A Holistic Approach for Assessing Occupational Health Risk due to Fugitive Emissions in Petrochemical Processes: Leak Hazard Index (LHI)

Yousef A. Alhamdani[1], Mimi H. Hassim[1]*, Salim M. Shaik[2]

[1]UTM-MPRC Institute for Oil and Gas/Safety and Health Research Group, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Johor.

[2]Institute of Sustainability for Chemicals, Energy, and Environment (ISCE2), Agency for Science, Technology and Research (A*STAR), Pesek Road, Jurong Island, Singapore 627833, Singapore.

*Corresponding author: mimi@cheme.utm.my, shaik_salim@isce2.a-star.edu.sg.

===

ABSTRACT

Fugitive emissions (FE) are unintentional and undesirable leaks of hazardous gases that come from petrochemical piping components such as valves, flanges, and pumps. Fugitive emissions represent a serious threat to the health of petrochemical workers. Based on the source, pathway, receptor (SPR) model, the occupational health (OH) risk due to fugitive emissions is a combination of the health hazards that originate from the source (i.e. process materials, conditions, and design), the leak hazard that represents the pathway, and the exposure hazard that takes place at the receptor. These three hazards bear a resemblance to the severity, probability of leakage, and probability of exposure, respectively. The severity was covered in a previous article related to this study. This paper concentrates on the probability of leakage. The exposure will be covered in a subsequent work to be published later. The OH risk is usually evaluated based on fugitive emission amount estimations made based on emission factors developed for different process piping components. This type of evaluation, however, does not consider maintenance that is put in place to control leaks from process piping components. This paper attempts to address and reduce this gap through the development of an index-based method named the Leak Hazard Index (LHI). The LHI is meant to determine the probability of leakages, taking into consideration the effectiveness of maintenance programs that are regularly executed to reduce or prevent leaks from process piping components. The demonstration of the LHI reveals a reliable and realistic evaluation of the probability of leakage.

Keywords: *fugitive emissions; occupational health; leak hazard; leakage probability*

1. INTRODUCTION

Fugitive emissions refer to the unintentional and undesirable leaks of harmful gases from pressurized equipment and piping components inside an industrial plant or petrochemical facility. The main sources of fugitive emissions include, but are not limited to, valves, piping flanges, pumps, storage tanks, and compressors (Alauddin et al., 2023; Brereton et al., 2018; Sotoodeh, 2021). These emissions are referred to as “fugitive” because they are unanticipated or undetectable by standard monitoring and control devices. In addition, these emissions are not taken into account and calculated during the design of the equipment and piping components (Sotoodeh, 2021).

Fugitive emissions have become less tolerated by industry and regulatory agencies due to their impact on plant productivity, environment, and health (Alauddin et al., 2023). With regards to health, fugitive emissions are believed to be the primary source of continuous exposures of workers to toxics in chemical plants during normal operations (Aziz et al., 2013; Lipton and Lynch, 1994). Prolonged exposure, even at low concentrations, to these hazardous substances has the potential to cause adverse effects on workers’ health. Respiratory diseases are among the occupational diseases reported among petrochemical workers due to daily exposures to harmful chemical agents such as benzene (Kafaei et al., 2019).

Concerns over the occupational health effects associated with fugitive emissions, especially in the petrochemical industry, have resulted in the development of various occupational health risk assessment methods. These assessment methods were developed by different parties such as academia, industry, and private or governmental bodies. The most common methods used for assessing OH risk due to fugitive emissions are the inherent occupational health index-based methods (Hassim and Edwards, 2006; Hassim and Hurme, 2010a,b; INSIDE, 2001; Johnson, 2001). In the process of OH risk assessment, these methods usually provide approximate estimations of fugitive emissions in order to evaluate the personal exposure of workers. The fugitive emissions estimations are usually made based on emission factors developed by the Environmental Protection Agency (EPA) for different process stream services, e.g. gas/vapour, light liquid, and heavy liquid (Hassim and Hurme, 2010a). The main drawback associated with this type of assessment is that the fugitive emission estimations used in the assessment are made with no regard to maintenance programs applied to key fugitive emission sources such as valves, connectors, pumps, compressors, etc. Industries usually implement different maintenance programs in order to reduce these emissions, e.g. the use of advanced leak detection and repair technologies, improved maintenance and inspection procedures, and the installation of emissions control devices (Alauddin et al., 2023).

These maintenance programs can have a significant impact on the amounts of fugitive emissions. This implies that maintenance performance can be used to measure the probability of these leakages (i.e. fugitive emissions).

This paper presents an index-based method named the leak hazard index (LHI), which is developed to determine the probability of leakage. Unlike the previously developed index-based methods, which estimate the amounts of fugitive emissions, the LHI determines the probability of leakage by using maintenance performance-related indicators. Although the LHI can be used independently to determine the probability of leakage based on maintenance performance, it is primarily intended to be a part of the methodology proposed for a holistic OH risk assessment. This assessment method assesses OH risk due to fugitive emissions as a combination of the severity, the probability of leakage, and the probability of exposure. The proposed methodology integrates the source, pathway, receptor (SPR) model and the layers of protection (LOP) concept. The SPR model is used to identify hazards that contribute to the overall occupational health risk, namely the source hazard (i.e. chemicals, process conditions, and equipment), the pathway hazard (i.e. leak hazard), and the hazard at the receptor (i.e. exposure hazard). The LOP concept implies taking into consideration the layers of protection (LOP) that are hierarchically placed to control these hazards. These layers of protection are, namely, less hazardous chemical substances, less hazardous process conditions, and less hazardous process design at the source; maintenance at the pathway; and occupational health and safety management system (OHSMS) and safety culture of workers at the receptor. Figure 1 is a depiction of the general idea of the proposed methodology.

The source hazard was covered in a previous published paper related to this study. The previous paper presented an index-based method named the inherent health hazard level index (IHHLI), which is meant to measure the severity. While the probability of exposure will be covered in future work, this paper is concerned with the probability of leakage. The scope covered in this paper is highlighted by the dotted box in Figure 1. The following section presents a review of the OH risk assessment literature. A literature review on maintenance performance and its role as a leakage probability measure is provided in a subsequent section.

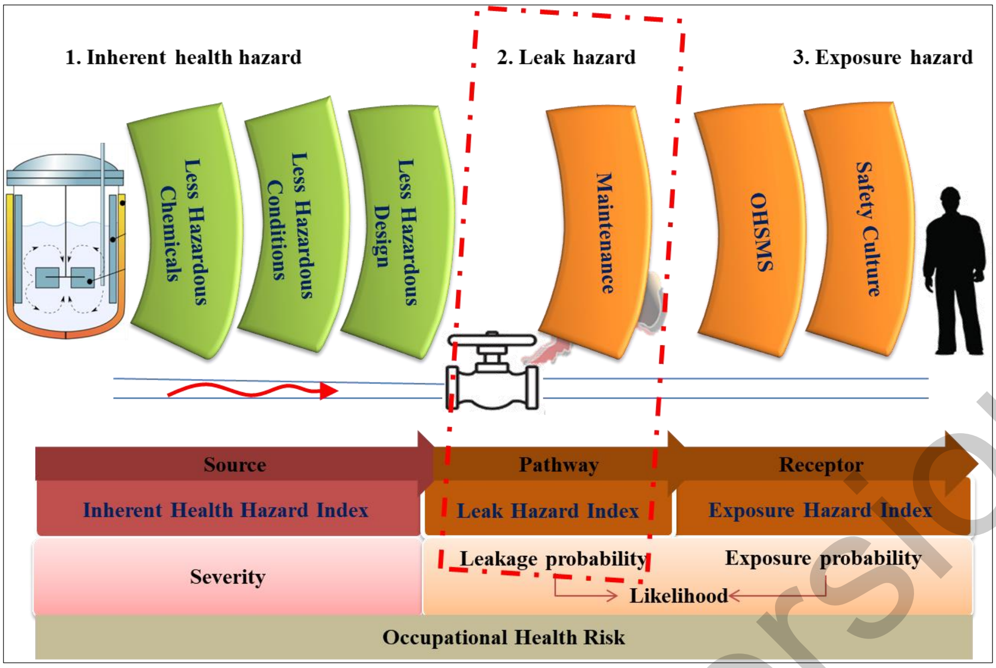


Figure 1 Occupational health risk assessment hybrid approach

2. OCCUPATIONAL HEALTH RISK ASSESSMENT: REVIEW OF LITERATURE

Over the last two decades, attention to the occupational health aspect has increased noticeably. Several assessment methodologies have been developed to assess occupational health risks in the chemical and petrochemical industries. Most of the occupational health assessment methods are index-based and usually intended to assess health hazards during chemical process development and early design stages. Among the most noticeable contributions to the OH risk assessment are the Health Hazard Index (HHI) (INSIDE, 2001), Process Route Healthiness Index (PRHI) (Hassim and Edwards, 2006), Health Quotient Index (HQI) (Hassim and Hurme, 2010a), and Occupational Health Index (OHI) (Hassim and Hurme, 2010b).

