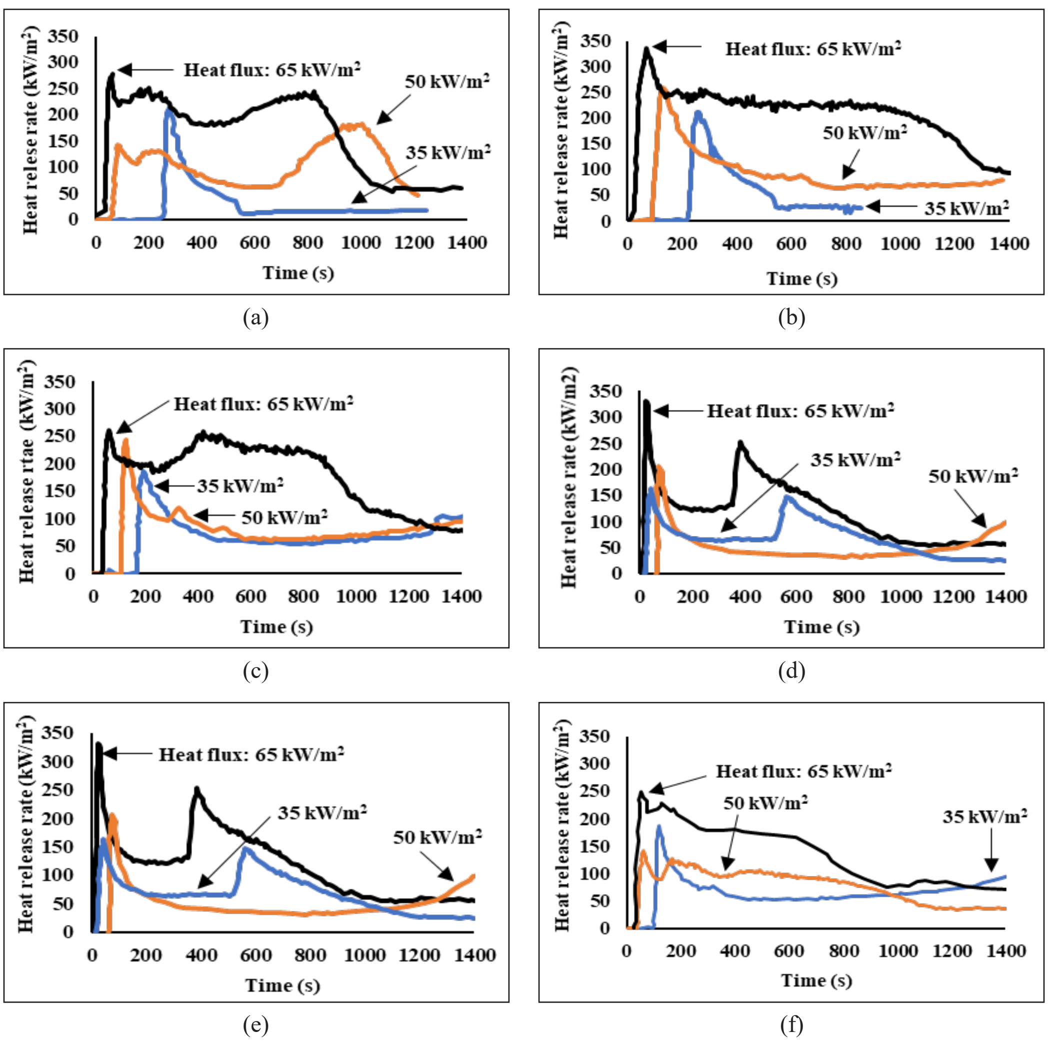

Figure 3. Variation of heat release rate with time of : (a) *Shorea laevis*; (b) *Vatica rassak*; (c) *Koompassia malaccensis*; (d) *Heritiera*; (e) *Shorea parvifolia*; and (f) *Cratoxylum arborescens* under different heat fluxes

