

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

Yousef A. Alhamdani¹, Mimi H. Hassim^{1,*}, Salim M. Shaik²

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

²Institute of Sustainability for Chemicals, Energy, and Environment, 1 Pesek Road, Jurong Island, Singapore 627833

*Corresponding author: mimi@cheme.utm.my

ABSTRACT

Fugitive emissions from petrochemical facilities have become a major concern due their impact on plants productivity, environment, and health. In regards to health, petrochemical workers are at higher occupational health (OH) risk due to their continuous exposure to these harmful emissions. Inherent occupational health and safety indexes are the most common methods used for assessing OH risk due to fugitive emissions. These methods usually focus on the sources of health hazards such as chemical substances, process conditions, and process equipment. Therefore, these methods are considered good for measuring the severity of the OH risk. However, based on the source, pathway, receptor (SPR) model, the OH risk due to fugitive emissions is also dependant on the pathway and receptor, where leak and exposure hazards may take place, respectively. For a holistic OH risk assessment, these hazards need to be considered. This was achieved by developing an OH risk assessment methodology that provides a holistic and effective assessment that takes into consideration hazards at the source, pathway, and receptor. This paper focuses on the source part of the SPR model, while the pathway and receptor parts will be covered in future publications. This paper presents the development of an index-based method named as Inherent Health Hazard Level Index (IHHLI) for evaluating occupational health hazard. The IHHLI is developed by expert-based selection of most common and relevant health hazard indicators published in literature. The IHHLI is meant to determine the severity of OH risk posed by fugitive emissions.

Keywords: fugitive emissions; occupational health; health Hazard; petrochemical process, petrochemical workplace.

1 INTRODUCTION

In petrochemical workplaces, personal exposures of workers to harmful chemicals are mainly attributed to fugitive emissions and periodic emissions. Workers may be exposed to periodic emissions when performing periodic tasks such as sampling or during plant maintenance (Akerstrom et al., 2016; Aziz et al., 2013). However, during normal operations, fugitive emissions remain the main sources of continuous exposures of workers to toxics in chemical plants (Aziz et al., 2013; Lipton and Lynch, 1994). Workers are at health risk since a wide range of harmful substances, e.g. benzene, are directly released as fugitive emissions to the

workers' breathing zone in the plant on a daily basis. The sources of these fugitive emissions include valves, connectors, pumps, sampling connections, compressors, pressure-relief devices, and open-ended lines. The routine exposure, even at low concentrations, to these hazardous substances has the potential to cause adverse health effects to workers. Occupational diseases such as cancer and respiratory diseases have been reported among petrochemical workers due to routine and prolonged exposures to contaminants such as benzene and asbestos (Akerstrom et al., 2016; Kafaei et al., 2019; Nadal et al., 2009; Park et al., 2006). According to global estimates of occupational illnesses, exposure to hazardous substances is responsible for the death of nearly one million workers of the total work-related deaths in 2015. Respiratory diseases, typically due to inhalation of hazardous substances present in workplaces as fugitive emissions, contributed to nearly half of these deaths, accounting for 475,589 deaths (48%) (Hämäläinen et al., 2017).

More consideration is being given to fugitive emissions by authorities and petrochemical industry worldwide. The increasing attention towards fugitive emissions is mostly driven by productivity and environmental concerns (Bellassen and Stephan, 2015; Sotoodeh, 2021). Nevertheless, there is a growing concern over the occupational health effects associated with these fugitive emissions, especially in the petrochemical industry. This has resulted in the introduction of various occupational health risk assessment methods. These assessment methods were developed by different parties such as academia, industry, and private or governmental bodies. Inherent occupational health and safety indexes are the most widely used methods for assessing OH risk due to fugitive emissions. However, these methods assess occupational health risks by focusing on the source of health hazards, i.e. the process materials (harmful chemical substances), process equipment, and process conditions (e.g. extremely high temperature and pressure) (Aziz et al., 2013; Hassim, 2016; Hassim and Edwards, 2006; Hassim and Hurme, 2010a; Ng et al., 2014; Ng and Hassim, 2015). This type of assessment provides good indications of the level (or the severity) of the inherent health hazard borne by these sources. However, by employing the source, pathway, and receptor (SPR) model, occupational health risk due to fugitive emissions is not only attributed to the source of health hazards, but also to the pathway and receptor, where a potential leakage and exposure can occur, respectively. In addition, control measures such as maintenance, occupational health and safety management system (OHSMS), and safety culture of workers are put in a place to control leak and exposure, respectively. It is therefore essential to take all

these attributes into consideration when assessing occupational health risk due to fugitive emissions.

This research study aims at developing a holistic assessment methodology that takes into account both contributing factors and control measures when assessing the occupational health risk due to fugitive emissions. The assessment methodology would integrate the source-pathway-receptor (SPR) model and layers of protection (LOP) concept. The proposed methodology suggests assessing the overall occupational health risk initiated from the source hazard (i.e. chemicals, process conditions, and equipment), the pathway hazard (i.e. leaks), and the hazard at the receptor (i.e. exposure). While assessing the occupational health risk, the methodology also suggests taking into consideration the layers of protection (LOP) that are hierarchically placed to control hazards at each component of the Source-Path-Receiver (SPR) model. 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 OHSMS and safety culture of workers at the receptor. Figure 1 provides an illustration of the proposed OH risk assessment approach. The green-highlighted area is the part covered in this paper.

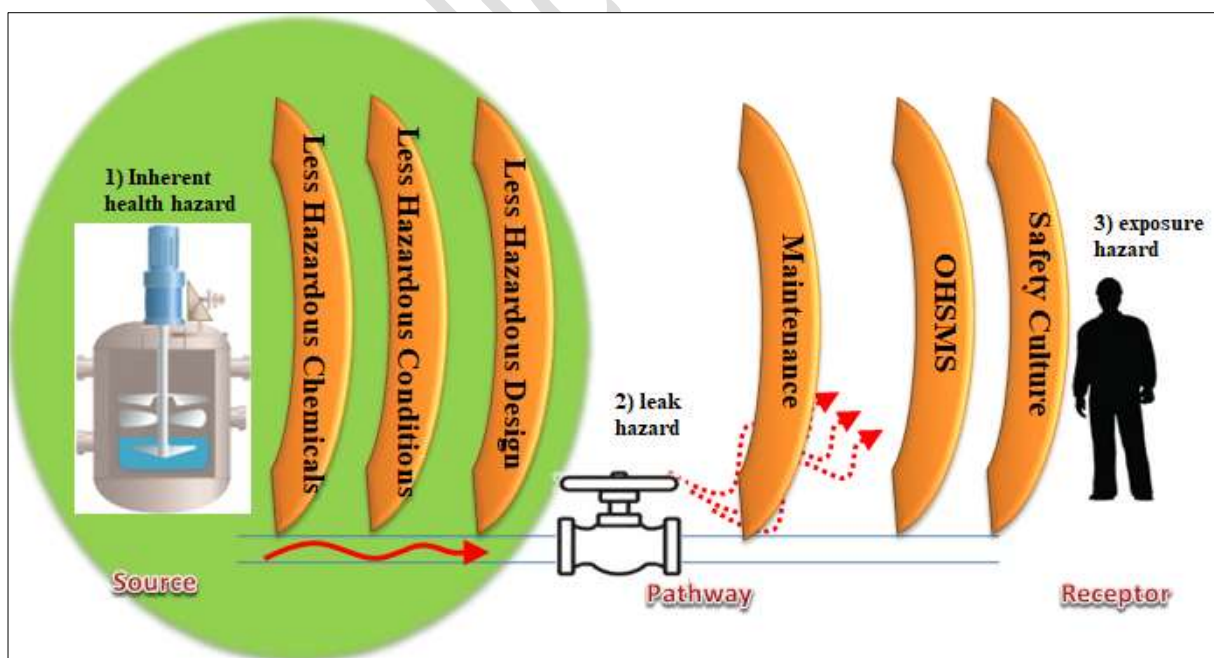


Figure 1 Occupational health risk assessment hybrid approach

With these hazards and controls in consideration, the proposed methodology would consist of three hazard indexes, i.e. inherent health hazard level index (IHHLI), leak hazard index (LHI), and exposure hazard index (EHI). The three indexes are intended to obtain three values, i.e. severity, probability of leakage, and probability of exposure, respectively. These three values are crucial for determining the OH risk due to fugitive emissions in a petrochemical workplace. Figure 2 illustrates the steps of using the proposed methodology. The yellow-highlighted area of the flow process of the proposed methodology represents the scope covered in this paper.

