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A Heuristic Framework for Inherent Occupational Health Assessment in Chemical Process Design

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This paper presents a systematic heuristic framework to assist process designers and engineers in assessing inherent occupational health during process development and design. Different methods for inherent occupational health assessment are available and can be selected based on the availability of the most comprehensive data at the stage of the assessment. A more detailed and accurate assessment can be performed in the process and instrumentation diagrams (P&IDs) stage via the Occupational Health Index method (OHI) due to the availability of more precise data on the process (i.e., detailed piping, instruments and equipment). In the event of P&ID is not available, Health Quotient Index (HQI) method can be adopted to assess chronic inhalative health risk due to fugitive emission from process components (e.g., valve, flange, etc.) in the stage where process flow sheet diagrams (PFDs) are already generated. A qualitative health assessment can be conducted using the Inherent Occupational Health Index (IOHI) if the detailed information is still lacking because it only requires the data from process reaction chemistries and the properties of the chemical substances present. It is worth mentioning that the proposed framework acts as a guideline for design engineers in systematically selecting the appropriate index and methodology to assess inherent occupational health in process industry.

1. Introduction

In avoiding work-related diseases among workers especially in chemical process industries, the concept of inherent occupational health is gaining increased attention to reduce occupational hazards that may adversely impact workers' health. Over the last few decades, different health hazard assessment methods have been developed but they have focused on short time acute exposures from abnormal events. For example, the Dow Chemical Exposure Index (CEI) was proposed by the Dow Chemicals (1994a) to evaluate relative rating of acute health hazards potential to people in neighboring plants or communities for chemical release incidents. Before that, Mond Index developed in 1970's (ICI, 1993) as an extension of the Dow Fire and Explosion Index (F&EI) (Dow Chemicals, 1994b) aimed to primarily concern with fire and explosion problems, but also toxicity as a possible complicating factor such as a delay caused by toxicity when tackling an incident. Tyler et al. (1996) developed a Toxicity Hazard Index to evaluate hazard due to short term incidents. They preferred 5 minutes exposure values since it can be expected that within that time a worker would have either escaped from the affected area or donned protective equipment. The Control of Substances Hazardous to Health Regulations (COSHH) Essentials was developed to evaluate the effects of chemicals exposure to employees during process operation of small scale, indoor processes (Maidment, 1998). A more detailed assessment method which is called as the INherent SHE Evaluation Tool (INSET Toolkit) was proposed to screen chemical process routes in process design based on safety, health and environmental (SHE) criteria (INSIDE Project, 2001).
The aforementioned assessment methods focus on very short term health impacts rather than workers' long term health. Thus, the concept of inherent occupational health was introduced with the aim to prevent occupational health hazards that may adversely impact workers' health. Different manual-based inherent occupational health assessment indexes for different stages of process development and design have

been developed to design inherently healthier process. For instance, the Inherent Occupational Health Index (IOHI) method for the research and development stage (Hassim and Hurme, 2010a), the Health Quotient Index (HQI) method for the preliminary design stage (Hassim and Hurme, 2010b) and the Occupational Health Index (OHI) method for the basic engineering stage (Hassim and Hurme, 2010c). Note that all the occupational exposures to harmful chemical substances and workplace conditions evaluated via the IOHI, HQI and OHI methods are as a result of day-to-day work activities under normal operating conditions, which is what the basic principle of occupational health is all about.

Other than manual-based calculation, systematic graphical-based method and computer-aided tools for inherent occupational health assessment have also been proposed to assist engineers to perform assessment in faster, easier and more attractive way. For instance, a simple graphical method was proposed by Hassim et al. (2013) which is capable of highlighting the sources of occupational health related hazards of chemical process routes following the hazards assessment. Abbaszadeh et al. (2012) formulated the IOHI code using MATLAB and presented in the Graphical User Interface (GUI); Pandian et al. (2013) developed an electronic chemical properties database and adopted logical functions in Microsoft Office Excel to calculate the IOHI value.

Although the proposed assessment methods are well-developed, there is no guideline for engineers to select the appropriate method to assess inherent occupational health of chemical process plant. In this work, a heuristic framework in assessing inherent occupational health in process development and design via different indexes (e.g., IOHI, HQI and OHI) is presented. This framework assists engineers to determine the appropriate method(s) based on the availability of information at the particular stage of the assessment.

