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Inherent occupational health assessment during process research and development stage

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ABSTRACT

Occupational health studies the interaction of work and health, especially the long-term effect of chemicals to health. In this paper an Inherent Occupational Health Index has been developed for assessing the health risks of process routes during process research and development stage. The method takes into account both the hazard from the chemicals present and the potential for the exposure of workers to the chemicals. The index can be used either for determining the level of inherent occupational health hazards or comparing alternative process routes for these risks. The method is tailored for the process research and development stage by including only such properties of chemicals and operating conditions of process, which are available already in this early stage. In the end of this paper the approach is demonstrated by comparing the inherent occupational healthiness of six methyl methacrylate process routes using three different types of index calculations; additive-type, average-type, and worst case-type. The study discloses that the average- and worst case-based approaches analyze the characteristics of a route better than the additive calculation, which is greatly affected by the number of steps in the route. A quantitative standard scale for the index is also developed to allow health level assessment of a single process.

1. Introduction

Process research and development aims to create process routes, which are economic, safe, healthy, and environmental friendly. The selection of process route based on these criteria needs to be done carefully since the fundamental decisions made at this phase will have a major effect on the later stages of the process lifecycle. Economic and technical aspects used to be the only essential aspects influencing the decision-making of companies earlier. However, now increasing attention is given on safety, health, and environmental (SHE) criteria because of legal requirements, company image, as well as economic reasons. These aspects can be considered even as a competitive advantage (Hurme, Tuomaala, & Turunen, 2003).

A safer, healthier, and environmental friendlier process can be achieved through internal and external means. In practice these both approaches are used to complement each other. Internal means, or widely known as the 'inherent' approach is however considered preferable, since it relies on the fundamental properties of the process and chemicals in aiming to eliminate risks by using less hazardous chemicals, smaller inventories of chemicals, and milder process conditions. In fact the chemical, which does not exist, does not pose a danger to anybody. The inherent approach requires less add-on protective systems, which also simplifies the process and makes it more easily manageable. Protective equipment may however fail and human may create errors. Therefore, designing a fundamentally safer, healthier, and environmentally friendlier plant is more appealing (Kletz, 1991).

2. Occupational health

Occupational health is the promotion and maintenance of the highest degree of physical, mental, and social well being of workers in all occupations by preventing departures from health, controlling risks, and the adaptation of work to people, and people to their jobs (ILO/WHO, 1950). In other words, occupational health is concerned with the two-way relationship between work and health. Subsequently, occupational health hazards are those factors arising in or from the occupational environment that adversely impact health (Lipton & Lynch, 1994).

Today, hundreds of millions of people throughout the world are working under circumstances that foster ill health or are unsafe. It

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Abbreviations

ACH	Acetone cyanohydrin based route
C2/MP	Ethylene via methyl propionate based route
C2/PA	Ethylene via propionaldehyde based route
C3	Propylene based route
EU	European Union
I_C	Penalty for corrosiveness
i-C4	Isobutylene based route
I_{EL}	Penalty for exposure limit
I_{HH}	Health Hazards Index
I_{IOHI}	Inherent Occupational Health Index
I_{MS}	Penalty for material state
I_P	Penalty for operating pressure
I_{PM}	Penalty for process mode
I_{PPH}	Physical and process hazards index
I_R	Penalty for R-phrase label
ISD	Inherently safer design
I_T	Penalty for operating temperature
I_V	Penalty for volatility
MMA	Methyl methacrylate
OELs	Occupational exposure limits
OHHI	Occupational Health Hazard Index
PRHI	Process Route Healthiness Index
R&D	Research and development
SHE	Safety, health, and environment
TBA	Tertiary butyl alcohol based route

is estimated that yearly over two million people worldwide die of occupational injuries and work-related diseases (Eijkemans, 2005). In fact more people die from diseases caused by work than are killed in industrial accidents (Wenham, 2002). Therefore enhancement of occupational health in industry, particularly in chemical process industry, is at least as important as improvement of process safety. However, because of its complex nature, occupational health has received less attention compared to process safety by chemical engineers.

Health differs from safety in terms of the exposure time and the abnormality of the circumstances. *Safety* deals with acute i.e. major, catastrophic short-term events that are unlikely to recur. Meanwhile, health is more related to chronic i.e. continuous, slow, low-level exposure over the time. *Occupational health* concerns with routine work activities carried out by employees experiencing a day-to-day workplace exposure under normal conditions. Therefore, health effects involve a lot of work related and technical factors that result in a complicated means of assessment, which compound the task of assessing occupational health in work places.

Generally, factors that might affect workers' health can be divided into five major categories of physical, chemical, biological, and ergonomic/mechanical as well as psychosocial factors (Hartley, 1999; Negash, 2002). Some of the factors, such as falls, trips, and burns are often classified under occupational safety rather than occupational health. The borderline between health and safety is therefore not clearly defined and the words are normally used together to cover both the subjects, which are much interlinked in industry.

3. Inherent occupational health

Inherent occupational health strives to eliminate or reduce the occupational health hazards by trying to eliminate the use of hazardous chemicals, process conditions, and operating procedures that may cause occupational hazards to the employees. There are twofold aims: Firstly to reduce the risk of inherent properties of chemicals (such as toxicity and high vapor pressure) by using friendlier chemicals or the chemical in safer physical condition (such as lower temperature) to eliminate the exposure. Secondly to reduce such process steps or procedures which involve inherent danger of exposure of the chemical. Examples of such operations are some manual operations where the worker is in close contact with the material, such as the manual handling and dosing of chemical, emptying, and cleaning of the equipment, etc.

The background of inherent occupational health is in inherent safety. Trevor Kletz originally presented the inherent safety principle in the early 1970s (Kletz, 1984). He proposed that the concept applies also to environment and industrial hygiene. In general level it is obvious that all SHE aspects are interlinked. Inherent SHE can be defined e.g. as the elimination of hazards by suitable process design so that processes are, by their very nature, safe, healthy, environmentally friendly, unaffected by change, and stable (Gillett, 2003). Kletz or others however did not elaborate the inherent health or its evaluation further.

In the early 1990s the EU INSIDE Project was started (2001) aimed at promoting inherent safety, health, and environmental protection (ISHE) within the European industry. The term inherent health hazards was used but not formalized further. Inherent health aspect was considered by evaluating the effects of airborne chemicals to health.

Inherent occupational health hazards were first formally discussed in detail by Hassim and Edwards (2006). An inherent occupational health hazard can be defined here as a condition, inherent to the operation or use of material in a particular occupation, industry or work environment, that can cause death, injury, acute or chronic illness, disability, or reduced job performance of personnel by an acute or chronic exposure.

4. Existing evaluation methods discussing health aspects

Gupta and Edwards (2002) conducted a survey to cross-section of chemical engineering professionals around the world on inherently safer design (ISD). Among the things surveyed include the incorporation of health and environmental aspects in ISD. It was proposed by some of the respondents that separate indexes are needed for each safety, health, and environment criteria rather than a composite one in decision-making.