In the health hazard index (HHI), a leak factor (LF) is used to estimate the overall personal exposure of workers in a petrochemical workplace. The exposure is estimated based on readily provided leak factors (LF) of different types of equipment and activities (e.g. LF for storages = 0.3, LF for compressors and reactors = 3, LF for pumping, mixing, and transfer = 1.5, LF for manual handling operation = 0.6, etc.). The leak factors of equipment, activities, and manual handling operations in the process are determined and summed up to obtain the overall LF of the process (INSIDE, 2001).

The process route healthiness index (PRHI) is used to calculate the worker exposure concentration, i.e. the concentration of released chemicals to which workers are exposed in a workplace. In the calculation process, the amounts of small leaks and fugitive emissions are estimated. The estimated amounts of released chemicals are then multiplied by an estimated exposure time (EET) (i.e. 6 hours/day) and divided by the average working time (AWT) (i.e. 8 hours/day). The obtained value is the worker exposure concentration (Hassim and Edwards, 2006).

The health quotient index (HQI) and occupational health index (OHI) are meant for assessing OH risk during two different process design stages, i.e. the preliminary process design stage and the basic engineering stage, respectively. For both indexes, the most crucial step in the assessment is the estimation of fugitive emissions, which are seen as the main source of workers' exposure in the workplace. Fugitive emissions are estimated based on pre-calculated emission rates for standard process modules, which represent typical equipment such as distillation, flash drums, strippers, etc. These pre-calculated emission rates are created based on the U.S. EPA emission factors for different process piping components in different process stream services, e.g. gas/vapour, light liquid, and heavy liquid (Hassim and Hurme, 2010b).

Generally, in the process of OH risk assessment, all the aforementioned methods estimate concentrations of chemicals released as fugitive emissions into workers' breathing zone. These estimations are usually made based on pre-calculated leak or emission factors for typical process equipment and piping components. However, the major disadvantage associated with such assessments is that, when estimating fugitive emission amounts, the maintenance of process equipment and piping components is left out of consideration. Process equipment and piping components, which represent major sources of fugitive emissions, are usually subjected to regular maintenance programs. This implies that maintenance can influence the amount of fugitive emissions, and hence it is important to consider it as a measure for determining the probability of leakage. The following section provides a review of the literature on maintenance performance and how it can be a leakage probability measure.

3. MAINTENANCE PERFORMANCE: A MEASURE FOR LEAKAGE PROBABILITY

Major sources of fugitive emissions, such as valves, flanges, and pumps, are subjected to regular maintenance programs, commonly known as leak detection and repair (LDAR). Maintenance efforts are usually focused on the components that offer significant leak reduction. Typically, when a leak is detected, the maintenance management decides whether to repair the leak immediately or to schedule the repair for the next facility turnaround. Therefore, the effectiveness of maintenance programs is, to a great extent, dependent on maintenance management performance. Effective maintenance programs reduce the probabilities of hazardous chemical leakage, typically in the form of fugitive emissions (Cheadle et al., 2022; Zhang et al., 2022).

However, maintenance that is meant for controlling or minimizing leaks can also have a negative effect and increase the rate of leakage in petrochemical plants (Han et al., 2019; Vinnem and Røed, 2015). Complex process plants that contain more process equipment and huge numbers of piping components require excessive maintenance, thereby allowing greater opportunities for human error or equipment failure (Athar et al., 2019; Kletz and Amyotte, 2010). Several studies have shown that maintenance represents a root cause of many of the leaks that occur in complex petrochemical facilities (Kletz, 2009; Okoh and Haugen, 2013; Vinnem and Røed, 2014). These leaks usually occur in association with maintenance activities such as inspection, cleaning, repair, replacement of components (removals and installations), and testing. Process components involved in maintenance-induced leaks include valves, pipes, instrument tubing, pumps, flanges, and blind flanges (Vinnem and Røed, 2015). Valves are believed to be the most frequent process component involved in leak accidents associated with maintenance, probably due to the large quantity of these valves and thus the high frequency of valve repairs and/or removals and installations (Vinnem et al., 2016).

Having the above discussion in mind, it is ascertained that maintenance has a direct and significant influence on the probability of leakage in petrochemical facilities. It is also ascertained that maintenance performance is directly dependent on: (1) maintenance management performance and (2) process complexity. Influenced by these two factors, effective maintenance can significantly reduce the leaks in the process, while poor maintenance or improper maintenance can severely damage the facility, resulting in higher leakage rates. This implies that maintenance performance can be used as a measure to determine the probability of leakage. To make this possible, maintenance performance needs to be measured based on maintenance management performance and process complexity.

In the literature, many maintenance performance measurement (MPM) frameworks have been introduced. Lists of different and various maintenance performance indicators (MPI) have been presented by many authors (Parida and Chattopadhyay, 2007; Muchiri et al., 2011; Raza et al., 2016; Saari, 2019). Based on the review of these MPM frameworks, much emphasis on equipment performance is observed. Most of the maintenance performance indicators presented by these frameworks are concerned with equipment performance. Similarly, indicators for measuring maintenance cost are considered important by many authors (Kumar et al., 2013; Muchiri et al., 2010). In addition, the MPIs presented are mostly of a lagging type. Lagging indicators (also known as reactive indicators) monitor the performance of maintenance based on the results or outcomes that have occurred, e.g. equipment availability, mean time to failure (MTTF) of equipment, and number of failures and downtimes (Herrera and Hovden, 2008). However, leading indicators (also known as proactive or predictive indicators) are usually more preferable as they provide precursory information on performance and, hence, can be used for improvement. A detailed description of these frameworks is provided in Annex A–1.

For measuring process complexity, four methods for process complexity measurement were found relevant to this research study: (1) Nelson Complexity Index (NCI) (Kaiser, 2017); (2) Equivalent Distillation Capacity (EDC) (Kaiser, 2017); (3) Bottom of Barrel (BoB) index (Termeer, 2013); and (4) Koolen process complexity measurement method (Koolen, 2001). A detailed description of these methods is provided in Annex A–2.

4. METHODOLOGY

This section describes the methodology that was employed in order to achieve the main goal of this research study. The methodology involved four main steps: (1) collection of MPIs (secondary data); (2) selection of MPIs that are appropriate for measuring the leakage probability; (3) aggregation of the selected indicators into an aggregate index; and (4) demonstration of the formed index. In the first step, an in-depth review of published literature was employed as a secondary data collection method by which maintenance performance indicators were identified, extracted, and gathered. In the indicator selection step, direct discussion with experts was the method employed in order to select indicators that are most relevant and useful for determining the leakage probability based on maintenance performance. In the aggregation step, the selected indicators were normalized and aggregated to form a composite index. In the fourth step, the aggregate index was demonstrated using a real refinery case study.

