A COMPREHENSIVE GUIDELINE FOR RISK ASSESSMENT AND MITIGATION STRATEGIES DURING PRELIMINARY DESIGN STAGE

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ABSTRACT

A conventional process design lifecycle starts with a screening process of alternative chemical reaction pathways until the detailed design of the entire plant. During the design of the process, mainly the flow diagram of the process, errors may arise due to wrong decisions and basis made, which will later cause problems to the following stages of the process lifecycle. Despite the availability of various methods, a proper detailed framework which guides users in selecting the appropriate method for their assessment is still missing. Therefore, this paper aims to address the above issue by proposing a systematic framework for safety assessment based on process information generated from PFDs during the preliminary design stage. The research on R & D and basic engineering design is currently on-going to develop the entire framework and will be presented in other papers. Technically, the framework is developed based on the methods screened to be suitable for application within the PFD-based context. The framework also provides recommendations on the strategies for reducing the safety hazard and risk in the process in the respective design stage. A case study on process design of biorefineries is conducted to illustrate the functionality and benefit of the proposed framework

Keywords: process flow diagram (PFD), safety assessment, safety index, systematic framework, safety hazard and risk

1.   INTRODUCTION

In recent times, the chemical industry has undergone rapid growth resulting from its versatility in creating an immense variety of domestic products. Regrettably, users are more susceptible to the hazards from this industry. There are three major hazards that usually occur which can cause loss of life, damage to property and the environment which are fire, explosion and toxic release. Apart from that, the expansion numbers of this industry may create a large number of accidents. The study by Khan and Abbasi [7] concluded that the increase in numbers of chemical processing plants have been accompanied by an increase in the probability of the accidents. Furthermore, 79% of accident cases in the chemical industry are caused by design errors [10]. The preliminary design stage is shown in the study by Kidam et al. [9] to contribute to about 21% of the design failure in such industrial accidents. In addition to that, an essential document is produced during the preliminary design stage which is the process flow diagram (PFD). The PFD contains the bulk of data necessary including equipment (process condition), material as well as energy balances for the design of a chemical process. Therefore, it is possible for designers to make some errors during calculations or basis made. Furthermore, according to Kletz [11], most of designers make errors because they have a limited time to check it. As a result, there are many methods and approaches that have been proposed for safety level in chemical process industries as stated by Khan *et al*.[8]. In this study based on comprehensive

literature review 13 process safety assessment methods are deemed to be suitable and commonly used in analysing inherent safety for preliminary design stage which use PFD as input data during the assessment, as summarized in Table 1. The details on characteristic for each assessment methods are discussed in the following section.

Table 1: Selected Safety Methods during Preliminary Design Stage.

Method	Type of Assessment	Hazard to be assessed	Outcome of Assessment	Developed by
Inherent Safety Index (ISI)	Semi-Quantitative	Fire, Explosion and Toxic Release	Hazard Determination	Heikkila [4]
i-Safe	Semi-Quantitative	Fire, Explosion and Toxic Release	Hazard Determination	Palaniappan, Srinivasan, Tan [15]
Toxic Release Route Index (TRRI)	Semi-Quantitative	Toxic Release	Hazard Determination	Zaini, Shariff, Leong [22]
Toxic Release Stream Index (TRSI)	Quantitative	Toxic Release	Hazard Determination	Zaini, Shariff, Leong [22]
Inherent Safety Index Module (ISIM)	Quantitative	Fire and Explosion	Hazard Determination	Leong, Shariff [12]
Process Route Index (PRI)	Quantitative	Fire and Explosion	Hazard Determination	Leong, Shariff [12]
Process Stream Index (PSI)	Quantitative	Fire and Explosion	Hazard Determination	Shariff, Leong, Zaini [17]
Integrated Risk Estimation Tool (IRET)	Quantitative	Fire and Explosion	Hazard Determination	Shariff, Rusli, Leong,Radhakrishnan, Buang [14]
Toxic Release Consequences Analysis Tool (TORCAT)	Quantitative	Toxic Release	Hazard Determination and Consequence/Probability Estimation	Shariff and Dzulkarnian [2]
Inherent Fire Consequences Estimation Tool (IFCET)	Quantitative	Fire and Explosion	Hazard Determination and Consequence/Probability Estimation	Shariff, Wahab [18]
Inherent Risk Assessment (IRA)	Semi-Quantitative	Fire and Explosion	Hazard Determination and Consequence/Probability Estimation and Risk Determination	Shariff, Zaini [19]
Toxic Release Inherent Risk Assessment (TRIRA)	Quantitative	Toxic Release	Hazard Determination and Consequence/Probability Estimation and Risk Determination	Zaini, Shariff, Leong [22]