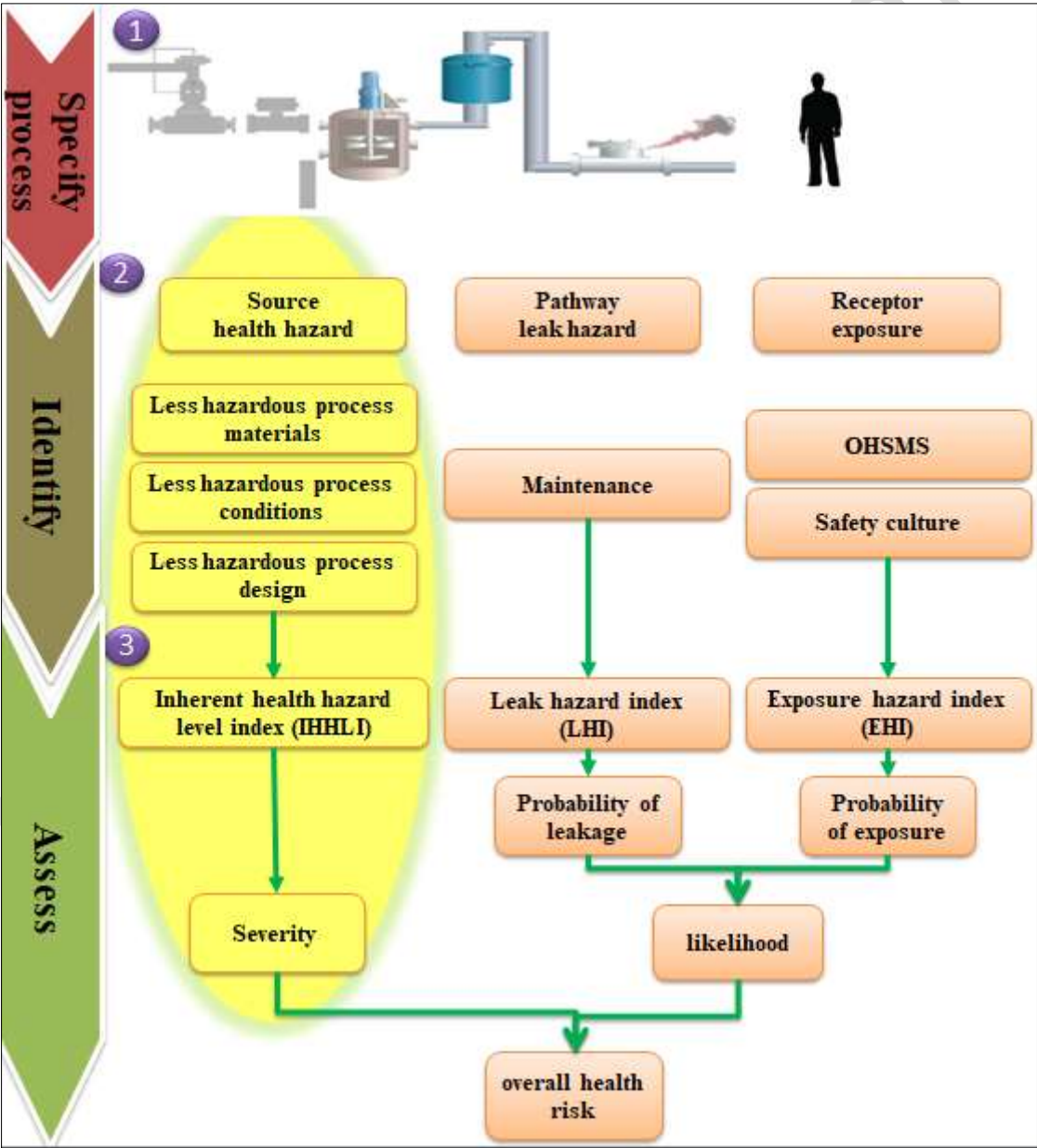


Figure 2 Process flow for using the proposed OH risk assessment tool

The development of this OH risk assessment methodology requires an in-depth and critical review of literature of different areas, e.g. occupational health risk assessment literature, maintenance performance measurement literature, occupational health and safety management system (OHSMS) literature, and safety culture assessment literature. Data collection is among the main tasks of developing this OH risk assessment methodology. The secondary data, i.e. various occupational health and safety (OHS) performance indicators and maintenance performance indicators are extracted and gathered by an in-depth review of the published literatures covered by this study. Interactions with experts and professionals from the relevant areas of knowledge are made through direct meeting and surveys in order to collect primary data of this research. For clear presentation of the results, the development of this OH risk assessment methodology is presented in three journal publications. This paper focuses on the source element of the SPR model, which is concerned with the sources of health hazard (i.e. harmful chemical substances, hazardous process operating conditions, and hazardous process equipment). The main aim is to develop an index-based method for evaluating occupational health hazard. The index is developed by selecting most common and relevant indicators published in literature. The selection of these indicators is based on experts' opinions and judgements.

2 OCCUPATIONAL HEALTH RISK ASSESSMENT: REVIEW OF LITERATURE

Generally, efforts towards health assessment in petrochemical industry have already started few decades ago. These efforts were contributed by different parties such as academia, industry, and private or governmental bodies. As a result, plenty of different assessment tools have been introduced. However, the health aspect was always a side concern for many of these assessment methods since they were primarily developed for assessing safety, environmental, or both safety and environmental aspects (Hassim, 2016).

Some of the notable assessment methods that pay attention to health-related effects alongside environmental aspect include: the Indexing System (IS) (Pratt et al., 1993), Human Toxicity Potential (HTP) (Guinée and Heijungs, 1993), and Chemical Hazard Evaluation for Management Strategies (CHEMS) (Swanson et al., 1997), EU Risk Ranking Method (EURAM) (Hansen et al., 1999), and Chemical Risk Ranking and Scoring (CRIRS) (Shin et al., 2014). Most of these methods assess health effects based on the chemical intake via the environmental compartments and not based on daily workplace exposure. However, based on experts, this method of assessment actually disagrees with the principles of occupational

health risk assessment (Adu et al., 2008). That is because the term “occupational health” implies two-way relationship between work and health. Therefore, the assessment of occupational health risk should deal with the factors that arise in/from the workplace environment and contribute to the health risk (Hassim, 2016). Nevertheless, based on this review, the EURAM and CRIRS place some emphasis on workers’ exposure by considering workplace factors, i.e. boiling point and vapor pressure of chemical substances. Based on that, it can be said that these two assessment methods are in partial compliance with the principles of occupational health assessment.