Among safety, health, and environmental aspects, safety issues draw the most attention from researchers in academia as well as industry. In spite of limited publications for health hazards, there are still quite a number of existing methods addressing this area in small part when focusing mainly on safety or environmental aspects. These include methods by Koller, Fischer, and Hungerbühler (1999, 2000) (EHS method), Shah, Fischer, and Hungerbühler (2003, 2005) (SREST), Mallick, Cabezas, Bare, and Sikdar (1996) (WAR), Sheng and Hertwich (1998) (HHS), and Srinivasan and Nhan (2008) (IBI). However, those methods attend to health aspect only as part of the other main aspects. For instance, the EHS, SREST, and IBI methods addressed health issue alongside safety and environmental issues. For health assessment, those methods covered only the health effects, but not the exposure propensity of chemical substances. In health hazard assessment, both factors need to be evaluated. The WAR and HHS methods evaluated environmental health hazards as a part of the environmental assessment activity.

The Dow Chemical Exposure Index (1998), CEI on the other hand, gives a very comprehensive method of assessing health hazards caused by acute exposure to chemicals. The assessment is carried out for each source identified to have a potential for releasing chemicals. However, it does not fit the interest of occupational health point of view, since it evaluates the acute health hazard risk to people from chemical release incidents, and not the long-term effects on workers during normal operation.

Tyler, Thomas, Doran, and Greig (1996) introduced Toxicity Hazard Index that ranks the relative acute toxic hazards of different chemical production units. This Mond-like index evaluates the toxicity potential of a unit, considering only short-term events and acute effects based on inhalation route of exposure. This is among the earliest works done in the assessment of toxicity hazards. It has been constructed so that the overall pattern closely follows the framework of the Mond Index. However, the Toxicity Hazard Index is more likely referred as safety-type assessment method, because it deals with acute toxicity alone rather than the overall aspect of health hazards. Furthermore it only treats the short-term accidental events, but not the low level and continuous releases. This is also the case of the HIRA method (Khan & Abbasi, 1998).

A work undertaken by a working group established by the Health and Safety Commission's Advisory Committee on Toxic Substances (Maidment, 1998; Brooke, 1998; Russell, Maidment, Brooke, & Topping, 1998) accounts for effects of chemicals exposure particularly to employees, with the ultimate goal of identifying appropriate control strategies. Known as the UK Scheme, the developed model scrutinizes both the intrinsic health hazard of substances used at work as well as surrogates for exposure potential. The drawback of the scheme is it targeting on existing plants, particularly small and medium size enterprises thus making it inconvenient for design stage implementation.

The most detailed method capable of assessing SHE aspects as well as other feasibility factors is the INSET Toolkit (INSIDE Project, 2001). The toolkit incorporates four stages of implementation, but the actual evaluation of SHE criteria is performed only in the second stage. Stage 1 involves general screening; with mainly non-SHE issues are addressed. Only Stage 2 deals directly with the ranking and selection of process routes based on the SHE aspects. The health performance of the routes is evaluated based on the hazardous material properties relating to health effects, the likely fugitive emission rate of that material as well as the chance that people are exposed to this. For chemical properties, the Health Harm Factor (HHF) is determined from R-phrase and qualitative classification. The Leak Factor (LF) is provided to estimate the fugitive release rate from process equipment and manual activities. The R-phrase classification and the LF score are very brief and incomprehensive. The potential exposure is assessed only by estimating the number of locations where manual-handling operations will be carried out in the process. The overall health index is calculated from these scores. Stage 3 concerns with process design optimization of the route(s) selected from Stage 2. Finally, the initial process design is developed in Stage 4 and subsequent evaluation is conducted to reduce process inventories and complexity.

The disadvantage of INSET toolkit is complexity. Aside from being complex, this method requires massive detailed information. Malmén (1997) and Ellis (1997) who applied the toolkit identified the difficulties; the long time required in index calculation, the need to screen a large number of alternatives, and the requirement for analysing complex issues at early stages.

Johnson (2001) developed in her Master thesis a method called the Occupational Health Hazard Index (OHHI) for assessing the occupational health hazards in design concepts. The OHHI is an earlier version of the method introduced by Hassim & Edwards (2006). The disadvantage of the OHHI method is in the way it assesses the factors being considered for the assessment. Some factors e.g. fugitive emissions are evaluated very concisely so that the accuracy is questionable. Some factors are over-evaluated requiring excessive data e.g. material properties and operational/maintenance activities.

For improvement, Hassim & Edwards (2006) has introduced an index called the Process Route Healthiness Index (PRHI). The proposed methodology is quite complicated and lengthy. The index includes wide range of factors in a single evaluation stage. The PRHI also requires plenty of information and some of the information is not available during the early process design stage. Due to its complex steps, the PRHI is not suitable for a simple and quick application. It is also inflexible as a result of the data requirements for the application. Basically, the PRHI requires process information throughout the process design phase; from the research and development to the detailed engineering stage. However, each aspect especially at the end of design phase is not thoroughly and accurately assessed. Besides, the index has the disadvantage of indirectly assessing several factors such as propensity for chemical emissions repeatedly. Despite the weaknesses of the PRHI, the work still serves as the first methodology, formally published in this area that gives some benefits from process design point of view.

Most of the methodologies discussed are not suitable for inherent occupational health hazards assessment of reaction pathways or process concepts, because they were developed for different objectives such as evaluating the impacts among public community and targeting for application on only operating plants. The methods, which are to some extent applicable for this purpose but have some disadvantages as discussed earlier are: the INSET Toolkit by INSIDE Project (2001), OHHI by Johnson (2001), and PRHI by Hassim & Edwards (2006).

5. The assessment methodology development

Because of the lacks in the existing methods, the aim of this research is to develop a tool that will assist users in making chemistry pathway selections based on the health risk level of several process routes. The goal is to develop a similar type of index as used in inherent safety such as the PIIS (Edwards & Lawrence, 1993) and the Inherent Safety Index (Heikkilä, Hurme, & Järveläinen, 1996), but directed to the occupational health aspect. The aim is to create a set of assessment methods tailored to different stages of process development and design such as; process research and development (R&D), preliminary design, and basic engineering. Much focus is given on the real usability of the index, especially availability of the data. The methods should rely on the information available on the particular stage. The method proposed in this paper is intended for the process research and development stage, which is the first stage of process design.

5.1. The process development and design stages

A typical chemical process goes through several phases of lifecycle such as research and development, design, construction, operation, retrofitting, and finally decommissioning. These stages differ from each other in terms of the amount and type of information available (Hurme & Rahman, 2005). The Inherent SHE (ISHE) principle can be incorporated at any stage of process design and operation. However, the best results will be achieved only if it is implemented during the process development and design phases. Plus, the opportunities and the costs for implementing inherent features are more attractive at these stages. Kletz (1991) pointed out that the relative costs of fixing a safety problem will be; \$1 at the research stage, \$10 at the process flow sheet stage, \$100 at the final decision stage, \$1000 at the production stage, and \$10,000 at the post incident stage. Due to these reasons, the scope of the method development has been focused on the first stages of plant lifecycle – this paper discussing the R&D stage. The approaches developed have to rely on the data available at these stages. The later the stage, the more abundant and accurate information exists, thus allowing the use of more rigorous methods.