Graphical Inherent Safety Assessment Techniques (GISAT)	Quantitative	Fire, Explosion and Toxic Release	Hazard Determination and Consequence/Probability Estimation and Risk Determination	Ahmad, Hashim, Hassim [21]

The abovementioned research works show that different methods will give a variance in terms of types of assessment, input data properties as well as target of assessment. Therefore, an appropriate framework is needed to guide users in selecting the most appropriate method for performing their safety assessment during design stages based on the data availability generated from PFD, target of assessment as well as accuracy expectation on final results.

2.   METHODOLOGY

Before presenting the established framework, the following sub-sections provide a brief overview of the systematic organisation of the study. The overall methodology is presented in Figure 1, which extends from reviewing and classifying the available process safety methods to the stage of demonstrating the framework on the case study.
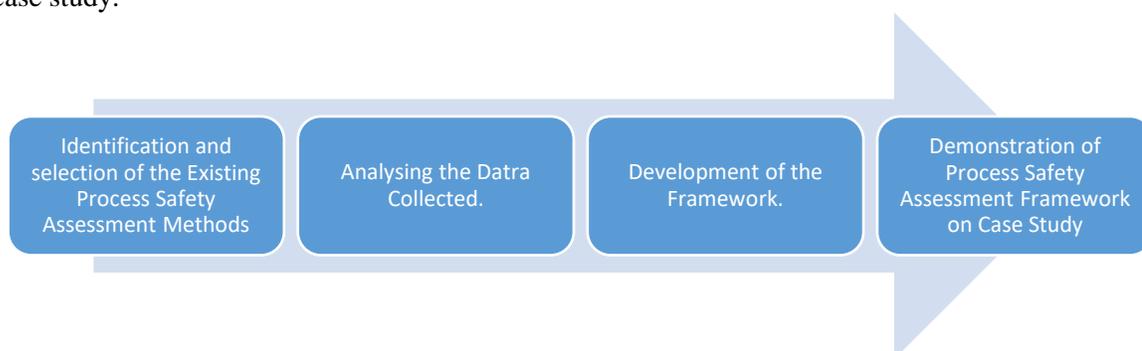

Figure 1: Overall Research Methodology Steps.

2.1   identifying and analysing selected safety assessment method

The second process information data to be considered for early assessment during the early process design stage is PFD. There are 13 methods to be chosen by users in analysing hazard levels of unit operations as more process data are generated from the PFD. All 13 methods have capability in utilising all information pertaining to operating conditions, inventories and flows of material substances in the process. All thirteen methods are allocated based on two types of data generated from PFD which are process layout (without simulation data) and process simulation data as shown in Table 2.