4.1. Indicators Collection via an In-depth Review of Published Literature

In-depth review of literature can be a formal data collection process by which data is gathered in a comprehensive way (Onwuegbuzie and Frels, 2016; Snyder, 2019). In this research study, a literature review was conducted so as to extract and collect the MPIs as secondary data. For the purpose of data collection, the in-depth review of literature included five tasks performed in two main stages, namely: (1) exploration stage and (2) in-depth review and indicator extraction stage. The exploration stage comprises the first three tasks, namely: (a) initiating the search for sources of the required indicators (scientific materials); (b) storing and organizing the scientific materials derived from literature; and (c) screening the derived scientific materials. In the first task, the search in the related domains of literature (i.e. maintenance performance measurement) was initiated. Pertinent keywords and combinations of keywords, as presented in Table 1, were used as input terms to search for and locate relevant scientific materials across various online databases and search engines, such as Science Direct, Research Gate, Wiley Library, Google, Google Scholar, and PDF Drive. In the second task, the extracted materials were gathered and stored in two forms: (1) stored as PDF documents on the researcher's computer discs and other backup storages, and (2) stored as links in data collection files created in the browser used for the search. In the third task, the derived materials were screened in preparation for the in-depth review and indicator extraction stage. The screening was simply done based on the existence of the desired performance indicators in the derived materials.

Table 1 Search terms and keywords

Research topic	Keywords and search terms
Maintenance performance measurement	• Maintenance performance measurement • Maintenance performance indicators • Process complexity measurement • Process complexity index

The second stage consists of two tasks, i.e. (d) in-depth review and (e) extraction of indicators. In the in-depth review, the selected source materials were reviewed in depth in order to identify maintenance performance indicators. In the final task, the maintenance performance indicators were extracted. As a result, seven (7) maintenance performance measurement frameworks and four (4) process complexity measurement methods were gathered. Figure 2 illustrates the main five tasks of the indicator collection process.

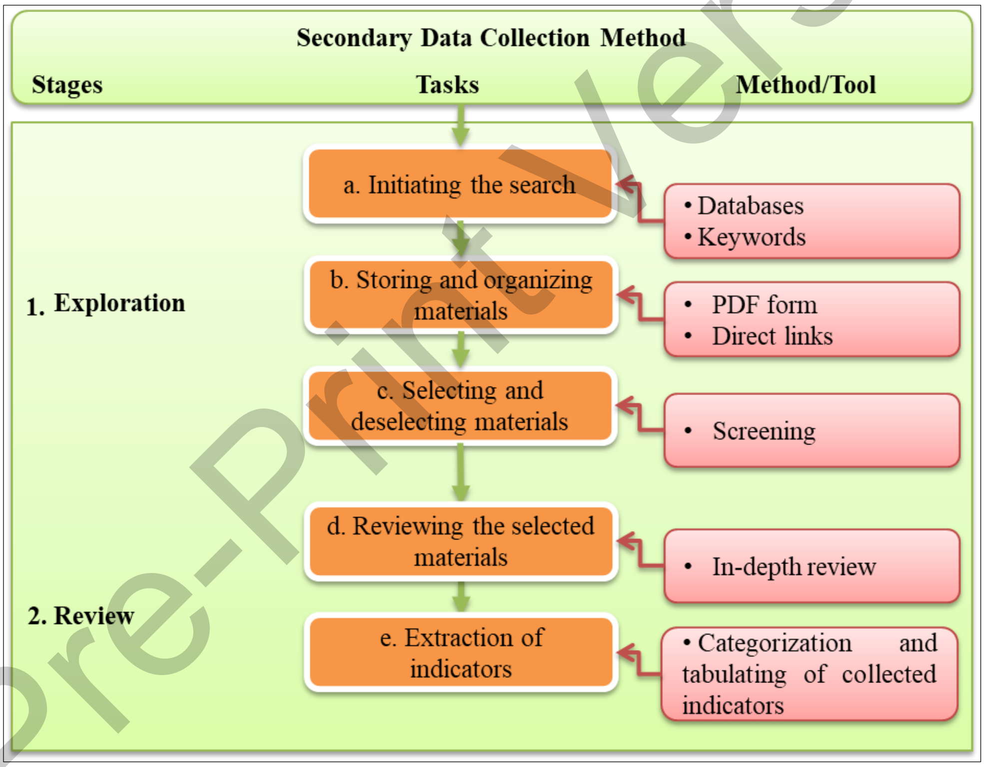


Figure 2 Secondary data (MPM indicators) collection method

4.2. Selection of Maintenance Performance Indicators (MPI)

The seven (7) MPM frameworks and four (4) complexity measurement methods were presented and discussed in a meeting with experts from two collaborating institutions, i.e. University Teknologi Malaysia (UTM) and the Institution of Chemical and Engineering Sciences (ICES). The main objective of the discussion was to select methods or a set of indicators that can be used to measure maintenance performance from a leakage control point of view. The advantages and limitations of the maintenance performance and process complexity measurement methods were argued. It was agreed that the MPM frameworks place much emphasis on "equipment performance". It was also observed that several MPM frameworks consider the human element as an essential indicator for measuring maintenance performance. However, the indicators used in these frameworks are mostly lagging or reactive indicators, which measure maintenance performance based on later outcomes such as the number or frequency of equipment breakdowns, MTTF, availability, and OEE.

Based on these observations, it was suggested that the Process Safety Management (PSM) auditing checklist can be partially adopted and utilized as an effective method for measuring the managerial aspect of maintenance performance, i.e. maintenance management performance. The PSM auditing checklist is contained in the OSHA 1910.119, a standard released by the occupational safety and health administration (OSHA) for process safety management of highly hazardous chemicals (OSHA, 1991). This suggestion was justified by the fact that the PSM includes sets of indicators that are related to both equipment and human performance. As emphasized earlier, both equipment and human performance are considered crucial for maintenance performance measurement. Another advantage is that the indicators included in the PSM auditing checklist are of a proactive type. Proactive indicators, unlike commonly used reactive indicators, are more predictive of future events based on the current performance being measured.

For the process complexity measurement, four (4) process complexity measurement methods were discussed, i.e. Nelson Complexity Index (NCI), Equivalent Distillation Capacity (EDC), Bottom of Barrel (BoB), and Koolen's process complexity measurement method. Among the key points highlighted during the discussion is that the first three methods, i.e. the NCI, EDC, and BoB, were developed to exclusively measure the complexities of refineries. The complexity measures obtained by these methods are only meant to classify refineries based on their refining capacities and construction costs. On the contrary, Koolen's process complexity measurement method can be used to measure the complexity of refineries or any chemical processing facilities. Koolen’s method measures the complexity of a process based on the count of equipment and process piping components. The complexity measures obtained are meant for the identification of possible process modifications and simplifications. Therefore, Koolen’s process complexity measurement method was agreed upon as an appropriate method for measuring process complexity from a maintenance performance point of view. This was also supported by the fact that the counted equipment and process piping components (e.g. valves and pumps) are actually the main sources of fugitive emissions and are usually subjected to regular maintenance programs. The counts of these process piping components are strongly relevant and meaningful inputs in measuring maintenance performance, especially from a potential leakage point of view. Therefore, the usefulness of Koolen’s process complexity measurement method for measuring process complexity and as a maintenance performance indicator is indisputable.

Based on the above justifications, the PSM auditing checklist and Koolen’s process complexity measurement method were selected to measure maintenance management performance and process complexity, respectively. For the purpose of this research, the PSM auditing checklist includes four elements with twenty-five (25) auditing questions, i.e. 8 auditing questions for contractor, 5 auditing questions for personnel training, 5 auditing questions for pre-startup safety review, and 7 auditing questions for mechanical integrity. The two elements “contractor” and “personnel training” are meant for measuring human performance, while the two elements “pre-startup safety review” and “mechanical integrity” are meant for measuring equipment performance. Modifications such as simplifying, rephrasing, and regrouping were made to the auditing questions. Regrouping means that the training-related auditing questions that were originally listed under the “contractor” and “mechanical integrity” indicators were relocated and listed under the “training” element. Among the twenty-five 25 auditing questions, four (4) highly influential questions were chosen as determinants or stopper indicators (i.e. indicators that decisively affect the overall result of the assessment). Table 2 presents the four elements provided with one auditing question as an example. The full PSM auditing checklist is included in Annex A–3.