In the *R&D stage*, the major decision made is the selection of chemical synthesis route. At this point, much of the detailed information is still missing, because the process is not yet designed. The only information available is the data from the process reaction chemistries and the properties of compounds present. The information on process concept is normally presented in the form of a block diagram. This data is valuable in foreseeing the potential hazards in the process.

As the process lifecycle proceeds to the *preliminary design stage*, process structure will be created and process flow sheet diagrams (PFD) will be generated. In this flow-sheeting phase, a more detailed analysis can be carried out. From the process structure, additional information such as mass and energy balances and major unit operations are available. This information allows for a more accurate screening between the competing processes.

A plant investment project starts with the *basic engineering*. Therefore, it is important to analyze the selected processes from preliminary stage in more depth before decisions are finally made. Most of the basic engineering consists of detailed process design. Process and instrumentation diagrams (P&ID) are generated. Much data on piping and instrumentation is available and information on working and maintenance procedures is obtainable. Basic engineering is the last step when changes can still be made at a moderate cost and the possibility of making some conceptual changes and to adopt ISHE principles still exist. The types of information available at these three stages as well as at the detailed engineering stage are presented in Table 1 (Hurme & Rahman, 2005).

5.2. The index-based method for inherent health hazard assessment

The goal of conducting an inherent hazards assessment is to assist process selection and design by providing means to evaluate the level of occupational health in the process. The decision-making can be performed if the candidates can be ranked by their occupational health risk. To do this, index-based methods for the assessment of especially inherent safety have been widely disseminated earlier. The characteristics of an ideal index can be summarized as following (Khan & Amyotte, 2005; Khan, Husain, & Abbasi, 2001; Koller et al., 1999; Russell et al., 1998):

(1) It has to be relatively simple, straightforward, not to be too time consuming and transparent, such that it can be easily understood and applied.
(2) It has to be flexible and usable, such that it can be consistently applied by many types of companies.
(3) It requires information, which is available in the stage of design concerned.
(4) It does not require any complex calculations.
(5) It gives reliable results that can aid in the decision-making process. And
(6) It does not require experts for its implementation, and the user's own knowledge can be benefited.

For the first part of the research, we have developed an index called the Inherent Occupational Health Index (IOHI), by aiming at the above-mentioned goals.

5.3. Exposure assessment

Chemicals released within a workplace, either accidentally or as fugitive emissions, will only be a threat to health once workers are exposed to them. Lipton & Lynch (1994) define exposure more specifically as a contact between the individual with the substance either as in gas, solid or liquid over time, so that the intake of a dose may occur through one of the routes of entry. Chemicals' characteristics, process conditions, and working activities can increase the workplace exposure. Route of entry describes the way chemicals enter the body. There are four possible routes of entry; through inhalation, skin or eye contact, ingestion, and accidental injection.

In chemical industries, inhalation is a primary and efficient route for exposure since respiratory system is the most common route for gases, vapors, aerosols, mists, fumes, and small particulates to enter the body. This is particularly true for industries handling low boiling compounds such as solvents due to the high volatility of these materials. Therefore inhalation is considered as a very important source of exposure occupationally (Lipton & Lynch, 1994). The significant impact of inhalation to cause health hazards in process industries is also recognized by Tyler et al. (1996), when they selected inhalation route in assessing toxicity hazards in the Toxicity Hazard Index.

Skin or eye contact is also typical in chemical plants, especially those that deal with heavy and less volatile substances, though its occurrence is not as frequent as inhalation. Skin effects, either absorptive, corrosive or scalding, may be caused by liquids spillage, leakage or splash. Even though they can be very severe, they are usually confined to a very short distance from the release point, whereas inhalation effects may be significant over a considerably larger range and therefore may affect wider area of working environment. Ingestion is the least common entry route into the body. Despite this, ingesting chemicals by accident may still happen. Typically, chemical exposure via ingestion route may occur through eating or smoking with contaminated hands. Injection is a common type of exposure in laboratories and hospitals, but rare in chemical industries. Overall, these sources are small and always rank behind inhalation and skin contact as contributors to the total dose.

Physical properties of materials, process conditions, equipment types, as well as work activities influence exposure to chemicals through inhalation. As for skin contact and ingestion, poor hygiene practices and work procedures appear to be the notable cause.

In the R&D stage, health effects resulted from inhalation, dermal contact, and ingestion are assessed briefly based on the R-phrases,

Table 1
Information availability at different process stages.

R&D design	Process predesign	Basic engineering	Detailed engineering
- First process concept - Process block diagram - Reaction steps - Types of chemicals - Physical/chemical/toxicity properties - Reaction conditions - Stoichiometric equations - Product yield	- All in R&D stage - Flow sheet (simple or detailed) - Mass/energy balances - Operating conditions - Major unit operations	- All in R&D and predesign stages - PI diagram - Process data on equipment, piping and instrumentation - Plant layout - Preliminary working procedures	- All in R&D, predesign and basic engineering stages - Detailed equipment, piping and instrumentation - Equipment sizing - Mechanical design/engineering - Structural, civil & electrical engineering - Design of ancillary services

health and safety information, and material safety data sheets (MSDS), which are the relevant information available at this stage. In the later design stages, exposure via inhalation will be assessed in more detailed way. The availability of more process information permits dermal exposure aspect to be included also.

6. The Inherent Occupational Health Index

Generally, health risk is defined as the probability that an individual exposed to a pollutant may experience an adverse health effect subsequent to the exposure (Kumar, Madasu, & Manocha, 1994). The health effects caused may be either short-term acute or long-term chronic effects. The level of health hazard arisen is determined by accounting for:

(1) The potential for harm.
(2) The potential for exposure.

The potential for harm is a function of types and amounts of chemicals present, duration and frequency of exposure, and conditions in the working environment. The physical properties of materials, operating conditions, human behavior, and work activities are among the factors that can increase potential exposure.

The health hazard index for the alternative processes is calculated based on the exposure and the effect of all chemicals and operating conditions in the process. In this paper, chemical exposure is assessed for processes under normal conditions. Thus, exposure caused by accidental emissions such as loss of containment, fire or explosion will not be included, since they are covered by inherent safety. The Inherent Occupational Health Index (IOHI) composes of two indexes; Index for Physical and Process Hazards (I_{PPH}) and Index for Health Hazards (I_{HH}). The Physical and Process Hazards Index represents the possibility for workers being exposed to chemicals, whereas the Health Hazards Index characterizes the health impacts and dangers as a result of the exposure. These indexes comprise of various factors (subindexes) described later. The IOHI for each process route is calculated as a sum of the two factors (Eq. (1)).

$$I_{IOHI} = I_{PPH} + I_{HH} \tag{1}$$

6.1. Index development

The principle adopted when developing the index was to include the factors that might give significant contributors to the arising of adverse health impacts. The selection of the factors is restricted by the availability of the information during the R&D stage. To quantify the hazards level, each factor is assigned with a number representing a penalty. The allocation of the penalties is based on the degree of potential hazards or the probability of exposure; the higher the hazard or the probability, the higher the penalty. The level of the consequences caused by the exposure determines the range of penalties assigned to each factor. A more meaningful factor will be given a larger penalty range (i.e. more significant weighting).