The Confidence Interval

The confidence interval is a range around a sample where a population means is likely to be found. The calculation for the determination of the confidence interval can be described as in Equation (1) (Curran-Everett, 2009):

$$\mu = \bar{x} \pm t_{\alpha/2}\, s/\sqrt{n} \quad (1)$$

Where μ is the population mean; $\bar{x}$ is the sample mean; s is the sample standard deviation; n is the sample size; α is the type I error (the proportion of the time the confidence interval does not overlap the population mean; and $t_{\alpha/2}$ is the critical value of the Student's t-distribution for a two-tail confidence interval. The margin of error is $\pm\, t_{\alpha/2}\, s/\sqrt{n}$, which mean the value of confidence interval consists of the upper bound; $\mu + t_{\alpha/2}\, s/\sqrt{n}$ and the lower bound (Equation (2)):

$$\mu - t_{\alpha/2}\, s/\sqrt{n} \quad (2)$$

The 95% confidence interval of HRR data obtained from the cone calorimeter test for each wood sample's replication is figured in Table 3. In this research, only the interval plot of means and confidence interval for heavy hardwood were applied as seen in Figure 4. Figure 4 shows that the certainty that the range of upper and lower bound interval of the heat release data contains the true mean is 95%. As the p-value from ANOVA (Table 2) conferred the differences between the means are not statistically significant, there is no reason to assess differences in group means.

Table 3
The mean, upper bound and lower bound limit for the HRR of Malaysian wood under different heat fluxes

Category	Species	Heat Flux (kW/m^2)	Replication	μ	Upper bound	Lower bound
Heavy Hardwood - Density range: 800 – 1,120 kg/m^3	*Shorea laevis*	35	Replication 1	103	236	-29
			Replication 2	88	247	-71
			Replication 3	85	226	-54
		50	Replication 1	82	170.5	-5.8
			Replication 2	85	170.1	-0.06
		65	Replication 1	157	168	145
			Replication 2	198	209	186
			Replication 3	160	171	148
	Vatica rassak	35	Replication 1	76	214	-62
			Replication 2	95	224	-33
			Replication 3	88	240	-62
		50	Replication 1	146	321	-29
			Replication 2	151	340	-40

Table 3 *(continue)*

Category	Species	Heat Flux (kW/m^2)	Replication	μ	Upper bound	Lower bound
	Vatica rassak	50	Replication 3	138	277	-0.4
		65	Replication 1	177	396	10
			Replication 2	180	350	26
			Replication 3	170	380	13
Medium hardwood - Density range: 720 – 880 kg/m^3	*Koompassia malaccensis*	35	Replication 1	77	162	-8
			Replication 2	89	208	-30
			Replication 3	71	143	-1.2
		50	Replication 1	129	261	-4
			Replication 2	119	245	-8
			Replication 3	112	231	-7
		65	Replication 1	168	333	2.3
			Replication 2	163	308	18.5
			Replication 3	192	360	25
	Heritiera	35	Replication 1	90	201	-21
			Replication 2	78	174	-18
			Replication 3	98	210	-14
		50	Replication 1	128	265	-9
			Replication 2	129	262	-4
			Replication 3	124	257	-8
		65	Replication 1	171	314	27
			Replication 2	142	278	5
			Replication 3	143	292	-6
Light hardwood - Density range: 400 – 720 kg/m^3	*Shorea parvifolia*	35	Replication 1	103	227	-22
			Replication 2	108	235	-19
			Replication 3	85	212	-42
		50	Replication 1	90	156	25
			Replication 2	95	174	17
		65	Replication 1	195	367	22
			Replication 2	188	359	17
	Cratoxylum arborescens	35	Replication 1	88	223	-48
			Replication 2	97	200	-6
			Replication 3	99	213	-14
		50	Replication 1	82	160	4
			Replication 2	73	144	2.5
			Replication 3	68	142	-5
		65	Replication 1	179	334	25
			Replication 2	155	288	23
			Replication 3	157	307	8