Table 2: Information (parameters) used in Safety Index Methods

Safety Data Needed		a	b	c	d	e	f	g	h	i	j	k	l	m
Process Condition	Temperature	x	x			x			x	x	x	x	x	x
	Pressure	x	x	x	x	x	x	x	x	x	x	x	x	x
MSDS	Lower/Upper Explosion Limit (UEL-LEL%)	x							x					
Inventory	Mass & Energy Balances	x	x	x	x	x	x	x	x	x	x	x	x	x
Equipment or Unit Operation	Preliminary Sizing Equipment	x	x											
Process Safety Simulation Data	Heating Value						x	x						
	Average Density			x	x		x	x						
	Toxicity Level (TL)			x	x									
	ΔFLmix						x	x						
	Heat Capacity											x	x	

a)ISI b)i-Safe c)TRRI d)TRSI e)ISIM f)PRI g)PSI h)IRET i)TORCAT j)IFCET k)IRA l)TRIRA m)GISAT

Based on process layout, there are 3 out of 13 methods (ISI, I-Safe and GISAT) to be selected by users in evaluating the safety level either for the whole process or for a particular process unit. The ISI, GISAT and i-Safe methods in this stage are extended in their ability in assessing hazard levels of process stream to unit operations. The total index calculated for both methods is used to rank the process units or the whole process. However, there are some differences in parameters to be assessed between these methods where the ISI method has the capability in assessing the process structure which refers to the configurations of process units in the particular process. Additionally, the ISI method also has the ability in measuring the possibility that a piece of equipment is unsafe. Other parameters to be quantified by ISI method are similar to the i-Safe method.

Meanwhile, the other 10 methods use process simulation data as indicator in their assessment. Specifically, there are three outcomes that can be obtained through simulation data which include i) process stream or route ranking ii) consequences of unwanted events iii) probability of death or unwanted events. There are 5 out of 10 methods which are capable in ranking the process stream or route namely ISIM, PRI and PSI which focus on explosion hazards, whereas TRRI and TRSI target on toxicity hazards only. Meanwhile, the others five methods (IRET, TORCAT, TRIRA, IRA and IFCET) can be grouped in two by function. Four methods are used for both probability and consequences of accident determination and one method can be used for consequences of accidents only. Specifically, there are two methods capable in quantifying the probability of death which are IRET and TORCAT, whereas TRIRA and IRA are formulated for the probability of unwanted events. However, the types of hazard to be assessed by these four methods are is significantly different, in which IRET and IRA are formulated for the determination of the consequences resulting from the explosion event. In contrast, TORCAT and TRIRA are tailored to estimate the consequences arising from toxic release. Furthermore, there are two types of fire and explosion scenarios that can be assessed based on simulation data through the IFCET method which are pool fire and the BLEVE model. This method is developed to estimate the potential consequences of BLEVE and pool

fire scenarios. Overall, the assessment from the thirteen methods was extended from process chemistry to also cover unit operations in the particular process to be evaluated. From Table 3 the results indicate that by using data from PFD and process simulation the user is able to rank the process stream and estimate the consequences and probability of unwanted events.

Table 3: Characteristics of Selected Methods for PFD Assessment

Method	a	b	c	d	e	f	g	h	i	j	k	l	m
Type of Method													
Quantitative			x	x	x	x	x	x	x	x	x		x
Semi Quantitative	x	x										x	
Type of Ranking													
Process Stream Ranking	x	x	x	x	x		x	x	x	x	x	x	x
Process Route Ranking	x	x				x							
Unit Operation Ranking	x	x											
Outcome of Assessment													
Hazard Determination	x	x	x	x	x	x	x	x			x	x	x
Consequences or Probability Estimation								x	x	x	x	x	
Risk Determination											x	x	