The Physical and Process Hazard (I_{PPH}) subindexes have the maximum penalty of three except for corrosiveness due to its lower tendency of causing direct chemical exposure compared to the others (Table 2). The Health Hazard (I_{HH}) subindexes however, are assigned with higher maximum penalties of four (except for chronic toxicity effects of five), because it is believed that the toxicity hazards of the chemicals pose the main health hazards risk to the exposed workers (Table 3).

Instead of the weighting of factors proposed in this paper, the user may tailor the method by applying weightings, which describe their own opinion or company policy.

Table 2
Physical and process hazards (I_{PPH}) subindexes.

Factor	Score formation	Penalty
Mode of process, I_{PM}	Continuous	1
	Semi-continuous/semi-batch	2
	Batch	3
Material phase, I_{MS}	Gas	1
	Liquid	2
	Solid	3
Volatility, I_V	*Liquid and gas*	
	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
	Solid	
	Non-dusty solids	0
	Pellet-like, non-friable solids	1
	Crystalline, granular solids	2
	Fine, light powders	3
Pressure, I_P (bar)	0.5–5	0
	5–50	1
	50–200	2
	>200	3
Corrosiveness, I_C – based on construction material	Carbon steel	0
	Stainless steel	1
	Better material	2
Temperature, I_T (°C)	<70	0
	70–150	1
	150–200	2
	>200	3

6.2. Physical and Process Hazards Index

The Physical and Process Hazards Index (I_{PPH}) describes the potential of materials as being exposure sources to workers. This exposure potential is expressed by the physical properties of materials and the operating conditions of the process.

Table 3
Health hazards (I_{HH}) subindexes.

Factor	Score formation	Penalty
Exposure limit, I_{EL}	*Solid (mg/m^3)*	
	OEL > 10	0
	OEL ≤ 10	1
	OEL ≤ 1	2
	OEL ≤ 0.1	3
	OEL ≤ 0.01	4
	Vapor (ppm)	
	OEL > 1000	0
	OEL ≤ 1000	1
	OEL ≤ 100	2
	OEL ≤ 10	3
	OEL ≤ 1	4
R-phrase, I_R	*Acute*	
	No acute toxicity effect	0
	R36, R37, R38, R67	1
	R20, R21, R22, R65	2
	R23, R24, R25, R29, R31, R41, R42, R43	3
	R26, R27, R28, R32, R34, R35	4
	Chronic	
	No chronic toxicity effect	0
	R66	1
	R33, R68/20/21/22	2
	R62, R63, R39/23/24/25, R48/20/21/22	3
	R40, R60, R61, R64, R39/26/27/28, R48/23/24/25	4
	R45, R46, R49	5

OEL, occupational exposure limit; R, R-phrase.

In the I_{PPH}, all the factors with the ability to either directly or indirectly increase risks of injuries or health effects are identified. For instance, the choice of process *operation mode* will definitely contribute to workplace exposure. Batch process appears to be the more hazardous operation compared to continuous and semi-continuous because it usually requires more frequent manual operations such as chemical handling. It also involves higher number of employees. This will increase the total worker exposure risk. Frequent start-ups and shut downs are normally involved in batch type processes. These may lead to extra equipment strain and more frequent maintenance works. In addition, batch processing also has the tendency to produce more fugitive emissions via solvents transferring between vessels during the operation and consequently, increase the exposure (McLellan and Partners Ltd. & John Crane International, 1997). Due to these reasons, continuous process is given the lowest penalty for its nature of reducing the likelihood of workers from being directly in contact with chemicals.

The *phase* of a chemical affects much on the way it will be handled and exposed to. The phase also affects the frequency and type of chemical exposure. Solids are mostly in form of powders or granules and often transported in bags or drums. Solid processing typically involves more manual work, such as bag emptying and manual loading, and less enclosed equipment, from which the dust involved tends to escape. Therefore solids transportation and processing tends to result in higher exposure compared to fluid handling in enclosed pipes and equipment, in which liquids and especially gases are commonly handled. Hence, the highest penalty is assigned to materials in solid form and lowest to gas handling.

Inhalation and absorption are major routes of entry in chemical industries. Potential exposure to chemicals via these two entry routes depends on the materials' physical properties that may increase their propensity to become airborne. *Volatility* of a liquid substance can be characterized by its vapor pressure or atmospheric boiling point. For solids a smaller dust like particle size will result to higher tendency to become airborne. Therefore lower boiling point liquids and smaller sized particles are given a higher penalty because of their properties of causing exposure. For both liquids and solids, the score formation is based on the COSHH Essentials (Maidment, 1998).

Operating *pressure* plays a vital role in exposing workers to process chemicals as well as dangers in the workplace. A higher pressure poses a higher risk for chemical exposure due to fugitive emissions through leakages. A higher-pressure process may also present a hazard to workers when performing maintenance works such as opening connections. A nil penalty is given to pressures 0.5–5 bar, since this is considered low in process industry. Penalty 1 is given for 5–50 bar range, etc. The penalty range follows mainly the pressure scale used by Heikkilä (1999) in the Inherent Safety Index.

Although good design makes allowances for *corrosion* and erosion, some corrosion problems may still occur in certain processes. The significance of corrosion in causing chemical releases and exposures in workplaces is well known. The corrosiveness of a chemical can be evaluated based on the necessitate construction materials, in which the chemical will be contained or handled. A chemical that will not corrode carbon steel is considered here as non-corrosive and it receives the lowest penalty. A chemical that requires better material than stainless steel is considered here as highly corrosive. A similar classification was used by Heikkilä (1999).

Temperature is an indicator of the heat energy in the system. When a chemical is released due to a leak, this energy enhances vaporization of a liquid material to make it as a fugitive emission. This aspect is related to the vapor pressure and volatility of the material, which were already discussed. On the other hand higher temperature increases the possibility of accidental burns. This should be considered, since occupational health does not deal with acute and chronic toxicity only, but often also small accidents leading to occupational injuries, such as burns, caused by the materials or equipment handled. Basically, burns are damage to skin and the underlying tissue caused by heat, chemicals or electricity.

The nil penalty is given for temperatures below 70 °C since they are low in process industry context. They do not cause burns and do not require protective insulation. The temperatures range up till 150 °C can be considered a typical temperature range for mild temperature processes (Heikkilä, 1999) and it is given penalty one. Penalty two is given to temperatures up to 200 °C and penalty three for temperatures over 200 °C. The temperature penalty range is formed based on the occurrence of first, second, and third degree burns. Here two causes of burns are considered, which are due to steam and surface contact. Different surfaces have different temperature limit values (BS EN 563, 1994); however 70 °C is the common threshold used in process industries. The score is formed based on steam exposure event (Lawton & Laird, 2003; Ng & Chua, 2002; Encyclopaedia of Human Biology, 1997).