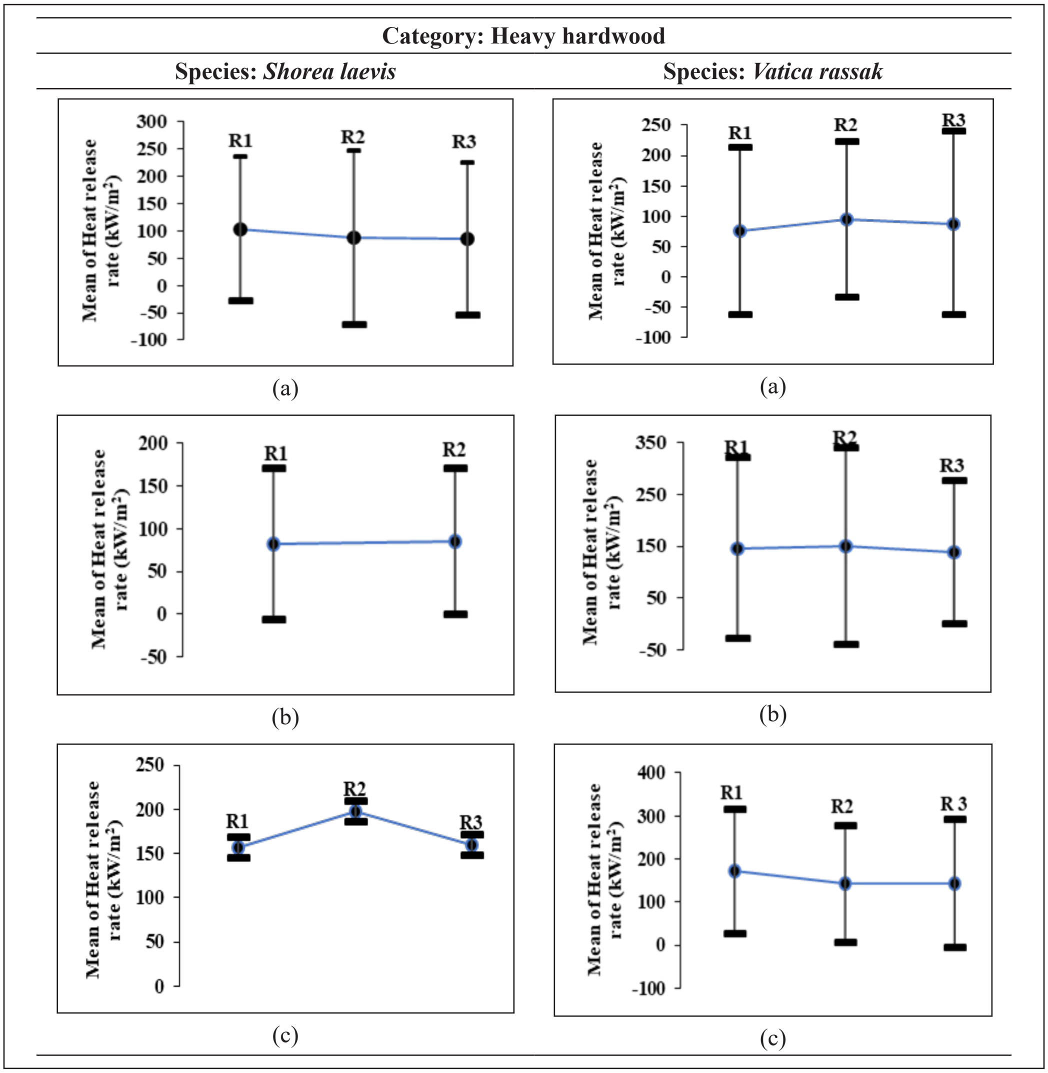

Figure 4. Interval plot to display mean and confidence interval of combustion test for heavy hardwood; (a) At Heat flux of 35 kW/m^2; (b) At Heat flux of 50 kW/m^2; and (c) At Heat flux of 65 kW/m^2

Intraclass Correlation Coefficient

The intraclass correlation coefficient (ICC) is a measure of the reliability of measurements. It assesses the reliability of measurement for data that has been collected as groups or sorted into groups, and the coefficient ranges from 0 to 1. The high value of ICC, which is close to 1, indicates a high similarity between values from the same group. The ICC analysis is constructed to check the reliability of the heat release rate measurements obtained from the replications of the combustion test at different heat fluxes, and the results are recorded in Table 4.