Among the assessment methods that evaluates health effects alongside safety aspect are Toxicity Hazard Index (THI) (Tyler et al., 1996), Dow Chemical Exposure Index (CEI) (Lewis, 1979), and Toxicity Damage Index (TDI) (Khan and Abbasi, 1998). These methods usually evaluate hazards to workers’ health based on short-term exposure and acute toxicity due to major releases or accidents. Basically, occupational health deals with the potential health effects on workers due to prolonged exposure to harmful chemical substances during normal operating conditions. Besides, based on views from safety experts, it is believed that acute toxicity from accidental releases belongs more to safety rather than occupational health assessment. Therefore, even though these methods are concerned with workers’ health, it is argued whether they can be used for occupational health risk assessment (Adu et al., 2008; Hassim, 2016).

There are also some assessment tools which assess health alongside safety and environmental aspects. Among the important ones are: safety, health and, environmental (SHE) assessment method (Koller et al., 2000), inherent safety, health and environmental evaluation tool (INSET) Toolkit (INSIDE, 2001), substance, reactivity, equipment and safety technology (SREST) (Shah et al., 2003), inherent benign-ness indicator (IBI) (Srinivasan and Nhan, 2008), Inherent SHE assessment approach (Hassim and Ali, 2009), the EHS index (Patel et al., 2012), and the Inherent Chemical Process Route Index (ICPRI) (Warnasooriya and Gunasekera 2017). Generally, these methods seem to be in compliance with with the basics of occupational health assessment as they evaluate hazards to workers’ health due to chronic exposure to harmful chemical substances during normal operating conditions (Hassim, 2016). However, the OH risk assessment resulted from these methods is usually too brief due to very limited OH-related indicators. For instance, inherent benign-ness indicator (IBI) uses one single indicator, i.e. toxicity, for evaluating hazards to worker’s health.

Several assessment methodologies have been developed to exclusively assess occupational health in 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 occupational health assessment are: the Occupational Health Hazard Index (OHHI) (Johnson, 2001), Process Route Healthiness Index (PRHI) (Hassim and Edwards, 2006), Inherent Occupational Health Index (IOHI) (Hassim and Hurme, 2010a), Health Quotient Index (HQI) (Hassim and Hurme, 2010b), and Occupational Health Index (OHI) (Hassim and Hurme, 2010c). The OHHI and PRHI consider continuous workplace exposure due to fugitive emissions, but also estimate airborne quantity due to accidental releases. Therefore, these two methods are considered in partial agreement with occupational health assessment fundamentals. The other methods, i.e. IOHI, HQI, and OHI, show the highest degree of compliance with occupational health assessment basics (Hassim, 2016). The OHHI, PRHI, HQI, and OHI require emissions quantification, i.e. fugitive emissions and periodic emissions. In these methods, brief estimations of fugitive emissions are made based on rough counts of the number of potential fugitive leak points from process flow and piping diagrams. Besides the quantitative calculation of emissions, the OHHI and PRHI also use inherent physical properties of substances and materials handling in assessing the exposure. The IOHI does not involve emissions quantification as it was developed for assessing OH risk at early design stage, i.e. research and development stage. Hence, this method uses parameters that require simple and available information such as inherent physicochemical and toxicological properties of chemical substances as well as process conditions and basic design.

3 METHODOLOGY

The section describes the methodology that was employed in order to achieve the prime aim of this research study. A three-phase approach was applied for conducting this study. The systematic approach includes: (1) collection of health hazard indicators, (2) selection of health hazard indicators, and (3) aggregation of the selected indicators. In the first phase, an in-depth review of published literature is employed as a secondary data collection method by which health hazard indicators are identified, extracted and gathered. In the indicators selection phase, different methods are employed in order to select indicators that are most relevant and

useful for evaluating occupational health (OH) hazard. The aggregation phase, the selected indicators were normalized and aggregated using an additive aggregation approach.

3.1 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, beside the revision of the current state of relevant knowledge and identification of the gaps in OH risk assessment, literature review was conducted in a manner so as to extract and collect the secondary data, i.e. health hazard indicators. For the purpose of data collection, the in-depth review of literature was conducted in five steps performed in two main stages, namely: (1) exploration stage and (2) in-depth review and indicators extraction stage. The exploration stage comprises the first three steps, 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 of the derived scientific materials. In first step, the search in the related domains of literature (i.e. inherent OH risk assessment) 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, and Wiley Library, Google, Google Scholar and PDF Drive. In the second step, 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 step, the derived materials were screened in preparation for the in-depth review and indicator extraction stage. The screening is simply done based on the existence of the desired performance indicators in the derived materials.

The second stage consists of two steps, i.e. (d) in-depth review and (e) extraction of indicators. In the in-depth review step, the selected source materials are in-depth reviewed in order to identify the health hazard indicators. In the final step, health hazard indicators were extracted. A list of 94 health hazard indicators was then compiled as presented in Annex A. Figure 3 illustrates the main 5 steps of the indicators collection process.

Table 1 Search terms and keywords

Research topic	Keywords and search terms
Occupational health hazard evaluation	<ul style="list-style-type: none"> • Occupational health hazards • Inherent occupational health assessment • Inherent occupational health index

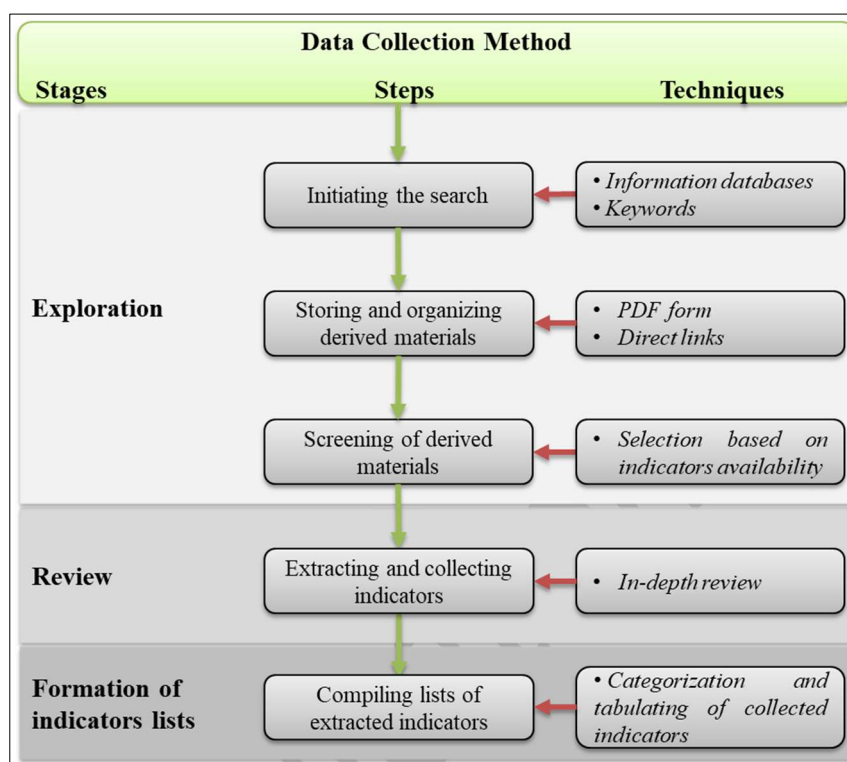


FIGURE 3 Secondary data collection method.

3.2 Selection of occupational health hazard indicators

The selection of occupational health hazard indicators involves three essential tasks, namely: (1) qualitative analysis of secondary data (health hazard indicators), (2) primary data (experts' opinions) collection, and (3) statistical analysis of primary data. The purpose of the qualitative analysis of the collected indicators was to eliminate indicators that dealt with health hazard initiated by a catastrophic safety or environmental event. The qualitative analysis also aimed at excluding the redundant indicators so that only representative indicators will be subjected to experts' judgment and opinions. Experts' opinions were then collected as primary data of this research study through a survey. A statistical analysis of experts' opinions was conducted in order to confirm the selection of the indicators that are most relevant and useful for evaluating OH hazard due to fugitive emissions. Detailed description of the methods employed is presented in the following sections.