In this paper, a heuristic framework is presented in the next section, which is followed by the detailed description of each of the methods. Finally, conclusion and future works are given.

2. Heuristic Framework

A heuristic framework to assist process engineers in the inherent occupational health assessment is proposed in this work. Figure 1 shows a framework for inherent occupational health assessment in chemical process design. The whole assessment basically starts with identifying the availability of process information. In the P&ID stage, detailed process data can be utilized to identify occupational health hazards and subsequently to quantify the associated health risks to workers more comprehensively. Occupational Health Index (OHI) method is adopted to assess inherent occupational health of the proposed design with the availability of process equipment, piping and instruments details. The assessment of chronic inhalative exposure risk for non-carcinogen and carcinogen, acute inhalative exposure risk and dermal/eye exposure risk can be carried out via this method. In a case where P&ID is not available, PFD can also be utilized in the assessment as outlined in the Hazard Quotient Index (HQI) method. Fugitive emissions from the process can be estimated based on the information on unit operations and material balances accessible from the PFD, which is described in detailed by Hassim and Hurme (2010b). Here, the health risk can be calculated by comparing the calculated concentration of the airborne chemical(s) in the workplace air by its correspond exposure limit value. In the event that engineers neither have P&ID nor PFD, they can still assess inherent occupational health properties of the process design even with the scarce availability of information on the process via the Inherent Occupational Health Index (IOHI). Note that the IOHI is a qualitative health hazard assessment based on the properties of the chemicals present and the process conditions. For all the three methods, the calculated risk or hazard values will be compared with the respective benchmark of acceptance risk or hazard. If the risk or hazard value is not acceptable (e.g., HQI is greater than 1, the level of IOHI falls into the category of “moderately hazardous” or “hazardous”, etc.), the improvement of process should be carried out to reduce the risk or hazard as low as reasonably practicable (ALARP). The details of different assessment indexes based on the availability of process information are discussed in the following sections.

3. Methods for inherent occupational health assessment

3.1 Occupational Health Index (OHI)

All non-carcinogens and carcinogens present as well as leaking points from process equipment, piping and instruments are first identified from the P&ID. This is followed by chronic inhalative exposure risk assessment as a result of fugitive emissions for all chemicals or substances *i* (for both non-carcinogens and carcinogens).