According to Table 4, the ICC is the average measure for all groups of replications of each species at the specific heat fluxes. The average measures elucidate how consistent are the samples of the same species react in combustion relative to each other on average from sample to sample. Hinge on 95% confidence level of ICC estimation, values less than 0.5 is considered as poor, between 0.5 and 0.75 is moderate, between 0.75 and 0.9 contemplates good correlation, while the ICC of 0.9 onwards is an excellent sign of reliability (Koo & Li, 2016). All six species timber samples conceived from optimal to excellent ICC range in the reliability test, which firmed on the high reliability and consistency of the data resulted from the cone calorimeter. The *Shorea laevis*, *Heritiera*, and *Cratoxylum arborescens* inscribed the ICC values between 0.928 to 0.998 at three different irradiances charged indicating excellent agreement between the replications with low variability. The 95% confidence intervals of ICC, ranging from 0.722 to 0.999, also strengthened the reliability for the data from the cone calorimeter. Additionally, the Cronbach's alpha values denote high internal consistency between the replications for the six species of Malaysian timber in the combustion test. In simple words, the data obtained from the combustion test replications are relative to one another for each species, and the consistency of data provided form with the combustion tests are highly reliable.

Table 4
The intraclass correlation coefficient (ICC) for HRR between repetitions of cone calorimeter test

Category	Species	Heat flux (kW/m^2)	ICC	95% Confidence interval		Cronbach's Alpha
				Upper bound	Lower bound	
Heavy hardwood	*Shorea laevis*	35	0.943	0.966	0.906	0.948
		50	0.992	0.996	0.985	0.993
		65	0.972	0.990	0.833	0.990
	Vatica rassak	35	0.918	0.955	0.843	0.935
		50	0.879	0.927	0.806	0.878
		65	0.974	0.984	0.957	0.975
Medium hardwood	*Koompassia malaccensis*	35	0.866	0.920	0.780	0.877
		50	0.937	0.963	0.897	0.942
		65	0.976	0.990	0.906	0.988
	Heritiera	35	0.944	0.969	0.896	0.954
		50	0.998	0.999	0.995	0.997
		65	0.928	0.961	0.859	0.944
Light hardwood	*Shorea parvifolia*	35	0.957	0.978	0.909	0.968
		50	0.820	0.868	0.754	0.821
		65	0.841	0.902	0.722	0.864
	Cratoxylum arborescens	35	0.937	0.962	0.898	0.939
		50	0.947	0.971	0.901	0.957
		65	0.966	0.983	0.922	0.977

CONCLUSION

Most of the combustibility tests for timber and timber-based products comprised heating a predefined quantity of the test sample for a set span and conducted to collect data on fire properties. The fire properties data are used for (i) fire modelling; (ii) prediction of real-scale fire behaviour; and (iii) pass/fail tests. The cone calorimeter is a fire testing tool that deployed the rule of oxygen depletion based on the principle that the heat release per unit mass of oxygen consumed has a value of 13.1 MJ/kg. This tool is utilized by many researchers in the fire engineering field to get combustion data for materials tested and these valuable findings are used as input to fire models and software when predicting the fire conduct.

The replications of the combustibility test are intended to observe the reliability and consistency of the data obtained from cone calorimeter tests. The main objective of this study was to assess the reliability and consistency of the timbers through replication of each predefined combustion test. The heat release rate curves obtained from the replications of combustion tests under three different heat fluxes of 35, 50 and 65 kW/m2 disclosed identical curves for *Shorea laevis, Vatica rassak, Koompassia malaccensis, Heritiera, Shorea parvifolia* and *Cratoxylum arborescens*. In order to assess the reliability and the consistency of the replications, the statistical analysis of single factor ANOVA was used to determine statistically the significant differences between the means of samples for each species tested in the combustibility test. From the observation of ANOVA analysis, the P-value of all the six species were higher than $\alpha = 0.05$, which means that the difference between the means of samples is not statistically significant. These P-values were an indication that the replications of combustion tests are closely alike between one another. Besides that, the range of interval indicates 95% certainty that the upper and lower bound limit contains the true mean of the samples. The reliability of the heat release rate data obtained from the replications was measured using the ICC test and resulted optimal to excellent ICC range. The ICC's outcome firmed the fact that the data from the cone calorimeter are reliable to statistically calculate the variation in measurements taken by a single instrument under the same conditions. The consequences of the statistical analysis of ANOVA, the confidence interval of means and the ICC test performed in this study lead to the confirmation that the results and reports of timber combustion properties obtained by the cone calorimeter are highly reliable.

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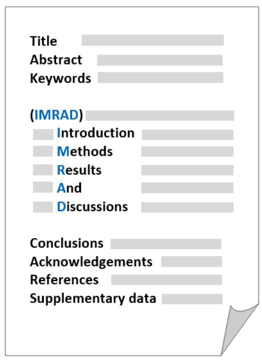

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