The Koolen process complexity measurement method considers six (6) variables for measuring the complexity of a process plant, i.e. the number of equipment accessible by the operator (***M***), the number of valves and set points of control loops (***N***), the number of input and output streams (**P**), the number of operator-unit interactions (***Q***), the number of measurement readings (***O***), and the number of external disturbances that require action from an operator (***R***) (Koolen, 2001). However, since this research deals with process complexity as an influential factor in maintenance performance, only the first four (4) variables were considered relevant and therefore adopted. The two variables "**O**" and "**R**" are considered a repetition of the variable (***Q***), and hence left out of consideration. The original symbols of the four adopted variables, i.e. **M, N, P,** and ***Q***, were replaced by more meaningful symbols, i.e. $\mathbf{N_{Equip}}$, $\mathbf{N_{Piping}}$, $\mathbf{N_{Stream}}$, $\mathbf{N_{Interaction}}$, respectively. The new symbols refer to the number of major pieces of equipment, the number of piping components, the number of input and output streams, and the number of operator-unit interconnections, respectively. The combination of these four variables forms a process complexity method named by this research as the Process Design Complexity Index (PDCI), which is a modified method of Koolen's process complexity measurement method.

Table 2 PSM auditing checklist

1. Contractor
1. Has the contractor been selected based on their HSE performance and programs?
2. Training
1. Have employees involved in the maintenance or in maintaining the ongoing integrity of process equipment been trained in an overview of that process and its hazards and in the procedures applicable to their job tasks?
3. Pre start-up safety review
1. Has the employer performed a pre start-up safety review for modified facilities when the modification is significant enough to require a change in the process safety information?

4. Mechanical integrity
1. Has the employer established and Implemented written procedures to maintain the on-going integrity of process equipment?

4.3. Aggregation of the Selected Indicators

The PSM auditing checklist and the PDCI were aggregated in order to form an aggregate index named “Leak Hazard Index (LHI)”. An additive aggregation approach was used to aggregate the scores of the individual indicators of the PSM auditing checklist and the PDCI. For the aggregation of the total scores of the PSM auditing checklist and the PDCI, a Matrix Plot was used in order to form the the probability of leakage value.

The aggregation process started with forming a score for the PSM auditing checklist. A common auditing checklist score formation system was used to form the score of the PSM audit checklist. In this scoring system, each auditing question is provided with five answer options. These answer options are: “Yes”, “No”, “Partial A”, “Partial B”, and “Partial C”. These answers indicate “complete compliance”, “no compliance”, “significant level of compliance”, “reasonable level of compliance”, and “low level of compliance”, respectively. Based on these answers, each question would be assigned a score of “4”, “0”, “3”, “2”, or “1”, respectively. The answer of each question is obtained based on information collected by an auditor using one or several auditing methods (e.g. physical inspection (PI), interview of personnel (IP), and document review (DR)). Table 3 summarizes the score formation system of the PSM auditing checklist.

Table 3 Score formation system of PSM auditing checklist

Question answers	Interpretation	Score
Yes	Complete compliance	4

No		Total absence of compliance	0
Partial	Partial A	Significant level of compliance	3
	Partial B	Reasonable level of compliance	2
	Partial C	Low level of compliance	1

As the PSM audit checklist includes 25 auditing questions, with the above score formation system, the total score of the PSM audit checklist would range from 0 to 100. However, the additive aggregation method is known for its compensability disadvantage; where poor performance in some indicators can be compensated for by sufficiently high performance in other indicators. This may result in a biased composite index that would not entirely reflect the information of its individual indicators (Nardo *et al.*, 2016). In order to reduce the impact of this disadvantage, a conditional additive aggregation approach was believed to be suitable for aggregating the score of the PSM auditing checklist. In this conditional additive aggregation approach, if any of the the 25 auditing questions is answered as “No, score = 0” or “Partial C, score = 1”, it is considered a major flaw from occupational health point of view. Thus, the auditing process shall stop and the final auditing result shall be “0” until correction is made. If each of the 25 questions is scored at least as “Partial B” with score of “2”, the auditing continues and the scores of all questions can be summed up in order to obtain the final PSM audit score. A “5-score categorical scale” was used in order to normalize the total score of the PSM auditing checklist and interpret it into a qualitative description of the level of maintenance management performance. By doing this, the normalized score would range from 1 to 5, with 5 indicating an excellent level of performance, as presented in Table 4.

Table 4 Maintenance management performance measurement scale

PSM auditing score	Maintenance management performance score	Description
0 – 20	1	Very poor
21 – 40	2	poor
41 – 60	3	Acceptable with improvement
61 – 80	4	Good to very good
81 – 100	5	Very good to Excellent

For the formation of the PDCI score, the equations proposed by Koolen were used (with modifications as elaborated earlier). Equation 1 is to calculate the complexity of any process unit in a process plant, while Equation 2 is to calculate the overall complexity of the process plant (Koolen, 2001). These calculations may result in huge PDCI scores. For the normalization of the PDCI score, a 5-score categorical scale was used. The categorical scale has five categories, as presented in Table 5. Each category is assigned a score and a qualitative description of process complexity. The normalized value of process complexity ranges from 1 to 5, with 5 expressing a high level of complexity. The 5-score categorical scale was built based on the EPA equipment leak component counts, where the count of these components for a typical refinery or chemical plant is estimated to approximately ranges from 1000 to 100,000 (EPA, 2007; EPA, 2016). The limits of this scale were formed based on a "20,000" interval.

$$C_{Unit} = \boldsymbol{N_{Equip}} + \boldsymbol{N_{Piping}} + \boldsymbol{N_{Stream}} + \boldsymbol{N_{Interaction}} \quad (1)$$

$$C_{Plant} = \sum_{1}^{n} C_n \quad (2)$$

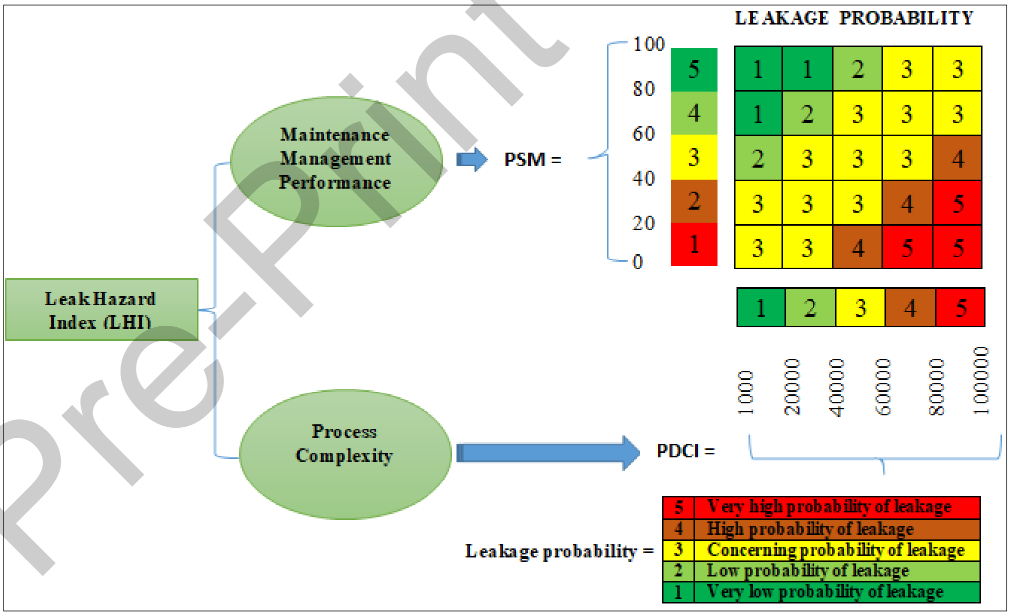
Where: $\boldsymbol{C_{Unit}}$ is the complexity of a unit, $\boldsymbol{C_{Plant}}$ is the overall complexity of a plant, and $\boldsymbol{C_n}$ is the sum of complexities obtained for the units in the plant (Koolen, 2001).