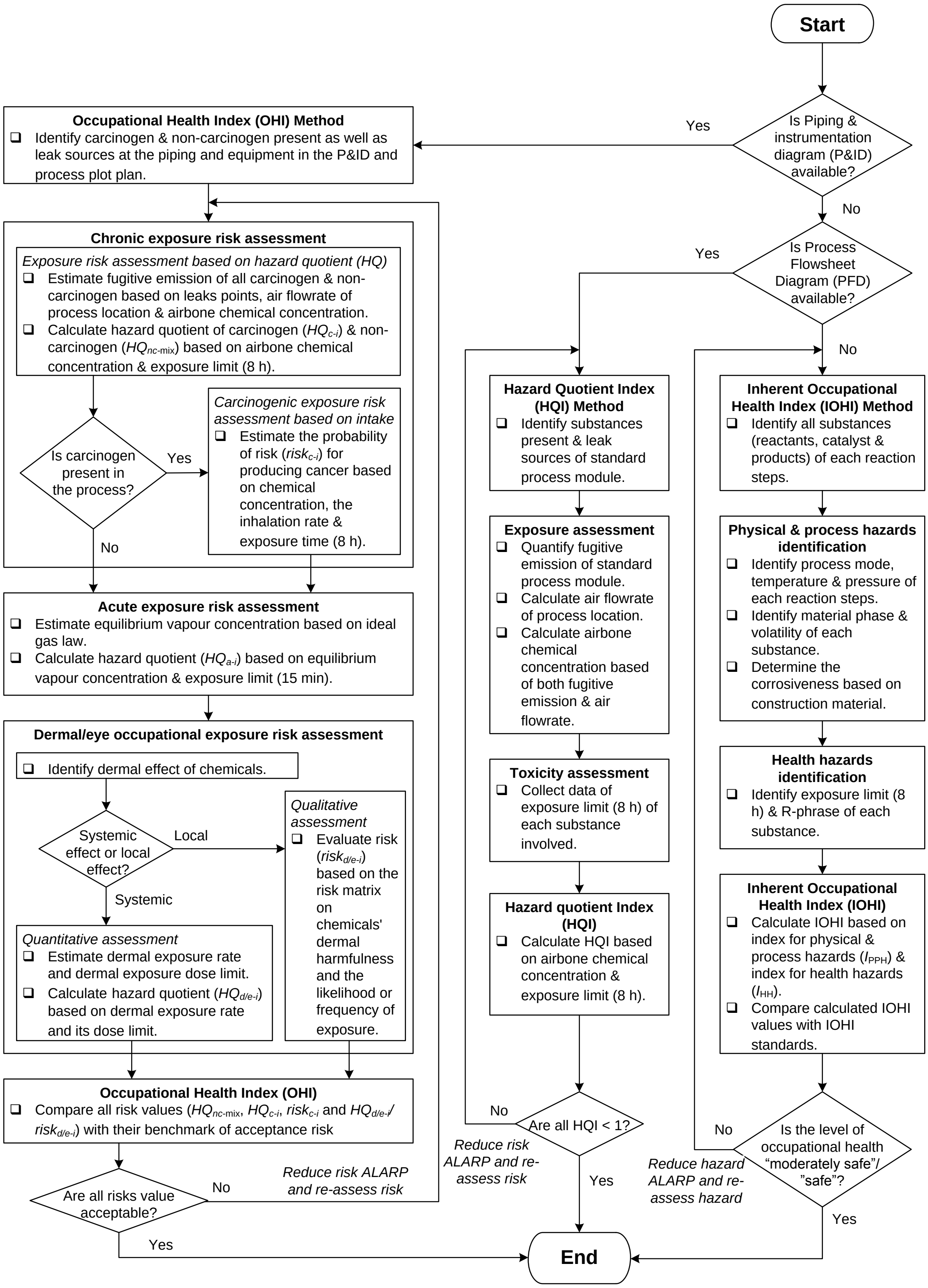

Figure 1: Heuristic framework for inherent occupational health assessment in chemical process design

3.1.1 Chronic inhalative exposure risk assessment

Fugitive emissions of non-carcinogens ($m_{nc\text{-}i}$) and carcinogens ($m_{c\text{-}i}$) are first calculated from the piping details. Then the air flowrate within the process area is estimated based on data on wind speed (v) and the cross-section area (A) of the process, obtainable from the plot plan. These data serve as input in calculating the airborne chemicals concentrations in the process. The airborne chemical concentration of non-carcinogens ($C_{nc\text{-}i}$) and carcinogens ($C_{c\text{-}i}$) are determined as:

$$C_{nc\text{-}i} = m_{nc\text{-}i} / vA \qquad \forall i \qquad (1)$$

$$C_{c\text{-}i} = m_{c\text{-}i} / vA \qquad \forall i \qquad (2)$$

Health hazard quotients for long-term exposure to fugitively released non-carcinogens ($HQ_{nc\text{-mix}}$) and carcinogens ($HQ_{c\text{-}i}$) are calculated based on the airborne chemical concentrations and their respective exposure limit (8 h).

$$HQ_{nc\text{-mix}} = \Sigma_i\, C_{nc\text{-}i} / C_{ELnc\text{-}i} \qquad (3)$$

$$HQ_{c\text{-}i} = C_{c\text{-}i} / C_{ELc\text{-}i} \qquad \forall i \qquad (4)$$

where $C_{ELnc\text{-}i}$ and $C_{ELc\text{-}i}$ are reference exposure limit of non-carcinogens and carcinogens (mg/m^3). Note that $HQ_{c\text{-}i}$ is calculated for individual carcinogenic substances while $HQ_{nc\text{-mix}}$ is calculated for mixture of non-carcinogen substances. For detailed explanation of hazard quotient of both individual and mixture chemicals, it can be referred to the original work of Hassim and Hurme (2010c).
In the event of carcinogen presents in the process, additional carcinogenic exposure risk assessment based on intake (rather than concentration in air as presented above) is carried out. The probability of risk ($risk_{c\text{-}i}$) for getting cancer is calculated based on chemical intake rate ($m_{CDI\text{-}i}$) and slope factor ($m_{SF\text{-}i}$).

