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A Heuristic Framework for Process Safety Assessment during Research and Development Design Stage

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Process safety assessment is one of the most powerful approaches that can be used to communicate the strategies of hazard identification as well as risk assessment in the chemical process industry. Process safety has been introduced decades ago. Its importance and needs have become more obvious due to the constant increase of plant operation scales in the process industries. The increasing scale of process plant can be especially dangerous due to the presence of additional or higher magnitude of hazards. Between years 1996 and 2014, study shows that there are various methods that have been developed for the assessment of process safety including qualitative, quantitative as well as the combination of both. Despite the availability of an enormous number of methods, there is no detailed guideline on how to select which is the most suitable one that suits the scope, nature, interest and constraint of the assessment. This has led to slow adoption of detailed assessment (especially inherent safety) among industries, which based on the survey, have responded that too complicated methods have discouraged them from using the available methods. This is especially critical during the process design phase since not much information is already available. The best time to apply process hazard analysis is during research and development (R&D) design phase due to cost and time constraint. The main purpose of this study is to develop a framework for safety assessment in the R&D design phase of chemical processes. The framework was developed based on two aspects - (i) the methods screened to be suitable to be included in the framework and (ii) the specific stages in the design phase itself. This is important since different stage offers different type and amount of process information. Different method also requires a different type of information for the assessment. A simple case study is presented to demonstrate the application of the proposed framework.

1. Introduction

In today's world, chemical process industries play an important role in human life. They contribute in many parts of human life to make it easy to live and to increase the standard of living by producing variety of products. The raw materials of chemical industries are derived from various sources such as mines, forests, land, oil and gas. Thus, the processed chemicals will be used in many industries to improve or preserve. On contrary, increasing the applications of chemicals could give rise to negative impact in case where appropriate hazard and risk management is not practised during process design stage. A lack of proper control can result in an accident with serious consequences to workers, public as well as the environment. It shows that, safety is a key role in industry in order to provide a more benign workplace for workers. In that event, process safety management systems (PSMS) was introduced which played a large role in helping to lower the incidence of unexpected releases and other accidents at chemical facilities. It can be expressed as strategies of hazard identification and analysis, risk assessment and evaluation, safety measures and safe critical decision making. A systematic and extensive assessment of the safety hazards towards chemical process industries must be studied and assessed profusely. Until now, there are many methods and approaches have been proposed for quantify safety level in chemical process industries.

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This can be seen from the study was carried by the Khan and Abbasi (1998) that based on review of 62 methodologies in evaluating risk and their advantages and disadvantages. In their study, a comparison also was made between indexes in order to identify which index more accurate in ranking various units of a chemical process industry on the basis of the hazards of accident fires, explosion and toxic release. According to Khan et al. (2015) from year of 1996 to 2014 a varieties of safety assessment methods were introduced which includes of qualitative, quantitative as well as combination of these. There are lacks on how to use each of safety assessment method based on certain scenario. The important part in assessing and quantifying safety is availability data information at early of design stage such as chemical and physical data properties. Each of design phases would produce different information. For instance, piping and instrumentation diagram (P&ID) may generate from basic engineering phase but not in preliminary design phase. For that case, a comprehensive safety assessment method would be selected such as Hazard and operability study (HAZOP) in the light of ability to detect errors up to 95 % of errors from P&ID as stated by Taylor (2007). This shows that, the selection of safety assessment method is based on collected input data. The main purpose of this study is to develop a comprehensive framework for safety assessment in R&D design phase. It is inevitable that; this framework also would guide user to choose an appropriate method based on their situation. This is highly important due to many methods would be produced in future. Apart from that, by developing a heuristic framework that act as guideline, it would minimise or eliminate any hazard that may arise during process design stage. The term heuristics can be referred as method of teaching which allowing users to learn by discovering things themselves and learning from their own experiences. By using the proposed framework, the users will be assisted in selecting the most appropriate method for assessment, according to their needs and constraints, and hence gaining the most benefits from the assessment conducted. It can expedite duration of the project directly and give benefit to analyser indirectly. This work is more focused more on index based approaches in conducting safety assessment. This is because, an index based method is the most common techniques used in assessing the level of safety of chemical process during its design phase. Quantitative indices basically provide numerical value as their outcomes. The selected design phases in this study are chosen due to highest opportunity for carrying safety assessment as discussed by Hurme and Rahman (2005) in their work.

2. Literature Review

Literature review on the available safety assessment during chemical process design stage and concept of inherently safer design were studied as the background in this work. As stated previously, this study more concentrated on R&D design phase only due to the limitation of pages. A comprehensive study on all design stages must be performed profusely in order to screen the most appropriate method to suit each design stage.