3.   HEURISTIC FRAMEWORK FOR PROCESS SAFETY ASSESSMENT

Following the proposed research methodology in the previous section, a systematic framework which comprises of selected safety assessment methods as well as their strategies for minimisation of hazards or risks based on inherent safer design (ISD) keywords is presented in Figure 2. First, users need to identify and select the particular process stream, process route or unit operation to be assessed (it can also be more than one) before performing the assessment. Next, all data needed for the assessment on chemical substances or process will be collected and analysed. The typical process information from the chemical process can be indicated as three types of chemical substance properties (MSDS), process flow diagram (PFD) data, and piping and instrumentation diagram (P&ID) data according to the design stage as discussed earlier. As shown in Figure 2, the first data to be considered are chemical properties and process condition data followed by the PFD and the P&ID data. In a case where chemical properties and process condition data (MSDS) for the particular chemical substance is not available, searching for safety data must be repeated. The reason is to provide missing information needed using information from similar nature of the processes or chemicals with what the users are assessing that can be used instead. The term 'missing information' means that the required information is not found in the MSDS. For instance, if data on the stability of hydrochloric acid is not available, then the stability data from the similar group of this acid such as nitric or sulphuric acid can be used since these acids are categorised as the strong acids group.
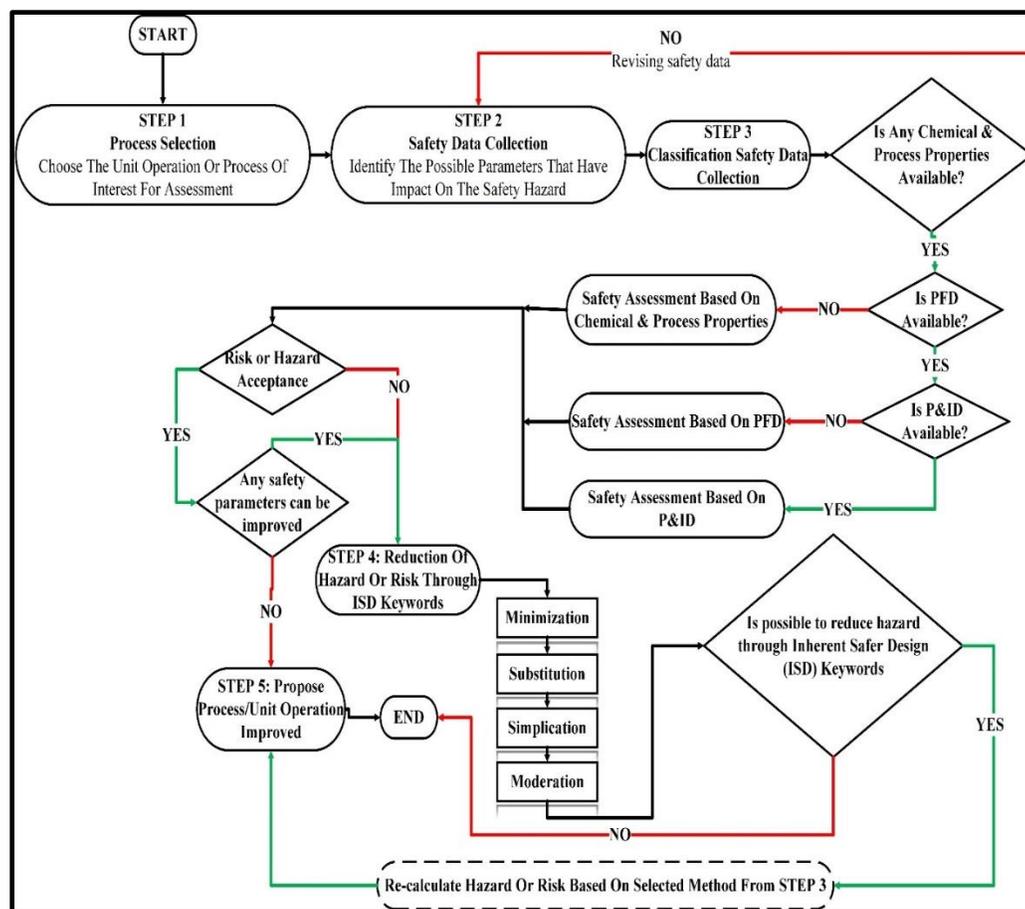
Figure 2: Heuristics framework for Process Safety Assessment based on Different Process Information.