$$risk_{c\text{-}i} = m_{CDI\text{-}i} / m_{SF\text{-}i} \qquad \forall i \qquad (5)$$

3.1.2 Acute inhalative exposure risk assessment

In addition to chronic exposure risk assessment, acute inhalative exposure risk assessment should be conducted to evaluate the health risk due to large exposure to chemical(s) within short-term duration. The equilibrium vapor concentration ($C_{eq\text{-}i}$) can be estimated based on ideal gas law:

$$C_{eq\text{-}i} = p_i M_i / RT \qquad \forall i \qquad (6)$$

where p_i is the vapor pressure of chemical i at temperature T, M_i is molecular weight of chemical i and R is ideal gas constant.
Then the health hazard quotient ($HQ_{a\text{-}i}$) is determined as follows:

$$HQ_{a\text{-}i} = C_{eq\text{-}i} / C_{ELeq\text{-}i} \qquad \forall i \qquad (7)$$

where $C_{eq\text{-}i}$ is equilibrium vapour concentration of the chemical and $C_{ELeq\text{-}i}$ is the correspond exposure limit (15 min).

Table 1: Risk matrix for local dermal/eye exposure (Hassim and Hurme, 2010c)

Probability/frequency of exposure	Low toxicity R21, 36, 38	Moderate toxicity R24, 34, 43, 48,	High toxicity R27, 35, 39, 41
Impossible/Zero contact	No risk *No action*	No risk *No action*	No risk *No action*
Improbable/Low contact	Negligible *No action*	Minor risk *Monitoring needed*	Moderate risk *Measure needed*
Possible/Daily contact	Minor risk *Monitoring needed*	Moderate risk *Measure needed*	Serious risk *Measure necessary*
Probable/Continuous contact	Moderate risk *Measure needed*	Serious risk *Measure necessary*	Intolerable risk *Immediate measure*

3.1.3 Dermal/eye exposure risk assessment

Next, dermal/eye exposure risk assessment is to be conducted. The dermal effect of chemicals is first identified. The effect is considered as local if the effect is caused by liquids or solids that may cause irritation, corrosive or other local effects. The dermal risk matrix which comprises of chemicals' dermal harmfulness and the likelihood of exposure is developed to evaluate risk ($risk_{d/e}$). Table 1 shows the risk matrix of local dermal/eye effects based on data from the R-phrases. Please note that the detailed descriptive terms of the likelihood or frequency of exposure can be referred to the original work of Hassim and Hurme (2010c).

In case where the systemic effects cause serious health damage by prolonged exposure, a quantitative dermal risk assessment should be conducted. The hazard quotient ($HQ_{d/e\text{-}i}$) can be calculated based on dermal exposure rate ($m_{a\text{-}i}$) and its dose limit ($C_{\mathrm{DEL}\text{-}i}$). The hazard quotient ($HQ_{d/e\text{-}i}$) is given as:

$$HQ_{d/e\text{-}i} = m_{a\text{-}i} / C_{\mathrm{DEL}\text{-}i} \qquad \forall\, i \qquad (8)$$

where the unit for both $m_{a\text{-}i}$ and $C_{\mathrm{DEL}\text{-}i}$ is mg/day. Detailed information on the quantitative assessment of dermal systemic effects is available from Hassim and Hurme (2010c).

3.2 Hazard Quotient Index (HQI)

In this method, the chemicals present in the process are first identified from the mass balances data as well as the standard process modules employed in the process (e.g., absorber, liquid extractor, stripper, etc.) based on the PFD drawing. Then, fugitive emissions of chemical substance *i* (m_i) from process streams of the identified units can be estimated using the precalculated emissions approach (Hassim and Hurme, 2010b). The wind flow cross section area (A) of the plot can be calculated from the actual plot dimensions, or from an estimated plot area (i.e. sum of the precalculated module areas) assuming a square plot as a first estimate. To calculate the wind cross section area (A), typically 7 m maximum height for the leak points is assumed.