Table 5 Process complexity scale

PDCI values	Normalized PDCI values	Interpretation
1000 – 20,000	1	Very simple
20,001 – 40,000	2	Simple
40,001 – 60,000	3	Low complex
60,001 – 80,000	4	Medium complex
80,001 – 100,000	5	High complex

The two values, i.e. the value of maintenance management performance and the value of process complexity, were further aggregated in order to form the LHI. However, at this level, the two values cannot be additively aggregated due to the fact that they correlate differently with the performance of maintenance. Maintenance management performance positively correlates with maintenance performance, whereas process complexity negatively correlates with maintenance performance. Therefore, a plotting matrix was used as a means of aggregation, as illustrated in Figure 3. By this method of aggregation, the two values of maintenance management performance and process complexity are plotted on the matrix to produce the value of the LHI, which represents the value of leakage probability. The probability of leakage value ranges from 1 to 5, with 5 indicating a high leakage probability.

It is of great importance to highlight two features of the LHI. First, although the final scaled values of maintenance management performance and process complexity ranges from 1 to 5, the value “5” has different interpretations. For “maintenance management performance”, the value “5” indicates excellent performance (positive), whereas for “process complexity”, the value ‘5” indicates a very complex process (negative). Therefore, the colour range (red–brown–yellow–light green to dark green) indicates the degree of satisfactory, with the red colour indicating unsatisfactory and green colour indicating satisfactory. Secondly, the distribution of the colours in the matrix is made to insure conservative but reasonable evaluation of the probability of leakage. For example, if the maintenance management performance is evaluated as very good or excellent (score of 5) and the process is measured as complex (score 4), the probability of leakage will still be determined as concerning (score 3). This could be conservative given the high maintenance management performance, but reasonable when considering the complex process. Figure 3 presents the plot matrix used to determine the probability of leakage. Figure 4 illustrates the aggregation process of the LHI.



	1	2	3	4	5
5	1	1	2	3	3
4	1	2	3	3	3
3	2	3	3	3	4
2	3	3	3	4	5
1	3	3	4	5	5

5	Very high probability of leakage
4	High probability of leakage
3	Concerning probability of leakage
2	Low probability of leakage
1	Very low probability of leakage

Figure 3 Calculation of probability of leakage

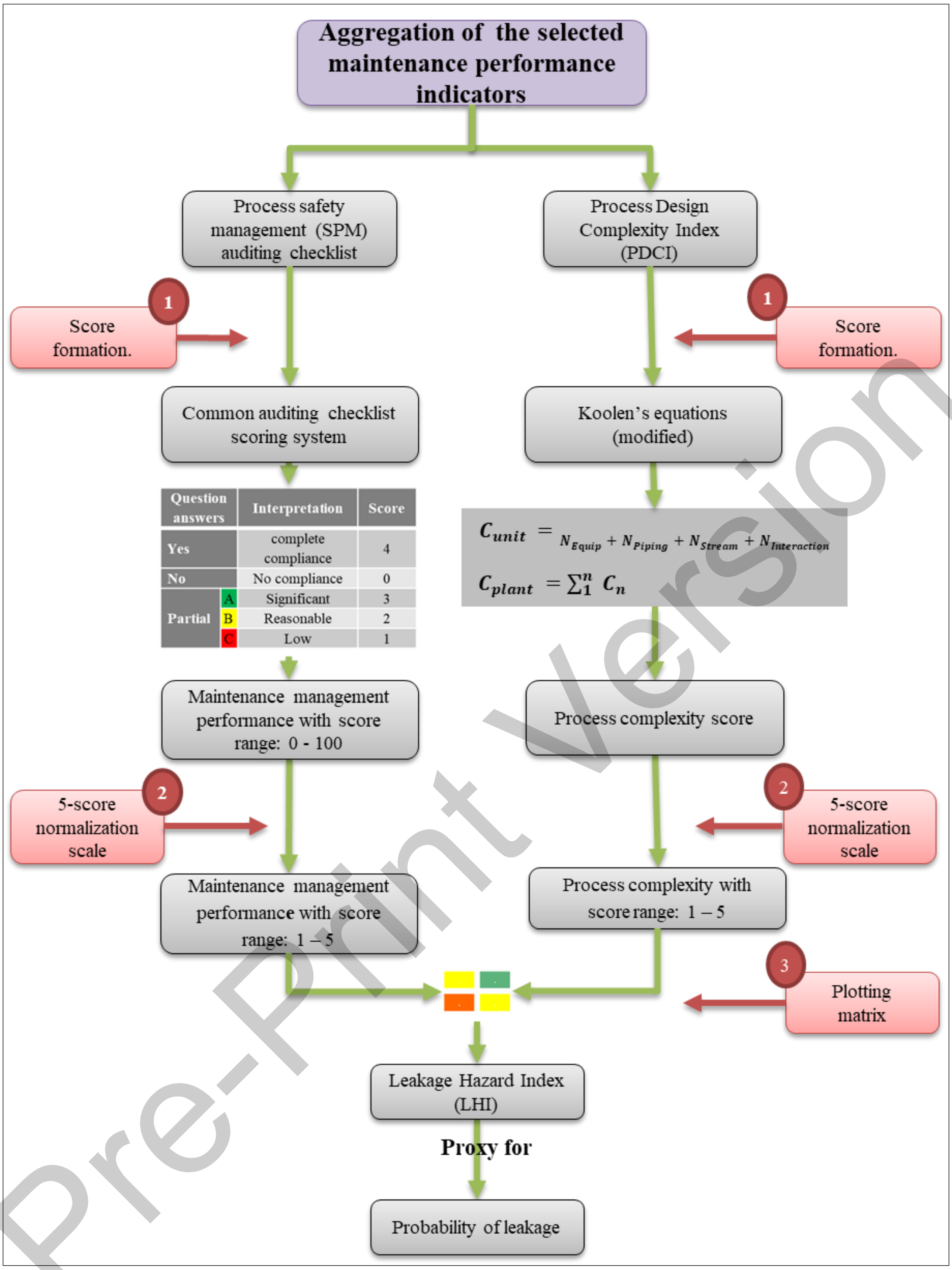


Figure 4 Aggregation process of maintenance performance indicators

4.4. Demonstration of the Aggregate Index: Refinery Case Study

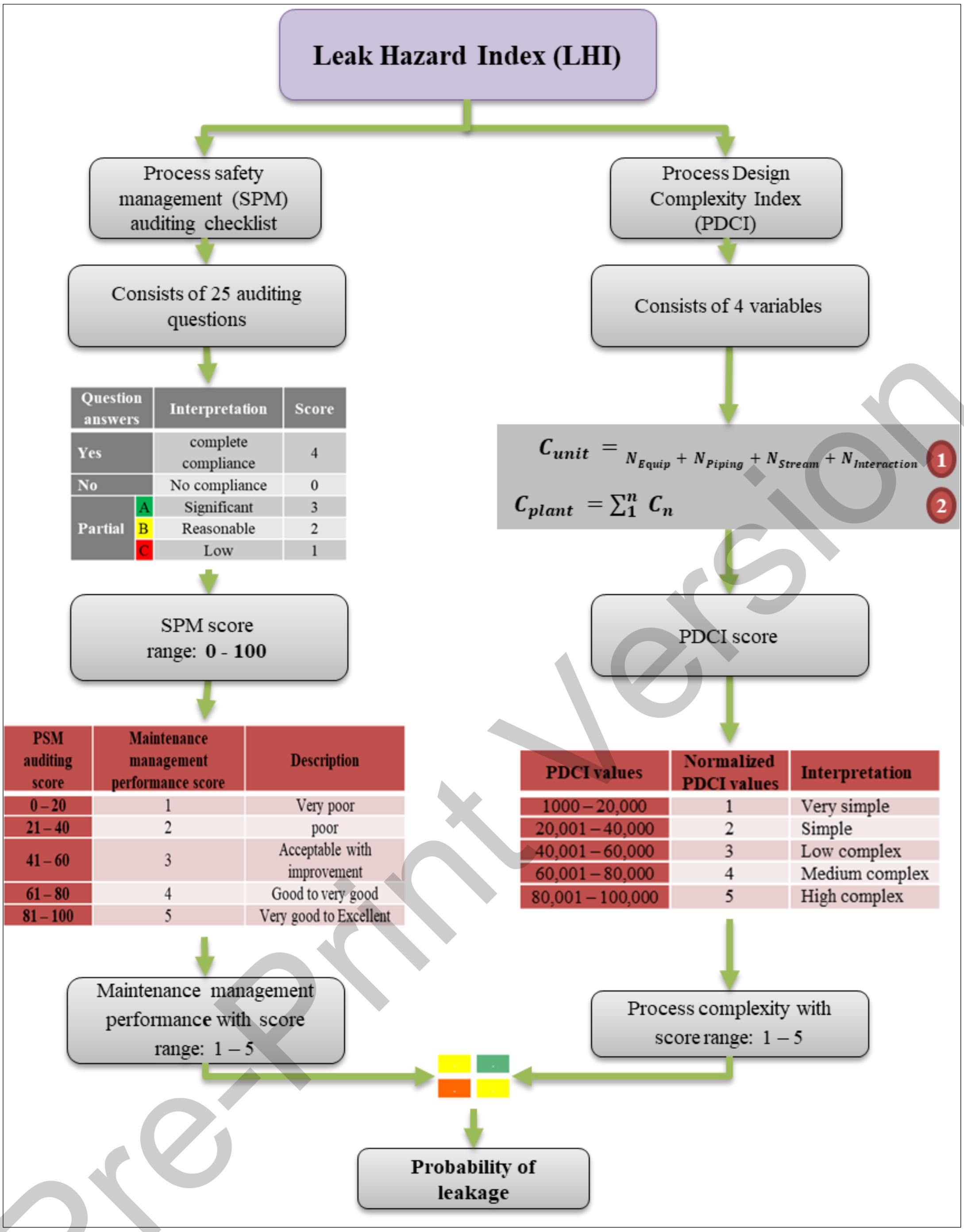
A real refinery case study was used to demonstrate the application of the LHI. Data needed for this demonstration include maintenance management-related information and process complexity-related information. Data related to maintenance management were mainly obtained by a short interview conducted with a safety professional from the refinery (the full interview protocol can be found in Annex B). It is of great importance to mention that, due to limited access, alternative data sources were used to obtain some of the needed data. Scientific literature, where common knowledge on refining processes can be found, was used as a source of the required data. This includes published books on refining processes and the process and instrumentation design (P&ID) of common refining units. Table 6 presents the needed data, sources of the data, and values that would be produced.