3.2.1 Qualitative analysis of secondary data

An initial list of 94 indicators derived from sixteen (16) health hazard evaluation methods was compiled (Annex A). By simple qualitative analysis, this list of indicators was screened and reduced by excluding indicators that are meant for evaluating health hazard based on major release or environmental scenarios as well as by eliminating redundant indicators. As an example, indicators such as “*toxicity*”, “*chronic toxicity*”, “*oral toxicity*”, “*respiratory toxicity*”, “*irritation*”, and “*corrosiveness*” are actually meant to measure one thing, which is the intrinsic harmful nature of a chemical substance. Another example, the indicators “*threshold limit value (TLV)*”, “*R-phrase*”, and “*exposure limit value*” are actually data input which are usually used to evaluate the toxicity of a chemical substance. Therefore, such indicators are eliminated to keep only one representative indicator, e.g. indicators above are represented by “*toxicity*”. The screening process resulted in a list of eight (8) indicators. The 8 indicators was proposed for OH hazard evaluation and presented in a Google-form survey for experts’ judgement.

3.2.2 Primary data (experts’ opinions) collection: survey

This survey is meant to obtain experts’ opinions on the importance of a set of indicators that are proposed for evaluating OH hazard of fugitive emissions in petrochemical workplaces. The main aim is to confirm the usefulness of these indicators and eventually rank them based on their contribution to the OH hazard due to fugitive emissions. In the process of developing this survey, a list of eight (8) indicators derived from literature was compiled (details are provided in the qualitative data analysis section). Definitions of these indicators were presented in order to highlight how each indicator is linked and may contribute to the level of health hazard. The provided definitions are extracted from relevant and authentic literature. A seven-point Likert scale (*Not important at all, of very little importance, of little importance, to some extent important, important, very important, and extremely important*) was selected as a scoring system for the survey. The Likert scale is to aid experts in reflecting their opinions on the importance of each proposed indicator. A space for experts’ comments was also provided for each indicator. The seven-point Likert scale and comment space were used in order to avoid limiting experts to very limited choices and also to allow them add on their own remarks (if any) on the proposed indicators. Most importantly, using the seven-point Likert scale as a scoring system would enable both selecting/deselecting and ranking the proposed indicators. The survey was then distributed through official institutional emails to a selected group of

experts. Twelve (12) experts have participated in the survey. The survey is provided in Annex B.

3.2.3 Statistical analysis of primary data

A simple statistical analysis of experts' opinion (primary data) was conducted using Microsoft Excel worksheet. This was done by converting the experts' opinions into scores. As presented in Table 2, based on the options provided in the Likert scale, the expert's opinion of an occupational health hazard indicator may range from "not important at all" to "extremely important" assigning it a score which ranges from "1" to "7", respectively. The total score of an indicator was then calculated by simple summation of the scores assigned by the 12 experts. The total score of an indicator would range from "12" to "84". For an indicator to be selected, a total score of "55" or above must be obtained. With the total score of "55", it is assured that more than half (> 50%) of the experts has agreed on the indicator as "important". The total scores of the selected OH hazard indicators were also used for ranking and weighting purposes.

Table 2 Level of importance and assigned score

Level of importance	Score
Not important at all	1
Of very little importance	2
Of little importance	3
To some extent important	4
Important	5
Very important	6
Extremely important	7

3.3 Aggregation of the selected indicators

Aggregation combines the values of a set of indicators into a single measure, usually referred to as an 'aggregate' or a 'composite'. The literature of composite indicators offers several techniques of aggregation. The widely used are additive techniques that range from summing up values of contributing indicators to aggregating weighted and normalized indicators. The most widespread additive aggregation is the linear summation of weighted and normalized indicators. However, this method of aggregation imposes restrictions on the nature of individual indicators. For a set of individual indicators to be additively aggregated, they have to be additively independent. Additive independence implies that each indicator has to have an additive effect. An indicator that has an additive effect is separate from other indicators

and can independently contribute to the phenomenon being measured without being affected by changes in other indicators (Nardo *et al.*, 2008).

The individual indicators selected by this research (i.e. OH hazard indicators) are, to a certain extent, additively independent. Therefore, the additive aggregation method was used to aggregate the selected sets of these individual indicators and construct an aggregate index. Although simple and widely used, an undesirable feature of the additive aggregation method is the full compensability; 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. In order to reduce the impact of this disadvantage on the SPR-LOP tool, several highly influential individual indicators have been chosen as determinants (indicators that decisively affect the composite value).

4 RESULTS

The qualitative analysis of the collected indicators, which includes indicator-by-indicator review, comparing, screening, and rephrasing, has resulted in a set of eight (8) indicators. Four (4) of these eight (8) indicators represent the toxicological physical, and chemical properties of the chemical substances employed in a petrochemical process, namely: (1) toxicity, (2) volatility, (3) vapor density, and (4) the ability to cause corrosion. The other four (4) indicators represent the process properties, i.e. process conditions and design, namely: (5) process mode and handling, (6) number of valves, (7) temperature, and (8) pressure. These indicators are presented in Table 3. The 8 indicators were then shared with twelve (12) experts (see Table 4) via surveys in order to verify their usefulness in evaluating OH hazard of fugitive emissions in petrochemical workplaces.

Table 3 Occupational health hazard indicators

No	Indicator	Category
1	Toxicity	Toxicological property
2	Vapor density	Physical property
3	Volatility	
4	Ability to cause corrosion	Chemical property
5	Process mode and handling	Process design
6	Number of valves	
7	Temperature	Process conditions
8	Pressure	

Table 4 Participating experts for OH hazard selection

No	Expert/Job	Years of experience
1	Lead Teaching & Learning Specialist	Above 10 years
2	Executive	4 – 6 years
3	Executive (Industrial Hygiene)	4 – 6 years
4	University's Lecturer	Above 10 years
5	Principal Engineer	Above 10 years
6	Manager, Technical Planning	Above 10 years
7	Process Safety Specialist	Above 10 years
8	Advisor/Mfg support services	Above 10 years
9	Operation Safety Engineer	7 – 10 years
10	GM, Operations	Above 10 years
11	Lecturer	4 – 6 years
12	HSE Coordinator	Above 10 years

Generally, there is a complete agreement among the experts on the importance of the 8 indicators. Toxicity indicator achieved the highest level of agreement ranging from “very important” to “extremely important” with total score of “82” out of “84” (see Figure 4A). This is expected as the toxicity of a chemical represents its intrinsic ability to cause adverse effects to human health. In addition, toxicity is found to be the most widely used indicator in literature for evaluating health effects in different settings, e.g. occupational and public settings. This goes in harmony with experts’ judgment on the toxicity importance as an indicator for evaluating OH hazard due to fugitive emissions.

The indicator “number of valves” takes the second place of importance. It achieved high level of agreement ranging from “important” to “extremely important” with total score of “78” out of “84” (see Figure 4A). This is logically acceptable and supported by the fact that there is a great agreement in related literature that valves represent the major source of fugitive emissions from petrochemical processing facilities. According to authentic sources such as Environmental Protection Agency (EPA), valves are responsible for approximately 62% of fugitive emissions in oil and gas facilities. In addition, valves are also a major source of maintenance-induced leaks.