2.1 Review on Evaluation Safety Assessment during Chemical Process Design Stage

In the research and development (R&D) phase, the process concept further developed. As a new project is started, the chemical process route for synthesising the desired product is selected. The process of developing process route is based on experimental or modelling data. In this step, the process concept from laboratory to pilot plant is developed. The selection of chemical process route is based on three main characteristics which are yield, product quality as well as safety. For safety aspect, there are potential hazard to be occurred in process chemistry as well as reaction system. Based on this problem, safety assessment could be carried briefly by using Safety Checklist as well as What-If analysis. Basic Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) are also applicable at this design phase (Rahman et al., 2005). Besides that, there are numbers of inherent safety indices are introduced. Among the available safety indices, the most common ones are PIIS (Edwards and Lawrence, 1993) and i-Safe (Palaniappan et al., 2004) since these methods can be used to assess the reaction system.

The second phase of the process design is preliminary process design stage where material and energy balance for the process are calculated and flow sheet diagram is generated. In regard to safety concern, there are some common design errors to be occurred such as process equipment is failed to operate at optimum condition due to error in process condition. Based on this problem, safety assessment could be carried briefly by using Safety Checklist as well as What-If analysis. Basic Fault Tree Analysis (FTA) and Event Tree Analysis (ETA) are also applicable at this design phase (Hurme and Rahman, 2005). Apart from that, a number of inherent safety indices are introduced in this phase in order to assess the inherent safety level of the chemical processes. Inherent Safety Index (ISI) proposed by (Heikkila, 1999) and Integrated Inherent Safety Index (I2SI) introduced by (Khan and Amyotte, 2004) are most common inherent safety indices used due to more information generated at this stage (Kidam et al., 2016). The information that generated during this phase can be simulating by using process simulator such as HYSYS which can be used in evaluating the safety level of the chemical processes by using inherent safety indices. For example, Integrated Risk Estimation Tool (iRET) (Mohd Shariff et al., 2006), Inherent Safety Index Module (ISIM) (Leong and Shariff, 2008), Inherent Risk Assessment (IRA) (Shariff and Leong, 2009) are tools that mostly used in this phase, which able to interact with process simulator.

The third phase is basic engineering design phase where a plant construction is produced from available data during this phase. The very important outcome generated from this phase is Piping and Instrumentation Diagram (P&ID) as well as the equipment process datasheets. As stated Kidam et al. (2015) in their study, the most critical design errors that usually occurred during this phase are materials of construction, protection system, utilities set-up and equipment sizing. Most of safety methods that proposed by researchers is focused on these problems. Among frequently used methods are the Hazard and Operability study (HAZOP), Failure Mode Effect Analysis (FMEA), MOND Index, Fire and Explosion Index (F&EI) and Chemical Exposure Index (CEI).
The last design phase was studied is detailed engineering phase. The main objective in this phase is to convert all documents and drawing for construction as well as commissioning. The most common errors to be occurred during this phase are poor layout, unsuitable parts and components as well as insufficient work instructions or poor standard operating procedure (SOP). Existing safety methods in this phase are checklist, What-if, FTA, FMEA and HAZOP.

2.2 Inherently Safer Design Concept

Inherently safer design (ISD) was introduced by Kletz (1991) which acts as proactive approach for hazard and risk management during process plant design and operation. Table 1 shows the several key designs strategies in Inherently Safer Design (ISD). The main purpose of these principles is to eliminate hazards by altering the design by using less hazardous chemicals, simpler equipment design as well as safer operating conditions.

Table 1: Main Principles of Inherent Safety (Kletz, 1991)

Principles	Explanation
Intensification	Reduction of the inventories of hazardous materials
Substitution	Change of hazardous chemicals by less hazardous chemicals.
Attenuation	Reduction of the volumes of hazardous materials required in the process. Reduction of operation hazards by changing the processing conditions to lower temperatures, pressures of flows
Limitation of Effects	The facilities must be designed in order to minimise effects of hazardous chemicals or energies releases.
Simplification	Avoidance of complexities such as multi-product or multi-unit operations, or congested pipe or unit settings.
Error Tolerance	Making equipment robust, processes that can bear upsets, reactors able to withstand unwanted reactions.

This inherent safety concept would be applied by engineers especially design and process engineer in designing process in order to make it process in safer condition. A study carried out by Mansfield et al. (1996) stated that, the lack of experience as well as understanding of the inherent safety principles are the critical problems to the implementations of this safety philosophy. This is one of the reasons this study is carried out which to produce framework which able to guide users in utilising these principles. A simple case study is presented to illustrate these principles in the proposed framework.

3. Research Methodology

The systematic planning of the development of framework is discussed and interpreted in this section. The main objective of this study is to produce a heuristic framework for process safety assessment in R&D design stage. In order to achieve this objective, a well-ordered step is constructed which start from reviewing and classifying the available process safety assessments methods to the stage of demonstrating the framework on simple case study.