Table 6 Data required for the index demonstration

Assessment method		Information Collected	Data Source(s)	Obtained values	
Leak Hazard Index (LHI)	**PSM auditing checklist**	**Maintenance Regime:** - Contractor performance - Training - Mechanical Integrity	Interview with Maintenance Representative	**Maintenance management performance**	**Leakage probability**
	Process design Complexity Index	Process Design	P&ID/ PFD	**Process complexity**	

5. RESULTS: Formation and Application of the Leak Hazard Index (LHI)

The LHI is composed of two measurement methods, namely the PSM audit checklist and the PDCI. The PSM audit checklist contains 25 auditing questions used to measure maintenance management performance, while the PDCI consists of four variables used to measure process complexity. In order to obtain the value of the LHI, the scores of the SPM auditing checklist and PDCI need to be calculated. The score of the PSM auditing checklist is quantified using the auditing checklist scoring system as presented and discussed in the methodology in Section 4.3 and recalled in Figure 5 below. The value of the PDCI is calculated using Equations 1 and 2, as explained in the methodology in Section 4.3 and recalled in Figure 5. The LHI value is then obtained by plotting the two values of maintenance management performance and process complexity on a matrix. The LHI is a proxy measure for the probability of leakage. Therefore, its value represents the probability of leakage, ranging from 1 to 5, with 5 indicating a high leakage probability. Figure 5 provides a graphic description of the formation of the LHI.



Question answers		Interpretation	Score
Yes		complete compliance	4
No		No compliance	0
Partial	A	Significant	3
	B	Reasonable	2
	C	Low	1

$$C_{unit} = N_{Equip} + N_{Piping} + N_{Stream} + N_{Interaction} \quad ①$$

$$C_{plant} = \sum_1^n C_n \quad ②$$

PSM auditing score	Maintenance management performance score	Description
0 – 20	1	Very poor
21 – 40	2	poor
41 – 60	3	Acceptable with improvement
61 – 80	4	Good to very good
81 – 100	5	Very good to Excellent

PDCI values	Normalized PDCI values	Interpretation
1000 – 20,000	1	Very simple
20,001 – 40,000	2	Simple
40,001 – 60,000	3	Low complex
60,001 – 80,000	4	Medium complex
80,001 – 100,000	5	High complex

Figure 5 Leak hazard index (LHI)

For demonstration purpose, the LHI was used to obtain the probability of leakage value of the Yemeni refinery, which was used as a case study. In the process, the two scores of maintenance management performance and process complexity were obtained. Maintenance management performance in the refinery was assessed using the PSM auditing checklist via a short interview with a refinery safety professional with 11 years of experience. The data obtained from the interview indicates a "*very good performance*" of the refinery maintenance management with a score of **"78"**.

This score is justified in detail based on the data obtained from the interview for each PSM auditing question as presented in Table 7. This score was normalized and converted to **“4”**, which is interpreted as “**very good performance**”.

For measuring the process complexity of the refinery, the PDCI is calculated based on a description of the refinery configuration from (The Free Library, 2014). Also, general knowledge from literature on typical refining process units is used (Gary *et al.*, 2007; Jones, 2015). Based on the available data as summarized in Table 8, the PDCI value for the Yemeni refinery is **“1320”**, which was normalized to a score of **“1”**. With this score, the refinery is considered a “**very simple refinery**”. The two scores of maintenance management performance (Y-axis) and process complexity (X-axis) were then plotted on a matrix to obtain a probability of leakage value of **“1”**, which indicates a ***“very low probability of leakage”*** (see Figure 6).

Table 7 Maintenance management performance of the Yemeni refinery

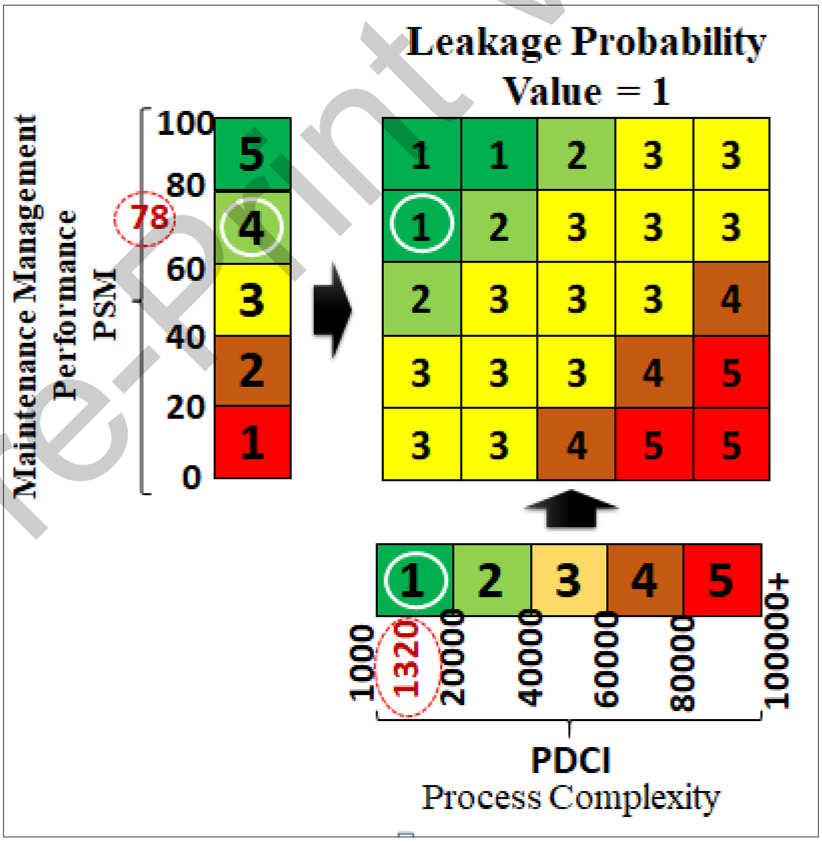
PSM indicator	Auditing questions	Summary of obtained data	Score
1. Contractor	1. Contractor been selected based on their HSE performance and history?	• Generally, experience of contractors and their employees is the most important requirement as it insures that they are aware of and familiar with the hazardous nature of the tasks assigned and related work safety rules and procedures. • Safety performance is also looked at when selecting a contractor.	**4**
	2. Contractor is well informed of hazards related to their work?	• The refinery safety department usually do briefings on safety in order to communicate OHS related information related to contractors' work before work begins.	**4**
	3. Contractor is well informed of procedures related to handling small releases?		**4**
	4. Contractor is well informed of the safe work practices in covered process areas?		**4**
	5. Contractor is periodically evaluated based on their OHS performance?	• The refinery safety department also monitors the contractors' performance during maintenance execution for evaluation purposes	**4**
	6. Contractor assured that their employees are kept well informed of the potential toxic release hazards related to their job.	• Experience of contractors and their employees is the most important requirement as it insures that they are aware of and familiar with the hazardous nature of the tasks assigned and related work safety rules and procedures.	**4**
	7. Contractor assured that each employee follows the the safe work practices?		**4**
	8. Contractor advised the employer of any unique hazards presented by their work, or of any hazards found by their work?	• No data that could provide direct answer to this question. However, based on the contractor performance indicated by the other questions, this question was assigned a score of "2" as reasonable evidence of compliance.	**2**
• **Total score for contractor performance =**			**Score = 30/32**
2. Training	1. Maintenance employees are trained in an overview of process under maintenance and its hazards and in the procedures applicable to their job tasks?	• Contractor is required to ensure that his employees are well trained for the job. • Safety induction and briefings are provided for all employees prior to execution of maintenance work.	4
	2. Training included emphasis on the specific OHS hazards and safe work practices applicable to the employees' job tasks?	• Safety induction and briefings are provided for all employees prior to execution of maintenance work.	**4**
	3. Each employee has received and understood the training required for their job tasks?	• No data that could provide direct answer to these questions. However, as safety induction and briefings are provided, these questions were assigned a score of "2" as reasonable evidence of compliance.	**2**
	4. Employees have the required knowledge, skills, and abilities to safely carry out their responsibilities?		**2**