With close level to that of “number of valve”, the “pressure” indicator takes the third highest level of agreement ranging from “important” to “extremely important” with total score of “77” out of “84” (see Figure 4A). Even though “pressure” is often looked at as a safety concern, it is considered a direct cause for releasing hazardous chemicals from the process, especially from pressure equipment. Pressure equipment is considerable source of pressurized

leaks from areas such as nozzles and bolted joints. In addition, such highly pressurized equipment is known for their high potential to develop cracks along welded seams, leading to more leaks. Therefore, taking the third place of importance by this indicator is understandable.

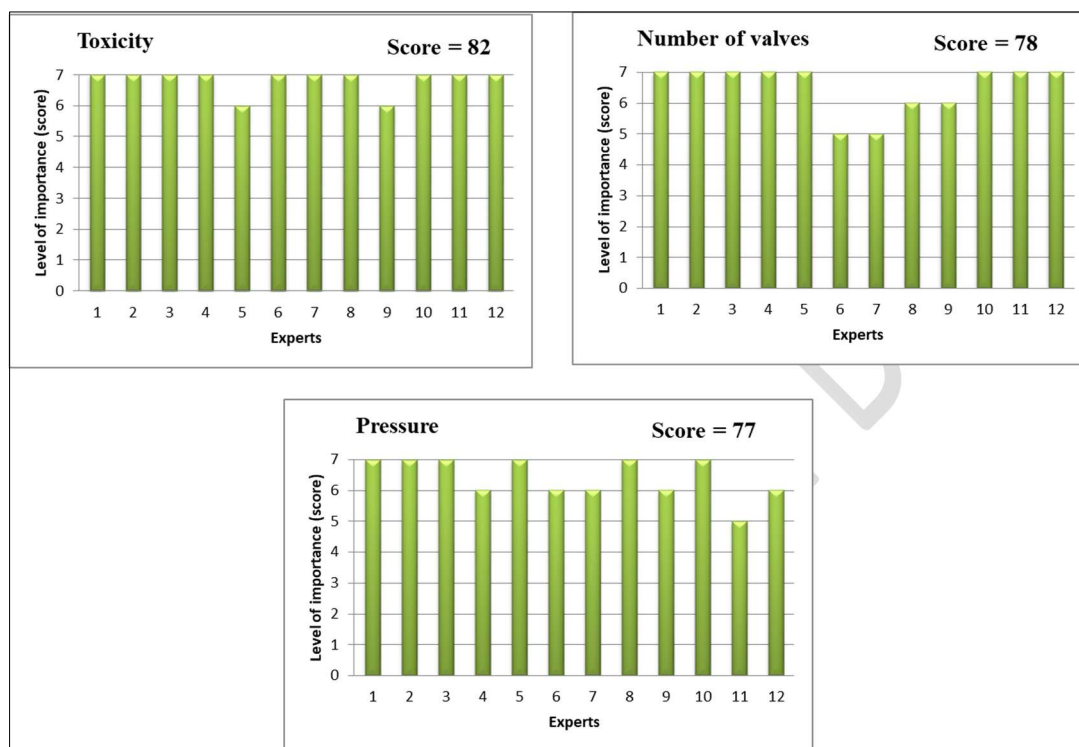


FIGURE 4A Score of importance of individual OH hazard indicators.

Almost same levels of agreement on the importance of the remaining indicators, i.e. volatility, process mode and handling, vapor density, temperature, and the ability to cause corrosion, were recorded with total scores of “70”, “72”, “73”, “73”, and “74”, respectively. Although slightly less important than the first three indicators, their contributions to the level of OH hazard in workplaces shall not be neglected. Volatility reflects the readiness of a chemical substance to exist in an airborne form which is the typical form for exposure, especially through the inhalation route. Process mode and handling refers to the type of process employed and the way process activities are handled, i.e. batch, semi batch/continuous, or continuous process. For example, batch processes pose greater health hazards as they are substantially more labor intensive than continuous processes, involve frequent start-ups and shutdowns, and require more manual handling. These conditions are opportunities for more exposures to hazardous chemicals. Vapor density refers to the density of a vapor of a chemical substance in relation to the density of air. In terms of OH hazard, vapor density

demonstrates the tendency of the heavier-than-air vapors to accumulate and travel along the ground (i.e. workers' breathing zone) posing toxicity or asphyxiation hazard to workers. Process temperature contributes to OH hazard through its thermal expansion and contraction effects which causes valves packing wears over time and increases valves leakage rate in the process. In addition, process temperature contributes to the vaporization of liquid process materials upon releases turning them to airborne gases which is the typical form for inhalative exposure. Finally, the significance of corrosion in causing chemical releases in chemical plants is well known and therefore the ability (of a chemical) to cause corrosion is seen as an indirect contributor to OH hazards.

Overall, based on the scale of importance presented in Table 5, the three indicators: toxicity, number of valves, and pressure are agreed on as "extremely important" for evaluating OH hazard due to fugitive emissions. The remaining indicators: volatility, process mode and handling, vapor density, temperature, and the ability to cause corrosion, are agreed on as "very important". Table 6 presents the individual scores, total score, and percentage score of each indicator. Figure 4B illustrates the individual scores (individual expert judgment) of each OH hazard indicator while Figure 5 illustrates the total score of each indicator (overall expert judgment).

Table 5 Scale of importance

Level of importance	Score (%)
Not important at all	< 50 %
Of very little importance	50% - 55%
Of little importance	56% - 60%
To some extent important	61% - 70%
Important	71% - 80%
Very important	81% - 90%
Extremely important	91% - 100%

Table 6 Individual and total scores of OH hazard indicators

Indicators	Individual scores												Total score	%
Toxicity	7	7	7	7	6	7	7	7	6	7	7	7	82	97.62
Number of Valves	7	7	7	7	7	5	5	6	6	7	7	7	78	92.85
Pressure	7	7	7	6	7	6	6	7	6	7	5	6	77	91.66
Volatility	7	7	7	5	7	4	7	4	6	7	4	5	70	83.30
Mode of process and handling	7	7	7	7	7	4	3	4	6	7	6	7	72	85.70
Vapor density	6	7	7	5	7	5	7	7	6	7	4	5	73	86.90
Temperature	6	7	7	5	7	6	5	6	6	7	5	6	73	86.90
Ability to cause corrosion	6	7	7	4	7	6	7	7	7	7	5	4	74	88.10

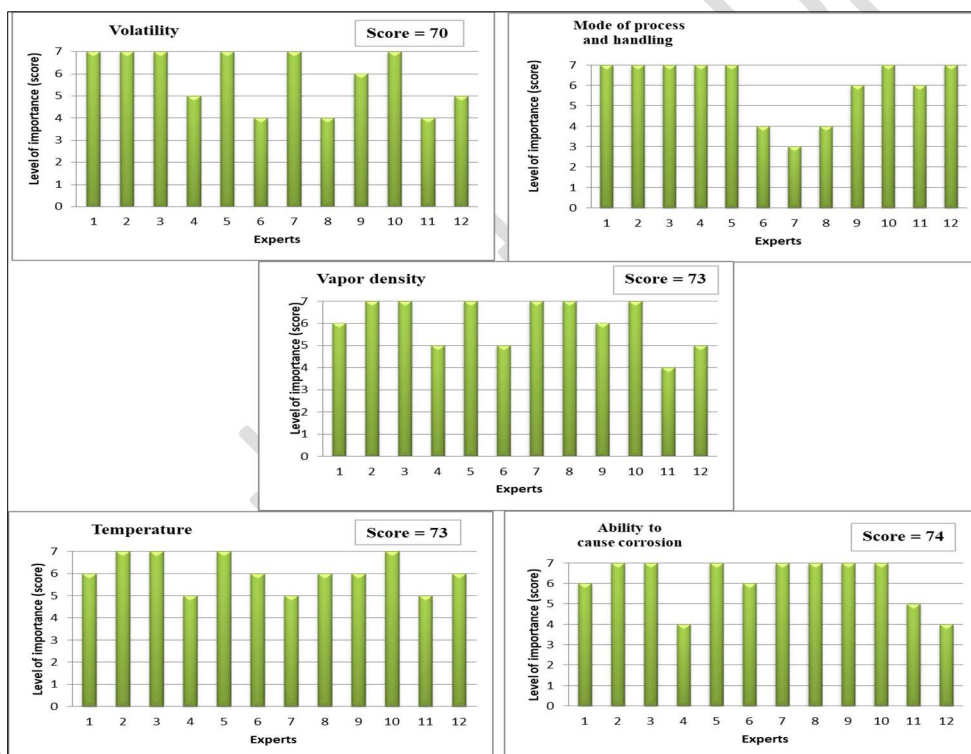


FIGURE 4B Score of importance of individual OH hazard indicators.