The Physical and Process Hazards Index (I_{PPH}) is calculated by summing up the penalty for all subindexes, as shown in Eq. (2).

$$I_{PPH} = I_{PM} + I_P + I_T + \max(I_{MS}) + \max(I_V) + \max(I_C) \quad (2)$$

The process conditions determine the process mode, temperature, and pressure subindexes. The other factors are penalized based on the dominant (i.e. most hazardous) chemical in the reaction step. The maximum penalty (worst case) received by any chemical in the reaction step will be chosen to represent the subindex for that particular reaction step in Eq. (2). Summary of the subindexes and their penalties are provided in Table 2.

6.3. Health Hazards Index

The Health Hazards Index (I_{HH}) describes the level of chemical hazards to human's health upon exposure by two subindexes. Exposure limit based subindex (I_{EL}) gives information on the chronic hazards of the chemicals in the working air. The R-phrase based subindex (I_R) on the other hand, describes the type of health effect that might be caused by the chemical. These two indicators were selected for the purpose of identifying the intrinsic harmful potential of chemicals present in the process.

Occupational exposure limit (OEL) is a health-based standard that are established following a rigorous evaluation of the available toxicological data (Brooke, 1998). They are used to describe the concentration of airborne substance in workroom air to which workers may be exposed repeatedly day after day, with the expectation that adverse health effects will not occur. The exposure limit based on the 8-h daily exposure time is used here, since it describes a chronic type of toxicity and demonstrates the actual working situation. Substances with lower OEL values are relatively more harmful to human's health, and therefore they receive a higher penalty in the *exposure limit based subindex* (I_{EL}) (see Table 3). The exposure limit values are published by various organizations (e.g. nationally), but typically they do not differ much. In the IOHI, the evaluation of chronic toxic exposure is based on the Occupational Exposure Limit (OEL) set by the UK Health and Safety Commission. This data is readily available for most chemicals in process industry and it is easily attainable. For solid, the exposure limits classification is made based on the COSHH Essentials (Maidment, 1998; Brooke, 1998; Russell et al., 1998). Meanwhile, the score formation for vapor is based on the Mond Index (ICI, 1985).

The European Union R-phrases describe the human health risk associated with the chemicals (Risk Phrases, 2001). The EU regulations require R-phrases information to be provided to users when a chemical or preparation is supplied for use at work. In the IOHI, R-phrases are divided into two groups of acute and chronic toxicity, so that upon conducting the assessment, users are aware of the toxicity effects possibly caused by the chemicals they are dealing with. The chemicals with chronic toxicity effect have a higher range of penalty (maximum value of 5) in comparison to those with acute effect (maximum value of 4) in the *R-phrase based subindex* (I_R) (see Table 3). The chronic toxicity was penalized by more severe scale because of its more problematic nature, such as the latency period involved before the long term health effects appear, which makes the counter measures are often too late.

The R-phrases are classified based on the severity of the adverse health effects. For acute toxicity, the penalty assignation is as follows: penalty 1 for irritation/mild effect; penalty 2 for harmful effect; penalty 3 for toxic/sensitization effect; and penalty 4 for very toxic/burn effect. For chronic toxicity: penalty 1 for mild effect; penalty 2 for danger of repetitive exposure; penalty 3 for possible reproductive/teratogenic effect; penalty 4 for may cause reproductive/teratogenic effect; and penalty 5 for cancer. The R-phrases have an advantage of being readily available to users at early phase of process development. Some substances, such as pesticides, are however excluded from the classification.

The Health Hazards Index is calculated by Eq. 3. The penalties are summarized in Table 3. Both subindexes, the one for Exposure Limit (I_{EL}) and the other for R-phrase (I_{EL}) are penalized according to the worst chemical in the reaction step (the one receiving the highest penalty) in the similar way as described earlier for the Physical and Process Hazards Index in Eq. (2).

$$I_{HH} = \max(I_{EL}) + \max(I_R) \qquad (3)$$

7. Case study on methyl methacrylate process

The Inherent Occupational Health Index is demonstrated by applying the method for a comparison of alternative process routes to produce methyl methacrylate (MMA). According to Nagai (2001), there are 17 routes known for synthesizing MMA, which include those applied in industrial production as well as those under research and development. Here, based on the available information six of the routes are selected for the assessment. The routes are:

(1) Acetone cyanohydrin based route (ACH).
(2) Ethylene via propionaldehyde based route (C2/PA).
(3) Ethylene via methyl propionate based route (C2/MP).
(4) Propylene based route (C3).
(5) Isobutylene based route (i-C4).
(6) Tertiary butyl alcohol based route (TBA).

Among the six process routes, the ACH is the most traditional, used widely by industry for MMA production. Most of these routes have totally different reaction chemistries. The clear difference is the main raw materials used. In the ACH based route, hydrogen cyanide is the primary reactant. As for the C2/PA and C2/MP, both utilize ethylene as the starting raw material to produce propionaldehyde and methyl propionate as intermediates, respectively. The C3 route uses propylene as raw material in producing isobutyric acid as an intermediate. The i-C4 route uses isobutylene and the TBA route uses tert-butyl alcohol as the main reactant. The other differences between these pathways are the operating conditions, number of reaction steps, and etc. Details of these routes are summarized in Table 4.

Table 4
Summary of six MMA routes.

Route/step	Raw materials	Products	Reaction phase	Temperature (°C)	Pressure (bar)
ACH	Acetone cyanohydrin (ACH)				
2	Acetone, HCN	ACH	Liquid	29–38	1
3	ACH, H_2SO_4	HMPA/HMPASE, H_2SO_4, C_4H_7NO, $C_4H_7NO.H_2SO_4$	Liquid	130–150	7
4	C_4H_7NO, $C_4H_7NO.H_2SO_4$, CH_3OH, H_2SO_4	MMA, NH_4HSO_4	Liquid	110–130	7
C2/PA	Ethylene based via propionaldehyde				
1	Ethylene, CO, hydrogen	Propionaldehyde	Gas	100	15
2	Propionaldehyde, CH_2O	Methacrolein	Liquid	160–185	49
3	Methacrolein, oxygen	Methacylic acid	Gas	350	3.7
4	Methacrylic acid, CH_3OH	MMA	Liquid	70–100	6.8–7.5
C2/MP	Ethylene based via methyl propionate				
1	Ethylene, CO, methanol	Methyl propionate	Liquid	100	100
2	Methanol, oxygen	Methylal	Gas	350–470	1–4.5
3	Methyl propionate, methylal	MMA, CH3OH	Gas	350	Low
C3	Propylene based				
1	Propylene, CO, HF	Isobutyryl fluoride	Liquid	70	90–100
2	Isobutyryl fluoride, water	Isobutyric acid, HF	Liquid	40–90	10
3	Isobutyric acid, oxygen	Methacrylic acid	Gas	320–354	2.5–3
4	Methacrylic acid, CH_3OH	MMA	Liquid	70–100	6.8–7.5
i-C4	Isobutylene based				
1	Isobutylene, oxygen	Methacrolein	Gas	395	1–1.5
2	Methacrolein, oxygen	Methacrylic acid	Gas	350	3.7
3	Methacrylic acid, CH_3OH	MMA	Liquid	70–100	6.8–7.5
TBA	Tertiary butyl alcohol based				
1	TBA, oxygen	Methacrolein	Gas	350	4.8
2	Methacrolein, oxygen	Methacrylic acid	Gas	350	3.7
3	Methacrylic acid, CH_3OH	MMA	Liquid	70–100	6.8–7.5

HMPA, 2-hydroxy-2 methyl propionamide; HMPASE, 2-hydroxy-2-methyl propionamide sulphate ester.
H_2SO_4, sulphuric acid; CH_3OH, methanol; CO, carbon monoxide; MMA, methyl methacrylate.
HCN, hydrogen cyanide; CH_2O, formaldehyde; CH_4, methane; NH_4HSO_4, ammonium bisulphate.