PSM indicator	Auditing questions	Summary of obtained data	Score
	5. Is there a training record which contains the date of training and the means used to verify that the employees understood the training?		**2**
• **Total score for Training performance =**			**Score = 14/20**
3. Pre start-up review	1. Employer performed a pre start-up safety review for modified facilities?	• Safety review is conducted upon minor changes.	4
	2. Pre start-up safety review confirmed that equipment is in accordance with design specifications?	• No major changes have taken place in the process. (Based on the interviewee's knowledge since started working in the refinery) • No data that could provide direct answer to these questions. However, based on general performance noticed, these questions were assigned a score of "2" as reasonable evidence of compliance.	**2**
	3. Pre start-up safety review confirmed that safety, operating, maintenance, and emergency procedures are in place and are adequate?		**2**
	4. Pre start-up safety review confirmed that modified facilities meet the requirements contained in management of change?		**2**
	5. Pre start-up safety review confirmed that employees whose job tasks will be affected by a change in the process have been informed of, and trained in, the change?		**2**
• **Total score for Pre start-up review =**			**Score = 12/20**
4. Mechanical integrity	1. There are written procedures to maintain the on-going integrity of process equipment?	• The refinery has inspection procedures for equipment and parts such as storage tanks, piping system, valves, pumps, and hoses.	**4**
	2. Inspections are performed on process equipment?		**4**
	3. The inspection procedures follow recognized and generally accepted good engineering practice?	• No data that could provide direct answer to this question. However, based on general performance noticed, this question was assigned a score of "2" as reasonable evidence of compliance.	**2**
	4. Frequency of inspections of process equipment consistent with applicable manufacturers' recommendations and good engineering practices, and more frequently if determined to be necessary by prior operating experience?	• Monthly and annually inspections are conducted.	**4**
	5. Inspection that has been performed on process equipment is documented?	• Same as in auditing question No. 3	**2**
	6. Deficiencies in equipment that are outside acceptable limits are corrected before further use?	• If any equipment leak is identified, it would be fixed right away.	**4**
	7. Maintenance materials, spare parts and equipment are suitable for the process application for which they	• Same as in auditing question No. 3	**2**

PSM indicator	Auditing questions	Summary of obtained data	Score
	will be used?		
• **Total score for Mechanical integrity =**			**Score = 22/28**
• **Total PSM score =**			**78**
• **Scaled PSM =**			**4**

Table 8 Process complexity of the Yemeni refinery

Complexity variable	Obtained data	Refinery Complexity
Number of accessible equipment (M)	**Distillation unit**: desalter, furnace, main tower, side towers (3), reboiler, heat exchangers (2), reflux drum, condenser, feed pump, and booster pump. **Reforming unit**: preheater, furnace, reformer, separator, condenser, and stripper. **Storage unit**: storage tanks (2) **M = 21**	PDCI = **1320** Scaled PDCI = **1** **Very Simple refinery**
Number of valves (*N*)	**Distillation unit**: 559 valves **Reforming unit**: 678 Valves **Storage unit**: 22 valves **N = 1259**	
Number of input and output streams (P)	**Distillation unit**: 16 **Reforming unit**: 10 **Storage unit**: 4 **P = 30**	
Number of operator's intervention *(Q)*	**Distillation unit**: 3 **Reforming unit**: 3 **Storage unit**: 4 **Q = 10**	



1	1	2	3	3
1	2	3	3	3
2	3	3	3	4
3	3	3	4	5
3	3	4	5	5

Figure 6 Leakage probability value of the Yemeni refinery

6. CONCLUSIONS

This paper presents an index-based method named the leak hazard index (LHI). The index utilizes indicators that are meant for measuring maintenance performance and process complexity and aggregates them into a proxy measure of the probability of leakage. The LHI presented in this paper is a part of a broader OH risk assessment approach that assesses OH risk as a combination of severity, probability of leakage, and probability of exposure. A real refinery case study was used to test the feasibility of the developed index. Based on the results of the case study, the LHI can provide meaningful and useful measures of the probability of leakage. In addition, the LHI can provide useful feedback on the maintenance performance of petrochemical processing facilities.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the Ministry of Higher Education Malaysia (MoHE) and Ministry of Higher Education, Yemen. This research is also supported by the Institute of Sustainability for Chemicals, Energy, and Environment, A*STAR.

REFERENCES

Akerstrom, M., Almerud, P., Andersson, E. M., Strandberg, B., and Sallsten, G. (2016). Personal exposure to benzene and 1,3-butadiene during petroleum refinery turnarounds and work in the oil harbour. *International archives of occupational and environmental health, 89*(8), pp. 1289–1297.

Alauddin, M., Khan, F. I., Amyotte, P. R., and Rayner Brown, K. (2023). Chapter Two - Fundamentals of inherently safer design. In F. I. Khan, P. R. Amyotte and M. Alauddin (Eds.), Methods in Chemical Process Safety (Vol. 7, pp. 23-81): Elsevier.

Aziz, N. N. N. A., Hassim, M. H., and Hurme, M. (2013). Computer aided estimation of fugitive emission rates and occupational air concentration in process design. *Chemical Engineering Research and Design, 91*(8), pp. 1373–1382.

Athar, M., Shariff, A. M., Buang, A., Nazir, S., Hermansyah, H., and See, T. L. (2019). Process equipment common attributes for inherently safer process design at preliminary design stage. *Process Safety and Environmental Protection, 128*, pp. 14–29.

Barker, A., and Robinson, R. (2015). Case study 3: monitoring requirements for fugitive emissions from fuels in the CDM. In N. Stephan and V. Bellassen (Eds.), Accounting for Carbon: Monitoring, Reporting and Verifying Emissions in the Climate Economy. Cambridge: Cambridge University Press, pp. 467-509.

Brereton, C. A., Joynes, I. M., Campbell, L. J., and Johnson, M. R. (2018). Fugitive emission source characterization using a gradient-based optimization scheme and scalar transport adjoint. *Atmospheric Environment, 181*, pp. 106–116.

Cheadle, L. C., Tran, T., Nyarady, J. F., and Lozo, C. (2022). Leak detection and repair data from California's oil and gas methane regulation show decrease in leaks over two years. Environmental Challenges, 8, pp. 100563.