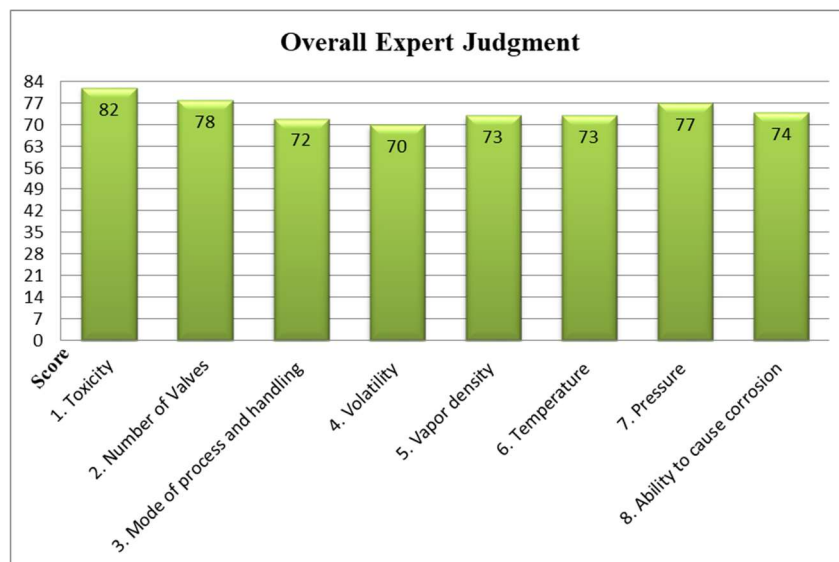


FIGURE 5 Overall expert judgment of indicators importance.

4.1 Formation of inherent health hazard level index (IHHLI)

The eight (8) selected OH hazard indicators, as discussed above, were weighted, normalized, and aggregated in order to form a composite index named as “Inherent Health Hazard Level Index (IHHLI)”. Each indicator was weighted and given a rank of importance based on experts’ judgement (Table 7). Next, based on the rank of importance, the indicators were provided with categorical scales (i.e. ranges of scores). The categorical scale varies from one indicator to another. The indicator with higher rank of importance is provided with a wider categorical scale reflecting greater contribution to the OH hazard level. Table 7 presents the indicators with their abbreviations, total scores, and ranks.

Table 7 Indicators ranks of importance

Indicators	Abbreviations	Total score	Rank
Toxicity	I _{TOX}	82	1
Number of Valves	I _{NOV}	78	2
Pressure	I _P	77	3
Volatility	I _V	70	7
Mode of process and handling	I _{MH}	72	6
Vapor density	I _{VD}	73	5
Temperature	I _T	73	5
Ability to cause corrosion	I _C	74	4

In this research, toxicity, number of valves, and pressure were found to be the most important contributing indicators to the level of OH hazard due to fugitive emissions and assigned the first (1st), second (2nd), and third (3rd) highest rank of importance, respectively. Based on that, the three indicators were provided with three categorical scales (with max scores of 6, 5, and 4, respectively). For the indicators “toxicity” and “pressure”, the categorical scales were adopted from Mond Index and Dow explosion and fire (E & F) index, respectively. In the toxicity categorical scale, the scores are formed based on the Threshold Limit Values (TLV) developed by American Conference of Governmental Industrial Hygienists (ACGIH) (Table 7A). For the pressure categorical scale, the scores are formed based on process pressure in bar (Table 8A). For the indicator “number of valves”, the categorical scale was developed by this research. The score limits of the scale were formed based on the EPA equipment component counts where it is estimated that the count of valves for a typical refinery or chemical plant ranges from 157 to 46,000 (EPA, 2007, EPA, 2016). Therefore, a nil score of “0” is given to process plants with number of valves < 157, while a max score of “5” is given to plants with number of valves > 46,000. The scores in between are assigned based on 10,000 interval (Table 8A).

Table 8A Score formation scales for the OH hazard indicators

Indicator	Categories	Score
1. Toxicity, TLV (I_{TOX})	TLV > 10000	0
	TLV ≤ 10000	1
	TLV ≤ 1000	2
	TLV ≤ 100	3
	TLV ≤ 10	4
	TLV ≤ 1	5
	TLV ≤ 0.1	6
2. Number of valves (I_{NOV})	< 157	0
	157 ≤ NOV ≤ 10000	1
	10000 ≤ NOV ≤ 20000	2
	20000 ≤ NOV ≤ 30000	3
	30000 ≤ NOV ≤ 40000	4
NOV > 40000	5	
3. Process pressure (I_P)	0.5–5 bar	0
	5–25 bar	1
	25–50 bar	2
	50–200 bar	3
	> 200 bar	4

The indicator “ability to cause corrosion” was assigned the fourth (4th) rank of importance. Both indicators “vapor density” and “temperature” were assigned the same rank of importance, i.e. the fifth (5th) rank. The indicators “process mode and handling” and

“volatility” were assigned the sixth (6th) and seventh (7th) rank of importance, respectively. These indicators, as discussed in the previous section, generally share the same level of importance (i.e. “very important” level). Therefore, these indicators were provided with categorical scales with scores ranging from “1” to “3”. The categorical scales of the indicators “ability to cause corrosion”, “temperature”, “process mode and handling”, and “volatility” were adopted from the inherent safety index (ISI) by (Heikkila, 1999) and inherent occupational health index is adapted (IOHI) (Hassim and Hurme, 2010a). For the vapor density, the categorical scale was created by this research. The scores were formed based on the reference value of the air density (Air = 1). If the vapor density is less than, equal to, or more than 1, a score of “1”, “2”, or “3” is assigned, respectively. Table 8B presents the categorical scales of the indicators.

Table 8B Score formation scales for the IHHLI indicators

Indicator	Criteria	Score
4. Ability to cause corrosion (I _C)	Not corrosive to carbon steel	0
	Corrosive to carbon steel	1
	Corrosive to stainless steel	2
	Corrosive to special corrosion resistance stainless steel	3
5. Process temperature (I _T)	< 70 °C	0
	70 – 150 °C	1
	151 – 300 °C	2
	> 300 °C	3
6. Process mode and handling (I _{MH})	Continuous	1
	Semi-continuous/semi-batch	2
	Batch	3
7. Volatility (I _V)	Very low volatility (boiling point > 150 °C)	0
	Low (150 °C ≥ boiling point > 50 °C)	1
	Medium (50 °C > boiling point > 0 °C)	2
	High (boiling point ≤ 0 °C)	3
8. Vapor Density (I _{VD})	Lower density; < 1 (air = 1)	1
	Equal density; = 1 (air = 1)	2
	Higher density; > 1 (air = 1)	3

Among the eight indicators, two indicators (i.e. process mode and handling (I_{MH}) and vapor density (I_{VD})) have score formation systems that range from “1” to “3”. This is because there is no possible category that can be added to their scoring systems and assigned the score “0”. For example, for the I_{MH}, there are only 3 possible categories (i.e. continuous “1”, semi-continuous/semi-batch “2”, and batch “3”). A continuous process cannot be assigned a score of “0” as it still can involve health hazard to workers. For the I_{VD}, there are only 3 possible categories (i.e. lower “1”, equal “2”, and higher “3” density to that of the air density). A

chemical with lower density than the air density cannot be assigned a score of “0” as it still can be exposed to by workers even at rare chances.