7.1. Selecting the scope of evaluation

One of the first steps in starting any assessment task is selecting the scope of evaluation. This is especially true when discussing integrated chemical processes, which may include processing units for making raw materials, treating side products and effluents. The selection of scope is important since the structure of most indexes is additive, i.e. the index values of all subprocesses are added up to make the total index for the route. This is also the case for the Inherent Occupational Health Index. However in this paper, other examples of index calculation approach will also be presented to unveil different perspectives of index-based method. The additive character of index may be fair, since it reflects the complexity of the process, which undoubtedly increases the possibilities for leaks and other accidents. On the other hand additiveness may overemphasize this aspect. We can ask if a one-step process with lethal chemicals is safer or healthier than a two or three step process with much safer chemicals. Gupta & Edwards (2003) point out that, due to the additive nature of the indexes, the processes with more steps tend to get the worst index values. Therefore the selection of a fair evaluation scope decision is important.

In the evaluation of MMA process routes this question is relevant with the acetone cyanohydrin route, which may have either six or three steps depending on the scope of evaluation. The six steps considered sometime in evaluation are the production of (1) hydrogen cyanide, (2) acetone cyanohydrin, (3) methacrylamide, (4) methyl methacrylate, and (5) the decomposition of ammonium bisulphate side product to SO_2, which is used in step (6) to produce sulfuric acid. Out of the six subprocesses in the ACH route, only three of them (steps 2, 3, 4) are however related to the actual production of MMA. The others (steps 1, 5, 6) are related to the production of raw materials and the disposal of by-products, and thus they are excluded from the assessment. This is considered fair since in the other five MMA routes, only the subprocesses for actual MMA production are assessed – not the raw material production or waste treatment even though the other processes also produce waste materials such as residues and wastewater but in much smaller extent (Gupta & Edwards, 2003). In the earlier inherent safety and health assessments (Edwards & Lawrence, 1993; Johnson, 2001; Rahman, Heikkilä, & Hurme, 2005; Hassim & Edwards, 2006) all the six steps have been typically included. Therefore because of this scope selection the ACH process was always regarded as the least safe or healthy alternative as pointed out by Gupta & Edwards (2003). Based on this argumentation, only steps 2, 3, and 4 of the ACH route (i.e. the actual production steps) are included in the assessment scope here.

7.2. The index calculation

Each subprocess of the MMA alternative synthesis routes is evaluated according to the IOHI assessment parameters. The penalties given to the steps are summarized in Table 5. Although index-based method is typically additive-type, the results can also be viewed in different ways. Here the flexibility of the method is illustrated by presenting the index assessment results in three perspectives; additive-type, average-type, and worst case-type calculations.

7.3. Results

7.3.1. Additive-type IOHI calculations

As described earlier the typical way of calculating the process route index in nearly all the index based methods is to sum up the subprocess indexes. Based on the results shown in Table 6, the C3 and the C2/PA routes have the highest index value compared to the others. This has already been expected due to the largest number of subprocess they have (four). Even though they receive the same values for the IOHI, I_{PPH}, and I_{HH}, these routes are totally different from each other in terms of the raw materials and operating conditions.

The ACH route receives the IOHI value of 44, which is very close to those received by the i-C4 and the TBA processes. This result outcome signifies that the ACH route is actually not that hazardous as always portrayed by the other assessment methods like the PIIS (Edwards & Lawrence, 1993), ISI (Rahman et al., 2005), *i*-Safe (Rahman et al., 2005), EHI (Cave & Edwards, 1997), AHI (Gunasekera & Edwards, 2003), and IETH (Gunasekera & Edwards, 2006) that rank the ACH as the least safe and environmentally friendly route. The question is, how much importance is given on the number of steps involved in the process route and which steps should be included in the assessment. Gupta & Edwards (2003) discuss this aspect from inherent safety point of view. In their analysis, the ACH route is not all that unsafe because single subprocesses are of average safety level compared to the other routes. Also in Lawrence's (1996) study two experts downgraded the hazards of the ACH route because of the experience they had had on this process and had found it to be very safe.

The close IOHI values calculated for i-C4 and TBA processes are however, not surprising since these routes are the same, except for

Table 5
Summary of Inherent Occupational Health Index calculations for MMA subprocess.

Route/Step	I_{PPH}						I_{HH}		I_{IOHI}
	I_{PM}	I_{MS}	I_V	I_P	I_C	I_T	I_{EL}	I_R	
ACH	1								
2		2	2	0	1	0	3	4	12
3		3	0	1	2	1	4	4	15
4		3	1	1	2	1	4	4	16
C2/PA	1								
1		2	3	1	0	1	2	4	13
2		2	3	2	1	2	4	4	18
3		2	1	0	1	3	3	4	14
4		2	1	1	1	1	2	4	12
C2/MP	1								
1		2	3	2	0	1	2	4	14
2		2	2	0	0	3	1	3	11
3		2	2	0	1	3	2	3	13
C3	1								
1		1	3	2	2	1	3	4	16
2		2	2	1	2	1	3	4	15
3		2	0	0	2	3	3	4	14
4		2	1	1	1	1	2	4	12
i-C4	1								
1		2	3	0	1	3	3	4	16
2		2	1	0	1	3	3	4	14
3		2	1	1	1	1	2	4	12
TBA	1								
1		2	1	1	1	3	3	4	15
2		2	1	0	1	3	3	4	14
3		2	1	1	1	1	2	4	12

Table 6
The Inherent Occupational Health Index values for MMA routes (additive-type).

Route	I_{PPH}	I_{HH}	I_{IOHI}	Ranking
ACH	21	23	44	4
C2/PA	31	27	58	5–6
C2/MP	24	15	39	1
C3	31	27	58	5–6
i-C4	23	20	43	3
TBA	22	20	42	2

Ranking 6, posses the worst case.

the raw materials. The first reaction step of the i-C4 route receives a lower I_P penalty than the similar subprocess of the TBA route due to its lower operating pressure. However, the i-C4 route receives a higher I_V penalty because of the presence of a highly volatile substance (isobutylene) in the reaction step. The C2/MP route offers the lowest risk of occupational health hazards, and hence is ranked as number one among the competing processes. The route contains only one highly toxic substance, which justifies the relatively low I_{HH} value it received compared to the remaining five alternative processes. In terms of the exposure potential (I_{PPH}), the C2/MP route has a comparable hazard level to the i-C4 process.