3.1 Identification of the Existing Process Safety Assessments.

The first stage of designing this framework is identification of the existing process safety assessment. In order to develop framework for safety assessment in chemical process design, it is important to go through all the previous that have been done related to process safety assessment. The data collection is conducted by identifying the available safety assessment that used during chemical process design.

3.2 Analysing of Selected Methods Process Safety Assessment.

After a series of investigation are conducted on previous studies, there are methods that seem more suitable to integrate for produce a framework. In this phase of analysing, there are two criteria that are taken into account which are types of method, and safety parameters in each of the methods. After all methods are collected in stage 1, research is continued by classifying methods according to the types of assessment. The methods are categorised as qualitative as well as quantitative analysis. By classifying according to types of analysis, it will easier to sort each of methods as well as developing process of the framework. Identification of the safety parameters used in each of method is a crucial part in this stage. This is because each of parameter to be assessed is directly related to the information available in R&D design stage.

3.3 Development of the Heuristic Framework.

The next stage is to develop a framework to quantify the level of safety in R&D design stage. The framework is formed according to design stages by focusing on method assessment (quantitative) and qualitative methods as alternative ways to assess safety level in chemical process design phase. All selected quantitative methods are grouped based on stages of process design.

4. A Heuristic Framework of Safety Assessment

The main objective of this work is to produce guideline for user mainly process engineer in conducting safety assessment in their design stage which reflect to research and development (R&D) design stage. Figure 1 shows a clear picture how the actual a proposed framework which consists of safety assessment methods and their strategies for minimisation of hazards or risks which based on inherent safer design (ISD) keywords. It can be seen from the Figure 1, the whole assessment starts with identifying the availability of process information. All input data generated from R&D phase can be fully utilised to identify hazard, quantify safety level and rank the associated process chemistry. The index based approaches are adopted to assess safety in selecting the safer process route at acceptable process condition (i.e., temperature and pressure). Each of the methods has different parameters to be analysed but same outcomes would be produced. In a case where there are insufficient input data to carry out an assessment, hence there are an alternative way to conduct safety assessment by performing what-if analysis and checklists. Here, hazard can be identified by combining the creative thinking of a selected team of specialist with knowledgeable in process chemistry fields. For all methods, the calculated index values and hazards will be compared with the respective benchmark. If the value of calculated index is not acceptable, four ISD keywords (minimisation, substitution, moderation and simplification) are take-over to reduce or eliminate the hazard as much as possible. A study carried out by Gupta and Edwards (2003) has revealed that the best time to apply ISD concepts is at the initial R&D. this is because if any changes have been made, it required low cost and time. Finally, the re-assessment of hazards can be performed until the index values and all hazards at acceptable range. A simple case study and their improvement strategies are discussed in the following section.

4.1 Case Study: Minimisation of safety hazard based on the availability of information at R&D Design Phase

The proposed framework is demonstrated by using a simple case study for assessing the safety hazards of chemical process during the R&D Stage. Since neither PFD nor P&ID is available, the alteration of the process parameters or the replacement of materials can be easily made at this early design stage. In a case where inherent safety index (ISI) is chosen, it composes of sub-index for chemical inherent safety index, I_{CI}, and sub-index for process inherent safety index, I_{PI}, as proposed by Heikkilä (1999). The calculation of the I_{CI} sub-index is calculated by summing up the penalties score received by all the seven parameters of I_{CI}. Next, the sub-index for I_{PI} is quantified by adding all the five parameters of I_{PI}. The detailed sub-indexes of the I_{CI} and I_{PI} can be referred to the original work of Heikkilä (1999). The ISI values of each reaction step are then calculated. The value of ISI is acceptable as long as the minimum value of ISI is obtained. In a case where the calculated ISI values are not acceptable, reduction of index value can be reduced based on ISD concept. For the chemical aspect side, minimisation can be applied by reducing the concentration of the hazardous compound with continuous monitoring. This particular reduction can help in minimising the parameters of toxicity I_{TOX}. Substitution of less flammable or corrosive materials can be applied to reduce ISI value by reducing the parameters of flammability, I_{FL}, as well as corrosiveness, I_{COX}. For process aspect side, moderation can be utilised by reducing the low reaction temperature and pressure as well. As a result, the index for temperature, I_T, and pressure, I_P, can be minimised. From simplification perspective, unnecessary reaction steps to produce desired product could be eliminated. The index for heat of side reaction, IRS can be decreased or diminished. This is not only simplifying the reaction steps but also eliminate the hazards associated with it. For some cases where there is insufficient information to be analysed, hazards survey could be performed by using what-if analysis. As mentioned previously, expect team should play their role to perform safety assessment. The team will be provided basic information on hazards materials, incident experiences as well as previous hazards review. The review team starts to generate a list of what if questions regarding the hazards. When the review team has completed listing of questions, simultaneously answers are developed for each question. Finally, a listing of recommendations is developed for further action. These recommendations become the main elements in hazard assessment report.