From the leak rate, wind speed and wind flow cross section area data, the airborne concentration of substance *i* (C_i) can be determined as:

$$C_i = m_i / vA \qquad \forall\, i \qquad (9)$$

Next, the exposure limits (8 h) data of each substance *i* ($C_{\mathrm{EL}\text{-}i}$) are collected as a reference for calculating the health risk. The health hazard quotient index of each substance *i* (HQI_i) is determined based on the ratio of C_i and $C_{\mathrm{El}\text{-}i}$ as follows:

$$HQI_i = C_i / C_{\mathrm{El}\text{-}i} \qquad \forall\, i \qquad (10)$$

In addition, the hazard quotient for chemicals mixture (HQI_{mix}) can also be determined using this approach. The HQI_{mix} is determined based on the summation of the individual hazard quotient of all substances *i* (HQI_i) present in the mixture. HQI_{mix} is given as:

$$HQI_{\mathrm{mix}} = \Sigma_i\, C_i / C_{\mathrm{El}\text{-}i} \qquad (11)$$

The value of HQI_i or HQI_{mix} of greater than 1 indicates risky to health since the concentration of airborne chemical concentration is higher than its correspond exposure limit. Therefore the generation of fugitive emissions in the process should be reduced ALARP.

3.3 Inherent Occupational Health Index (IOHI)

Similar to the other two methods, firstly all substances involved in the reaction chemistries to the desired product are identified. According to Hassim and Hurme (2010a), Inherent Occupational Health Index (IOHI) composes of sub-index for physical and process hazards (IPPH) and sub-index for health hazards (IHH). The calculation of the IPPH requires chemicals' physical and process hazards identification. This sub-index is calculated by summing up the penalties received by all the six parameters of the IPPH as shown in the following equation:

$$I_{\mathrm{PPH}} = I_{\mathrm{PM}} + I_{\mathrm{P}} + I_{\mathrm{T}} + \max(I_{\mathrm{MS}}) + \max(I_{\mathrm{V}}) + \max(I_{\mathrm{C}}) \qquad (12)$$

where I_{PM}, I_{P}, I_{T}, I_{PM}, I_{MS}, I_{V} and I_{C} are parameters of mode of process, pressure, temperature, material phase, volatility and corrosiveness of construction material, respectively. Please note that I_{MS}, I_{V} and I_{C} are penalized based on the worst (most hazardous or toxic) chemical in the reaction because each reaction step normally consists of more than one chemicals.

Next, the sub-index for health hazards (I_{HH}) is determined by parameters of exposure limit (I_{EL}) and R-phrase (I_{R}) of the chemical substances. To determine the I_{HH}, the I_{EL} and the I_{R} penalty value of the worst chemical will be taken to represent the hazard parameters of that particular reaction step. The I_{HH} is given as:

$$I_{\mathrm{HH}} = \max(I_{\mathrm{EL}}) + \max(I_{\mathrm{R}}) \qquad (13)$$

The detailed sub-indexes of the I_{PPH} and I_{HH} can be referred to the original work of Hassim and Hurme (2010a). The IOHI is given as:

$$\text{IOHI} = I_{PPH} + I_{HH} \quad (14)$$

The IOHI values are then calculated and compared with the IOHI standards proposed by Hassim and Hurme (2010a). The IOHI standard is summarized in Table 2. The reaction chemistry pathway to the desired product is accepted if the level of IOHI falls into the category of “moderately safe” or “safe”.

Table 2: IOHI standard (Hassim and Hurme, 2010a)

Category	IOHI scales for reaction step
Safe	0 – 7
Moderately safe	8 – 11
Moderately hazardous	12 – 15
Hazardous	16 – 26

4. Conclusion

In this work, a heuristic framework for inherent occupational health assessment in chemical process design is presented. Different assessment methods (e.g., OHI, HQI and IOHI) are compiled in this framework to determine the health risks or hazards caused by chemicals exposure and operating conditions in process industry. This framework helps engineers to select appropriate index method for inherent occupational health assessment based on the availability of process information. Strategies for reducing health hazards or risks upon exposure to the hazards can be included in the future work. Process improvement to reduce health hazards or risks ALARP based on inherently safer design (ISD) keywords of minimization, substitution, moderation and simplification can be applied.

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