7.3.2. Average-type IOHI calculations

In order to eliminate the influence of the number of subprocess on the final index value, the average IOHI, I_{PPH}, and I_{HH} index can be calculated for each process route (see Table 7). Except for the C2/MP, the average IOHI index for all the process options is almost equal. The ACH route receives the highest average IOHI value, followed by the C2/PA and C3 processes. The difference of the index values between the ACH and the next two routes however, is very small (14.7 and 14.5, respectively). Interestingly, the ACH has the smallest Physical and Process Hazards, I_{PPH} index – indicating it as the route with the lowest potential exposure hazard. For instance, the route operates under mild operating conditions of temperature and pressure range of 29–150 °C and 1–7 bar, respectively. It also contains less volatile substances compared to the other routes. However, the ACH route has the highest Health Hazards, I_{HH} index, which is significant in comparison to the other candidates. The presence of several toxic substances that acutely and chronically harmful to health, e.g. hydrogen cyanide, acetone cyanohydrin, and sulfuric acid contributes to the highest IOHI value calculated for the ACH route.

The opposite situation is observed for the C2/MP process. It has the highest I_{PPH} and the smallest I_{HH} index values. Besides the extreme operating temperature (range between 100 and 470 °C), the route comprises of highly volatile substances. The process however has the merit of being relatively less harmful to health as indicated by the I_{HH} value. The analysis of the advantage and disadvantage of each process is illustrated by the average I_{PPH} and I_{HH} index in Fig. 1.

7.3.3. Worst case-type IOHI calculations

According to the worst case-type approach, the route index is a summation of the maximum subindex penalties of the route. The highest penalty of each subindex is taken to represent the worst potential hazard of a process. E.g. for the ACH route, the I_{MS} penalties are 2, 3, and 3 (Table 5). For the IOHI calculation of this route, the maximum I_{MS} penalty of 3 is considered. This may avoid the same 'worst chemical' in different subprocess to be penalized repeatedly.

As presented in Table 8, the most harmful routes are the C2/PA and the C3. The ACH, C2/MP, and i-C4 have the same I_{IOHI} index value of 18. Interestingly, all of them poses different level of health and exposure hazard. The ACH has the highest I_{HH} index value of 8,

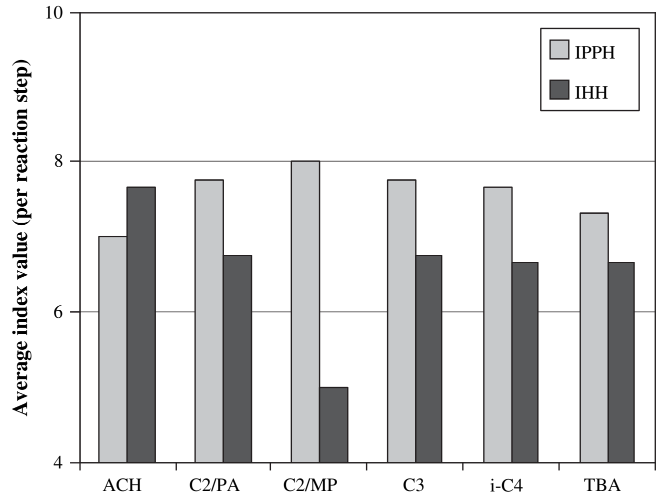

Fig. 1. The average I_{PPH} and I_{HH} values for MMA routes.

followed by i-C4 of 7 and C2/MP of 6. For the I_{PPH}, the processes have an opposite outcome with the C2/MP has the highest index value of 12, followed by i-C4 of 11 and ACH of 10. The reason for these results is as already being discussed in the 'average-type' section. In this approach, now the TBA route is ranked as the healthiest process. The reason is the low I_{PPH} index value due to low volatility, pressure, and corrosion subindex values. The TBA route has however comparable health hazard level to the i-C4 and C3 routes (see Fig. 2).

7.3.4. Comparison between the results

Here, the results obtained through the three different types of the IOHI calculations are compared. It is found that the additive- and average-types seem to give better resolution between routes compared to the worst case-approach. In terms of the I_{PPH} and I_{HH}, all the three approaches show unique characteristics of the processes. Overall, the results of these calculation types indicate the C2/MP and TBA as routes with lower health hazard level. The C2/PA and C3 are the most harmful routes according to the additive-type calculation (partly because of larger number of steps). Also in the worst case calculation these routes are the most hazardous. However the averaging calculation suggests the ACH as the most harmful one with only a small difference in index values compared to the two routes.

Each approach has ways in revealing the potential health hazards from different angles, e.g. the additive-type shows how complexity of a process affects the hazards level; the average-type reflects the average hazard of route steps; and finally the worst case-type exposes the worst side of a process from inherent healthiness aspect. If the influence of number of process steps is not emphasized, the averaging and worst case calculation approaches are preferable as they give better analysis of the route characteristics. Different ways of calculation reflect the healthiness level of the alternatives from different perspective as earlier discussed.

Table 7
The Inherent Occupational Health Index values for MMA routes (average-type).

Route	Average I_{PPH}	I_{PPH} rank	Average I_{HH}	I_{HH} rank	Average I_{IOHI}	I_{IOHI} rank
ACH	7	1	7.7	6	14.7	6
C2/PA	7.75	4–5	6.75	4–5	14.5	4–5
C2/MP	8	6	5	1	13.0	1
C3	7.75	4–5	6.75	4–5	14.5	4–5
i-C4	7.7	3	6.7	2–3	14.3	3
TBA	7.3	2	6.7	2–3	14.0	2

Ranking 6, posses the worst case.

Table 8
The Inherent Occupational Health Index values for MMA routes (worst case-type).

Route	Max. I_{PPH}	I_{PPH} rank	Max. I_{HH}	I_{HH} rank	Max. I_{IOHI}	I_{IOHI} rank
ACH	10	2	8	5–6	18	2–4
C2/PA	12	4–5	8	5–6	20	5–6
C2/MP	12	4–5	6	1	18	2–4
C3	13	6	7	2–4	20	5–6
i-C4	11	3	7	2–4	18	2–4
TBA	9	1	7	2–4	16	1

Ranking 6, posses the worst case; Max, maximum subindex penalty in a route.

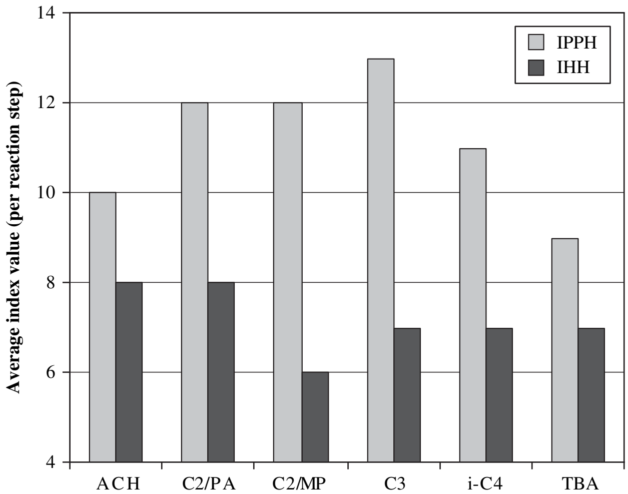

Fig. 2. The 'worst' I_{PPH} and I_{HH} values for MMA routes.