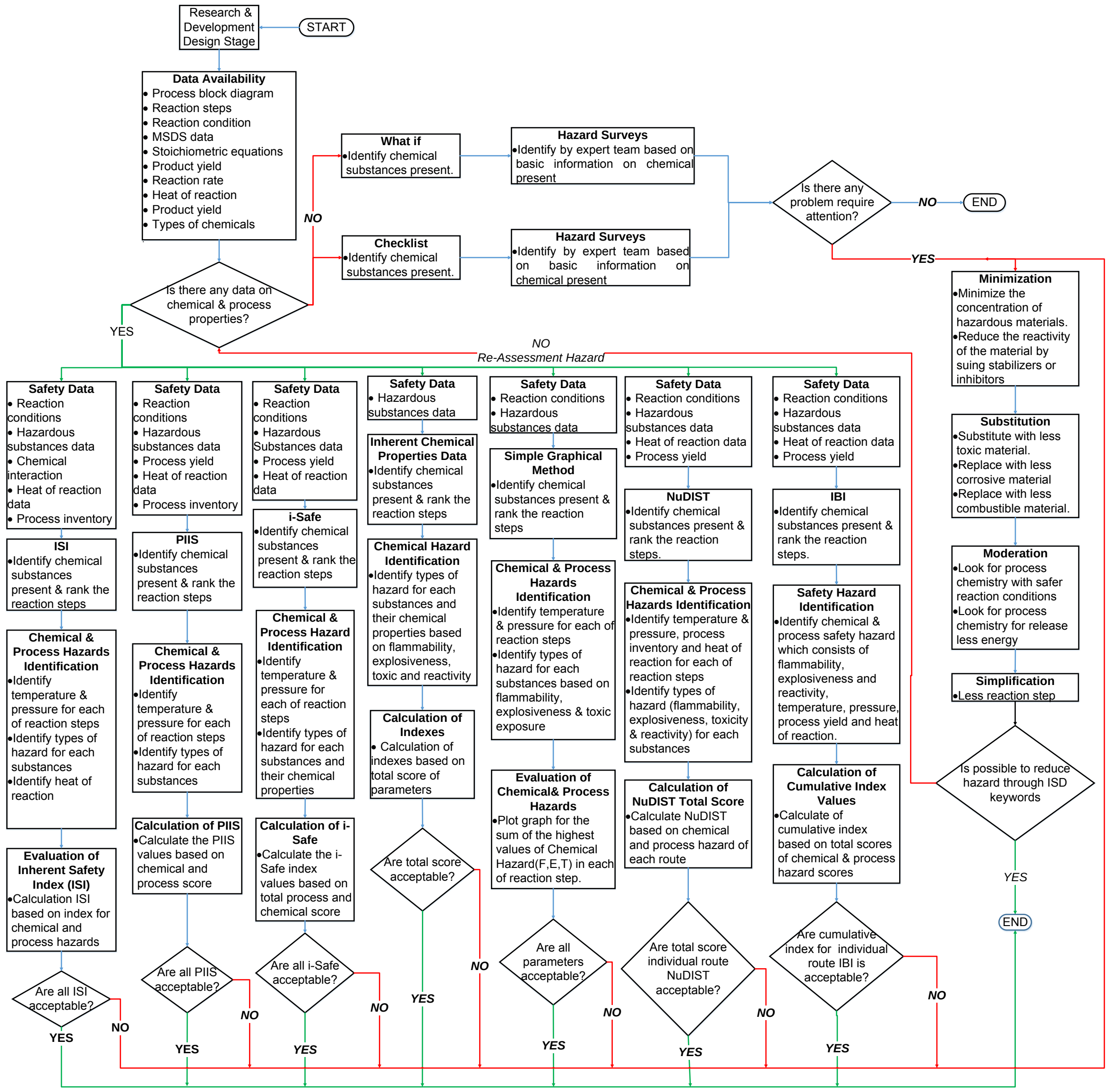

Figure 1: A heuristic framework for safety assessment during Research and Development (R&D) design stage

5. Conclusions

The proposed framework is assumed to be utmost beneficial to guide users on how to conduct process safety assessment based on availability of process information at the research and development (R&D) stage of process design. This framework has revealed that selection of appropriate safety assessment method is based on available information in R&D design stage which refer to the properties of the chemicals present and the process conditions. Reduction of hazard can be done by applying inherently safer design (ISD) after performing safety assessment. To enhance applicability of proposed framework, the PFD, P&ID and detailed plant layout can be included in the future works in order to extend this framework which covers all chemical process design stages.

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