EPA. (2007). Leak Detection and Repair: A Best Practices Guide. EPA-305-D-07-001, US Environmental Protection Agency.

EPA. (2016). Control Techniques Guidelines for the Oil and Natural Gas Industry, EPA 453/B-16-001, US Environmental Protection Agency.

Gary, J. H., Handwerk, G. E., and Kaiser, M. J. (2007). Petroleum refining: technology and economics. (5th edn). Boca Raton: CRC Press.

Hämäläinen, P., Takala, J., and Boon Kia, T. (2017). *Global Estimates of Occupational Accidents and Work-related Illnesses 2017*. Singapore: Workplace Safety and Health Institute.

Han, Y., Zhen, X., Huang, Y., and Vinnem, J. E. (2019). Integrated methodology for determination of preventive maintenance interval of safety barriers on offshore installations. *Process Safety and Environmental Protection, 132*, pp. 313–324.

Hassim, M. H. (2016). Comparison of methods for assessing occupational health hazards in chemical process development and design phases. *Current Opinion in Chemical Engineering, 14*, pp. 137–149.

Hassim, M. H., and Edwards, D. W. (2006). Development of a Methodology for Assessing Inherent Occupational Health Hazards. *Process Safety and Environmental Protection, 84*(5), pp. 378–390.

Hassim, M. H., and Hurme, M. (2010a). Inherent occupational health assessment during preliminary design stage. *Journal of Loss Prevention in the Process Industries, 23*(3), pp. 476–482.

Hassim, M. H., and Hurme, M. (2010b). Inherent occupational health assessment during basic engineering stage. *Journal of Loss Prevention in the Process Industries, 23*(2), pp. 260–268.

Herrera, I., and Hovden, J. (2008). Leading indicators applied to maintenance in the framework of resilience engineering: A conceptual approach. *The 3rd Resilience Engineering Symposium*. 28 – 30 October 2008. Antibes- Juan Les Pins, France.

INSIDE Project, (2001). The INSET Toolkit: INherent SHE Evaluation Tool. Available in PDF form at <https://www.icheme.org/~/media/Documents/ Subject%20Groups/Safety Loss Prevention/INSET Toolkit.pdf>. (Retrived: June 2020).

Johnson, V. (2001). *Occupational health hazard index for proposed chemical plant.* Master Thesis, Loughborough University, Loughborough.

Jones, D. S. (2015). Atmospheric and Vacuum Crude Distillation Units in Petroleum Refineries. In S. A. Treese, D. S. Jones and P. R. Pujado (Eds.), Handbook of Petroleum Processing (pp. 1-61). Cham: Springer International Publishing.

Kafaei, R., Rezaei, M., Ahmadi, M., Tahmasebi, R., Dobaradaran, S., Omidvar, M., et al. (2019). Metal(loid)s urinary level among workers of gas refinery and petrochemical companies: Health risk assessment of metal(loid)s in drinking water and dust. *Journal of Trace Elements in Medicine and Biology, 54*, pp. 183–190.

Kaiser, M. J. (2017). A review of refinery complexity applications. *Petroleum Science, 14*(1), pp. 167–194.

Kletz, T. (2009). Chapter 1 - Preparation for Maintenance. In T. Kletz (Ed.), What Went Wrong? (Fifth Edition). Boston: Butterworth-Heinemann, pp. 3–44.

Kletz, T. A., and Amyotte, P. (2010). *Process plants: a handbook for inherently safer design*.2nd edn. Boca Raton, Florida: CRC Press.

Koolen, J. L. A. (2001). Simple and robust plant design. *design of simple and robust process plants.* Toronto: Wiley VCH Verlag GmbH & Co pp. 23-34.

Kumar, U., Galar, D., Aditya, P., Stenström, C., and Berges-Muro, L. (2013). Maintenance performance metrics: A state-of-the-art review. Journal of Quality in Maintenance Engineering, 19, pp. 233–277.

Lipton, S., and Lynch, J. (1994). Handbook of health hazard control in the chemical process industry. New Jersey, United States: Wiley.

Muchiri, P., Pintelon, L., Martin, H., and Meyer, A.-M. (2010). Empirical Analysis of Maintenance Performance Measurement in Belgian Industries. *International Journal of Production Research - INT J PROD RES, 48*, pp. 5905–5924.

Muchiri, P., Pintelon, L., Gelders, L., and Martin, H. (2011). Development of maintenance function performance measurement framework and indicators. *International Journal of Production Economics, 131*(1), pp. 295–302.

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffmann, A., Giovannini, E. (2016). Handbook on Constructing Composite Indicators: Methodology and User Guide. Paris, France: OECD publishing.

Ng, R. T. L., and Hassim, M. H. (2015). Strategies for assessing and reducing inherent occupational health hazard and risk based on process information. *Process Safety and Environmental Protection, 97*, pp. 91–101.

Ng, R. T. L., Hassim, M. H., and Hurme, M. (2017). A hybrid approach for estimating fugitive emission rates in process development and design under incomplete knowledge. *Process Safety and Environmental Protection, 109*, pp. 365–373.

Okoh, P., and Haugen, S. (2013). The Influence of Maintenance on Some Selected Major Accidents. *Chemical Engineering Transactions, 31*, pp. 493–498.

Onwuegbuzie, A. J., and Frels, R. (2016). *Seven steps to a comprehensive literature review: A multimodal and cultural approach*. London: Sage.

OSHA, (1991). Process safety management of highly hazardous chemicals. https://www.osha.gov/lawsregs/regulations/standardnumber/1910/1910.119. (Accessed: 04 Novmebr 2021)

Parida, A., and Chattopadhyay, G. (2007). Development of a multi-criteria hierarchical framework for maintenance performance measurement (MPM). Journal of Quality in Maintenance Engineering, 13, pp. 241-258.

Raza, T., Muhammad, M., and Abd Majid, M. A. (2016). A Comprehensive Framework and Key Performance Indicators for Maintenance Performance Measurement. *Journal of Engineering and Applied Sciences, 11*, pp. 12146.

Saari, E. (2019). *KPI framework for maintenance management through eMaintenance : Development, implementation, assessment, and optimization.* PhD Thesis, Luleå University of Technology, Luleå.

Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, pp. 333–339.

Sotoodeh, K. (2021). 2 - Fugitive emissions from piping and valves. In K. Sotoodeh (Ed.), *Prevention of Valve Fugitive Emissions in the Oil and Gas Industry*: Gulf Professional Publishing, pp. 37–65.

Srinivasan, R., and Nhan, N. T. (2008). A statistical approach for evaluating inherent benign-ness of chemical process routes in early design stages. *Process Safety and Environmental Protection, 86*(3), pp. 163–174.

Termeer, C. (2013). *Fundamentals of Investing in Oil and Gas: Gas Investing, oil investing*. Clearwater, Florida: Chris Termeer Publishing.

Tyler, B., Thomas, A., Doran, P., and Greig, T. (1996). A toxicity hazard index. *Chemical Health & Safety, 3*(1), pp. 19–25.

Vinnem, J. E., Haugen, S., and Okoh, P. (2016). Maintenance of petroleum process plant systems as a source of major accidents? *Journal of Loss Prevention in the Process Industries, 40*, pp. 348–356.

Vinnem, J.-E., and Røed, W. (2014). Norwegian oil and gas industry project to reduce hydrocarbon leaks. *SPE Economics & Management, 6*(02), pp. 88–99.

Vinnem, J. E., and Røed, W. (2015). Root causes of hydrocarbon leaks on offshore petroleum installations. *Journal of Loss Prevention in the Process Industries, 36*, pp. 54–62.

Warnasooriya, S., and Gunasekera, M. Y. (2017). Assessing inherent environmental, health and safety hazards in chemical process route selection. *Process Safety and Environmental Protection*, 105, pp. 224-236.

Zhang, C., Xu, T., Wu, G., Gao, F., Liu, Y., Gong, D., et al. (2022). Reduction of fugitive VOC emissions using leak detection and repair (LDAR) in a petroleum refinery of Pearl River Delta, China. Applied Energy, 324, 119701.