8. Standard setting for the Inherent Occupational Health Index

Generally, an index is developed to link typical findings of risk analysis to scales of risk. The scales in turn, provide workable measures of hazards. Even though index-based method has many advantages and is being widely accepted for usage in a decision-making process, it has a limitation. Since the index value is meaningless as an absolute number, the index is somehow dysfunctional for users who intend to determine the level of the inherent occupational health hazard of their individual process, without the interest of performing any comparison (ranking) assessment. By providing the standard for the index, the index is applicable to determine the level of occupational healthiness, which is a task typically needed in the evaluation of existing plants.

To allow quantitative evaluation of occupational healthiness, as shown in Table 9 an IOHI standard was created to have four categories: safe, moderately safe, moderately hazardous, and hazardous. The standard was set up based on the penalty of the subindexes. As previously mentioned, a higher penalty represents a higher degree of hazard or probability for exposure. Therefore, for the 'safe' category, the standard was set up by summing up all subindexes penalty between 0 and 1. Depending on the subindexes, penalty between 1 and 2 was totaled up for the 'moderate' category which is further refined into moderately safe and moderately hazardous, and penalty between 2 and 5 was added up for the 'hazardous' category.

The scales as in Table 9 are readily used in the average-type or worst case-type calculations. To demonstrate the application, it was applied on the same case study. For the additive-type index calculations, the route index value has to be divided by the number of steps in the route. The results are presented in Table 10. It can be seen that all the routes can be categorized on average as moderately hazardous to health and they are even close to hazardous region except for the C2/MP route. However some subprocesses (such as the C2/PA second subprocess) can be categorized as hazardous (see Table 5) and the C2/MP second subprocess is the only one that is moderately safe, but none is classified as 'safe'.

Table 9
IOHI standards.

Category	I_{IOHI} scales[a]
Safe	0–7
Moderately safe	8–11
Moderately hazardous	12–15
Hazardous	16–26

[a] Per reaction step.

Table 10
Assessment results based on standards for MMA routes (for additive calculation).

Route	No. of steps	Route I_{IOHI}	I_{IOHI}/step	Status
ACH	3	44	14.7	Moderately hazardous
C2/PA	4	58	14.5	Moderately hazardous
C2/MP	3	39	13.0	Moderately hazardous
C3	4	58	14.5	Moderately hazardous
i-C4	3	43	14.3	Moderately hazardous
TBA	3	42	14.0	Moderately hazardous

9. Conclusions

Occupational health aspect, even though is less researched from process engineering point of view, it is at least as important as process safety because each year more people die from work-related diseases than are killed in industrial accidents. Therefore, it should always be evaluated alongside the other criteria to accomplish a comprehensive chemical process route assessment.

Inherent occupational health strives to eliminate or reduce the occupational health hazards by trying to eliminate the use of hazardous chemicals, process conditions, and operating procedures that may cause occupational hazards to the employees. Similar to process safety, the concept of inherent occupational safety and health has to be applied in every phase of a process lifecycle. The benefits are greater if the concept is incorporated as early as possible, especially during the early design stages. Formal assessment and ranking methodologies are needed to fulfill this task.

The Inherent Occupational Health Index has been proposed in this paper, to allow the occupational health evaluations to be already made early in the process R&D phase. The main difficulty in this phase is the scarce availability of information on the process. Therefore the method has been tailored for the information available in the R&D stage namely process conditions and health properties of chemicals. The subindexes cover the following aspects; process mode, temperature, and pressure as well as chemical's material state, volatility, corrosiveness, threshold limit value, and R-phrase.

The index can be calculated in different ways; either as an additive-type index, or analyzed averagely or based on worst case approach. The case study done revealed that the results of an additive type of index calculation are much affected by the number of steps in the route. In additive calculation the routes with more steps usually get worse index values. Therefore the averaging and worst case calculation approach allows better analysis of the route characteristics than the additive calculation, which mostly reflects the process complexity.

A quantitative scale for the index was developed for the index by setting up four categories of process hazard status – safe, moderately safe, moderately hazardous, and hazardous. The quantitative 'standard' is useful in estimating the level of healthiness of e.g. existing processes without aiming to rank different alternatives.

The case study revealed that all the MMA routes are moderately hazardous based on averaging calculations. Nearly all sub processes are moderately hazardous also, except the C2/PA second sub process, which can be categorized as hazardous. Even though the routes do not differ very much from total occupational health point of view, the subindex analysis reveals that the sources of risk may be completely different. For example the ACH has most risks in toxicity of chemicals whereas the C2/MP route has dominantly process related risks. This information is valuable in the occupational heath risk reduction.

Further development of the evaluation methods is directed towards creating more elaborate dedicated methods for later design stages such as process predesign and basic engineering.

Table A.1
Example of I_{IOHI} calculation for TBA second subroute.

Route (TBA)					Tert-butyl alcohol based						Step 2
$2CH_2CCH_3CHO$ (Methacrolein) + O_2 (Oxygen) → $2CH_2CCH_3COOH$ (Methacrylic acid)											Phase gas
Operating condition (process)											
Factor					Condition						Penalty
Temperature (°C), I_T					350						**3**
Pressure (bar), I_P					3.7						**0**
Physical property (material)							Health property (material)				
Substance	Material state	I_{MS}	Boiling point (°C)	I_V	Construction material	I_C	R-phrase (R)	I_R	OEL (ppm)	I_{EL}	
Methacrolein	Liquid	2	68	1	Stainless steel	1	R 23/24/25-34	4	8	3	
Methacrylic acid	Liquid	2	161	0	Stainless steel	1	R 21/22-35	4	20	2	
Maximum Penalty Selected		**2**		**1**		**1**		**4**		**3**	
Total subroute I_{IOHI}: **14**											

Appendix. Example calculations

The TBA subroute-2 is used to demonstrate the index calculations. In this reaction step, methacrylic acid is produced with methacrolein and oxygen act as the raw materials. This gas phase reaction takes place at 350 °C and 3.7 bar.

The calculations of the IOHI are made on the basis of the worst chemical situation. As described in Sections 6.2 and 6.3, the penalty for the temperature- and pressure-based subindexes (I_T and I_P) is determined from the reaction's temperature and pressure. Process mode subindex (I_{PM}) is evaluated only once for the whole TBA process route. The maximum penalty received by any substance in the reaction step gives the penalty value of the other subindexes. For example, in the TBA subroute-2, the 8-h exposure limits for methacrolein and methacrylic acid are 8 ppm and 20 ppm, respectively. Oxygen is a non-toxic gas. The corresponding penalty value of the I_{EL} is 3 for methacrolein and 2 for methacrylic acid. For calculating the index of this subroute, I_{EL} value of 3 is taken, which is the maximum penalty received by a substance in this subroute (bold in the form above). As for the R-phrase-based subindex (I_R), only the highest penalty received by the substance is considered to represent the I_R of the substance even though some substances are labeled with more than one R-phrase. For example, penalty 4 is taken to represent the I_R for methacrylic acid (R35 is underlined in the form above). Consequently, the I_R value of the subroute is determined based on the same concept as described for the I_{EL}.

The index calculation steps and the selection of the 'worst chemical' are summarized in the index calculation form above (Table A.1).

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