After weighting and normalizing the indicators, they were additively aggregated to construct the Inherent Health Hazard Level Index (IHHLI). By this method of aggregation, the IHHLI is calculated for the whole process plant by summing up the scores of the individual indicators as shown in Equation (1). The highest sum of the three indicators: toxicity (I_{TOX}), volatility (I_V), and vapor density (I_{VD}), received by any chemical in the process is considered in the calculation. For the two indicators: temperature (I_T) and pressure (I_P), the scores are assigned based on the highest temperature and pressure employed in the process.

$$IHHLI_{Process} = \text{Max}(I_{TOX} + I_V + I_{VD}) + I_T + I_P + I_{NOV} + I_{MH} + I_{MP} \quad (1)$$

4.2 Severity value

The totalled value of the IHHLI ranges from 1 to 30, considering the minimum and maximum likely values of the impacting indicators. As mentioned earlier, the value of the IHHLI is an illustration of the severity of the health hazard presents in the chemical processing facilities. However, this value is dimensionless and requires interpretation to be meaningful. Therefore, a 5-score categorical scale is used in order to normalize the total IHHLI value and interpret it into a qualitative description of severity as presented in Table 9 and illustrated in Figure 6. Based on this scale, if the IHHLI value falls into one of the categories “1 – 6”, “7 – 12”, “13 – 18”, “19 – 24”, or “25 – 30”, the severity is described as “Low”, “Mild”, “Moderate”, “Severe”, or “Extremely severe” and severity score of “1”, “2”, “3”, “4”, or “5” is assigned, respectively. As an exceptional case, if the IHHLI value falls into the category “7 – 12” or “13 – 18” with the most influential indicators (i.e. I_{TOX} , I_{NOV} , and I_P) scoring high, the severity is described as “Moderate” or “Severe”, respectively. This is done in order to reduce the compensatory effect resulted from using the additive aggregation method.

Table 9 Severity measurement scale

IHHLI value	Severity value	Description	Exceptional cases
1 – 6	1	Low	
7 – 12	2	Mild	
	3	Moderate	$I_{TOX} + I_{NOV} + I_P \geq 9$
13 – 18	3	Moderate	
	4	Severe	$I_{TOX} + I_{NOV} + I_P \geq 12$
19 – 24	4	Severe	
25 – 30	5	Extremely severe	

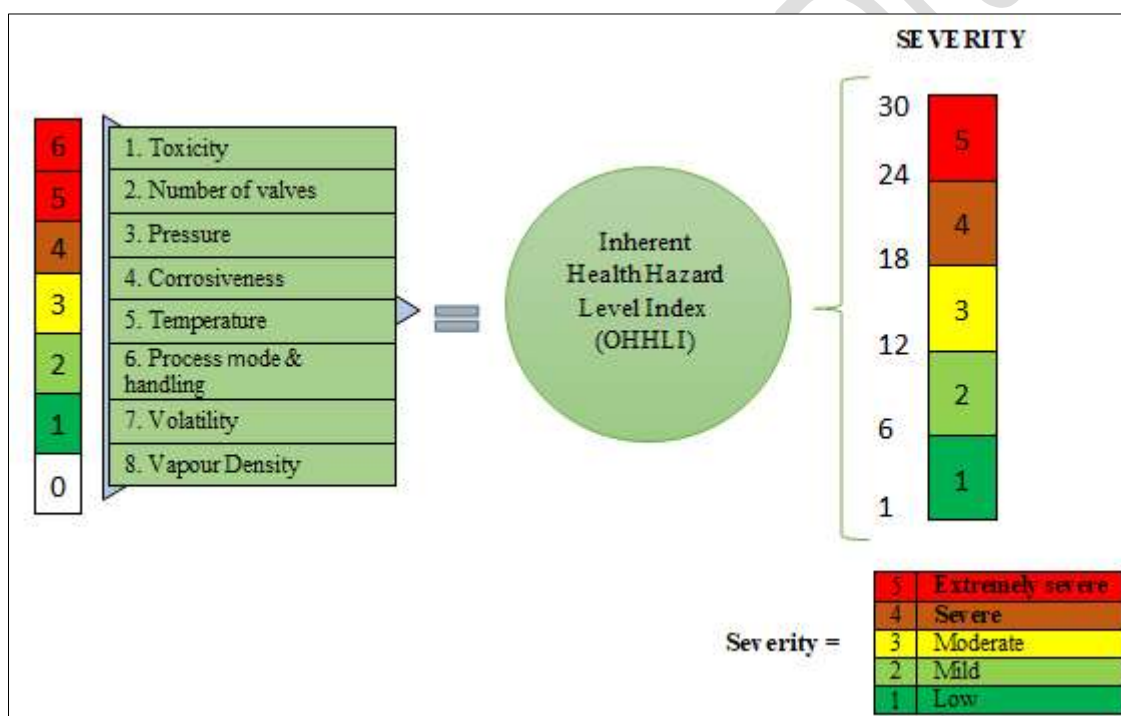


FIGURE 6 Steps of severity calculation.

4.3 Application of the inherent health hazard level index (IHHLI)

A real refinery case study was used as a case study for the demonstration of the the inherent health hazard level index (IHHLI). The case study refinery has a distillation unit with a capacity of 10,000 barrel/d. However, based on information provided by an OHS representative in the refinery, the refinery currently operates at maximum capacity of 8,500 barrel/d. The refinery also has a reforming unit with a capacity of 2,500 barrel/d. The refinery has the capacity to produce LPG, gasoline (3,054 barrel/d), diesel oil (3,600 barrel/d) and fuel oil (3,000 barrel/d). It has two storage tanks of 55,000 barrels capacity.

The health hazard severity of the refinery was calculated using the inherent health hazard level index (IHHLI). The data required for this calculation and benefiting indicators are presented in Table 10. Hydrogen sulphide (H₂S) gas was selected for this case study due to refinery concerns over its hazardous nature from both safety and health point of view. According to ACGIH (2019), hydrogen sulphide has a threshold limit value (TLV) of **“1 ppm”**. Hydrogen sulphide (in liquefied form) has high tendency to evaporate due to its low **boiling point (- 60.3 °C)**. In addition, hydrogen sulphide is heavier than the air with relative **vapor density of “1.19”** having the tendency to accumulate in low-lying areas, i.e. possibly in the workers’ breathing zone. Hydrogen sulphide is known as highly **corrosive to steels** (NCBI, 2022). The refinery operates in continuous process mode. However, there are situations where workers of the refinery would perform tasks manually with natural ventilation only (e.g. sampling, inspections, and maintenance).

Common knowledge and information available in the literature on refining process such as process temperature and pressure were used for the benefit of this assessment. The refinery has two major units, i.e. distillation and reforming units. The crude is usually processed in the distillation unit at a **process temperature range of 330 – 370 °C** (in the furnace). In the reforming unit, the highest operating conditions are as follows: **reaction pressure range of 5 – 45 atm.** and **reaction temperature range of 495 – 520 °C** (Gary *et al.*, 2007). For strict risk assessment, the worst scenarios are usually considered and therefore the operating conditions of the reforming unit are considered for the evaluation of the health hazard severity of this case study. It was estimated that the refinery contains **1259 valves**. The number of valves is estimated based on process component median counts estimation by US EPA for typical refineries with crude capacity less than 50,000 barrel/d (Lucas 2002).

Based on the data obtained, the indicators are scored using the scoring systems presented in Tables 8A & 8B. The obtained scores are summed up using Equation (1) of the IHHLI index. The total IHHLI value is **“22”**. This value is then converted using the severity measurement scale to obtain the severity value of **“4”**, which indicates severe health effect. Table 10 summarizes the calculation by listing the indicators along with the related data and assigned scores. Figure 7 illustrates how the severity value is scaled.

$$IHHLI_{process} = (5 + 3 + 3) + 3 + 2 + 1 + 2 + 3 = 22$$

Table 10 Severity calculation for Ma'rib refinery

Indicators	Data required	Assigned score
1. Toxicity	TLV = 1 ppm	5
2. Volatility	Boiling point: - 60 °C	3
3. Vapour Density	1.2 (air = 1)	3
4. Pressure	45	2
5. Temperature	520 °C	3
6. Process mode and handling	Continuous with manual activities	2
7. Ability to cause corrosion	Highly corrosive	3
8. Number of valves	1259 valves	1
Total IHHLI =		22
Scaled value of severity		4
Description		Severe health effect

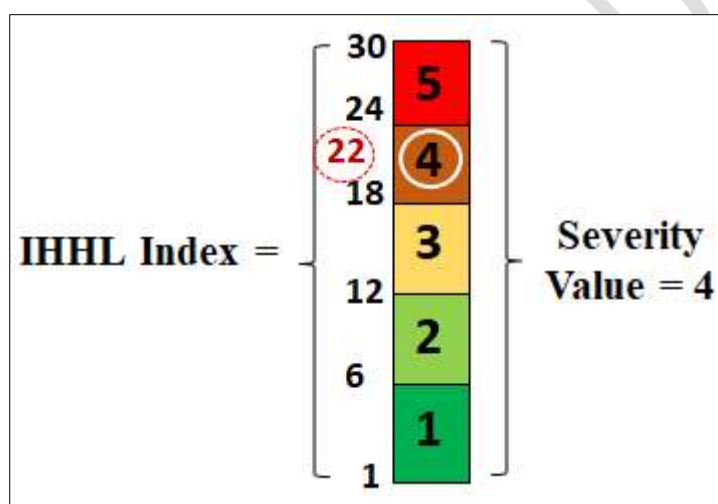


FIGURE 7 Severity value of Ma'rib refinery

In order to examine whether the IHHLI is able to provide more inclusive/precise OH hazard evaluation compared to other existing indexes, the severity of this case study was also calculated using the inherent occupational health index (IOHI). The IOHI was developed by Hassim and Hurme (2010) for evaluating inherent OH hazards at the research and development stage of process design. The IOHI is comprised of two main indexes, (i) index for health hazards (I_{HH}) and (ii) index for physical and process hazards (I_{PPH}). The I_{HH} considers two parameters which reflect the harmfulness of a chemical substance, these are: the exposure limits (I_{EL}) and the R-phrases (I_R) of chemicals present in the workplace. The I_{PPH} takes into account the parameters that might have the ability to directly or indirectly increase chances of exposure. These parameters include; volatility (I_V), pressure (I_P) (bar), temperature (I_T), process mode (I_{PM}), corrosiveness (I_C), material phase (I_{MS}).

Based on the data detailed above, the indicators are scored using associated scoring systems. The obtained scores, as presented in Table 11, are summed up. The total IOHI value is “17”. The IOHI does not provide a descriptive severity scale. However, by using severity scale provided in the IHHLI, the severity value obtained via the IOHI is “3” indicating moderate health effect. Table 11 summaries the calculation by listing the indicators along with the related data and assigned scores. Figure 8 illustrates how the severity value is scaled.

$$IOHI_{process} = 4 + 1 + 3 + 1 + 3 + 1 + 2 + 1 = 17$$

Table 11 Severity calculation for Ma’rib refinery (IOHI)

Indicators	Data required	Assigned score
1. Toxicity: exposure limit	OEL = 1 ppm	4
1. Toxicity: R phrase	R36/37, R67	1
3. Volatility	Boiling point: - 60 °C	3
4. Pressure	45	1
5. Temperature	520 °C	3
6. Process mode	Continuous	1
7. Corrosiveness	Highly corrosive	2
8. Material phase	gas	1
Total IOHI =		17
Scaled value of severity		3
Description		Moderate health effect

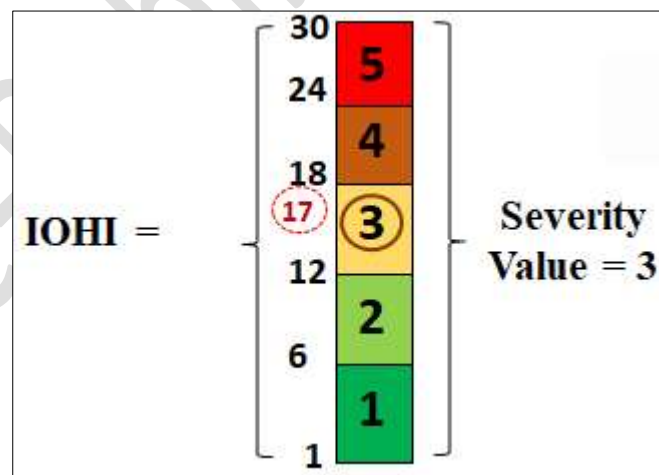


FIGURE 8 Severity value of Ma’rib refinery (IOHI)

The low IOHI severity value, compared to that of the IHHLI, could be attributed to the use of low score ranges for highly important indicators such as toxicity (ranging from 0 to 4) and corrosiveness (ranging from 0 to 2). In the IHHLI, toxicity is considered a core indicator as it

reflects the ability of a chemical to cause harm to health, and hence it was assigned a wide score range (ranging from 0 to 6). The low severity score may also be a result of using indicators that are less predictive of hazardous chemicals and their hazardous behaviour. For instance, based on the indicator “material phase”, the H₂S is assigned a low score of “1” for its presence in gaseous or vaporous form. This evaluation ignores the extremely toxic and accumulative nature of this chemical. In the IHHLI, the vapor density was used instead, as it enables a better prediction of toxic vapors given the fact that most of the toxic vapors are heavier than air. This makes the IHHLI more advantageous for evaluating inherent occupational health hazard of fugitive emissions.

5 CONCLUSIONS

Occupational health is among concerns imposed by fugitive emissions. Occupational health risk due to fugitive emissions is usually assessed by a means of indexed methods, i.e. inherent occupational health indexes. Based on the Source, Pathway, Receptor (SPR) model, beside the source of health hazards, the eventual occupational health risk is also dependent on the pathway and receptor, where a potential leakage and exposure can occur, respectively. In practice, petrochemical workplaces are equipped with control measures to tackle these hazards. For a holistic and accurate assessment of occupation health risk, these hazards and associated control measures need to be considered. This paper focuses on the source part of the SPR model and presents the Inherent Health Hazard Level Index (IHHLI) as an index method for measuring the severity of OH risk due to fugitive emissions in petrochemical workplaces. Pathway and receptor will be covered by future publications.

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