After the data have been collected and analysed, the next step is to select the most suitable and applicable method which is based on data availability, goal, scope and limitations in performing the assessment. For example, fire and explosion index (F&EI) is selected in a case a user intends to quantify the hazard magnitude resulting from fire and explosion hazard only by using data from P&ID. After the index and risk values are determined, the values are compared to the respective benchmark or acceptance of risk or hazard. The benchmark is an index or risk value of the degree of hazard which is selected by the user to define an acceptable safety level. Each method has its own benchmark to be referenced by a user in order to determine the safety level of the process to be evaluated.

In a case where the value of the calculated index or risk values is not acceptable (unacceptable risk) after comparing with the acceptable range (benchmark), then the ISD keywords will be applied to reduce or eliminate the hazard as low as reasonably practicable (ALARP). In ALARP determinations, the reduction of hazard can be performed as long as the benefit is not disproportionate to the risk. This is because the greater the risk, the more that should be spent on reducing it. Even in the case where the risk is within the acceptable limit, there are still possibilities of reducing the hazards further using the same keywords. This is achieved by assessing the same process condition or chemical substances using ISD keywords. The implementation requires the range of the process operating conditions or parameters that directly affects the index or hazard level. For example, there are nine potential parameters in the ISI method to be applied

to reduce the total ISI value. However, a suitable ISD keyword must be selected for each potential parameter for the reduction to be effected on the ISI value.

In a case where it is already impossible to further reduce the hazard or risk, the assessment on the process or unit operation is ended. For example, it is impossible to reduce any process parameter (temperature or pressure) of a distillation unit even if the calculated index is more than acceptable range. This is because the reduction may affect the product yield. Otherwise if there is still possibility to reduce the hazard or risk after the modifications have been made, the process or unit operations should be re-assessed by re-evaluating the hazard or risk level using the same method selected from Step 3. The same steps are repeated for the other process synthesis pathways or unit operations. Basically, different methods have different ways and approaches in evaluating safety hazards. Therefore, detailed explanations on the scope, parameters included in the assessment and types of output data for each method are discussed in the previous section.

3.1   Case study : integrated biorefineries

The case study has been gathered from the Long-Term Research Grant Scheme (LRGS) programme to convert biomass into value added products such as bio-hydrogen and succinic acid. This process is called as an integrated palm-based biorefinery system which consists of gasification and fermentation sections. This case study is intended to evaluate the safety margin for both sections. As can be seen form these figures, two different integrated PFD are synthesised which are capable in processing multiple feedstocks (oil palm fronds (OPF), empty fruit bunch (EFB) and palm kernel shell (PKS)) to produce a specified set of products. Based on mass balance provided (see appendix), it was found that 100 kg/h of EFB or 100 kg/hr of PKS was required to generate 7.11 kg/hr of biohydrogen via the gasification process. On the other hand, 100 kg/hr was needed to produce 15.09 kg/hr of succinic acid crystal via the fermentation process. Furthermore, by looking to the whole process, it inherently involves the production, treatment and utilisation of flammable and toxic gas mixtures and utilities. In addition to that, the process streams pose different hazards according to the type and amount of chemicals present. Therefore, an adequate risk assessment is needed for making this integrated process.

It is an essential for a complete risk assessment process to first analyse the process information and hazards associated with the process to be evaluated. In this case study, the ISI method is selected to evaluate the safety margin for both sections. Figure 3 shows a detailed methodology for evaluating and minimising inherent safety hazards and risks using the ISI method. In this evaluation of integrated biorefineries, the assessment is handled separately during the analysis by dividing into two sections: a) gasification and purification section b) fermentation and purification section. This index is calculated for both sections separately and the results are compared to each other. At the first step of assessment, all the process conditions for each of the unit operations in each of the process sections are identified. The highest temperature for gasification and purification process is 675 °C in the fluidised bed gasifier. However, the maximum temperature for the fermentation section is only at 180 °C in the alkaline pre-treatment process. For pressure evaluation, most of unit processes in integrated biorefineries are operated at 1 bar except for membrane separation in fermentation section which is operated at 5 bar which gives the maximum operating pressure in this process. Then the score is allocated for the maximum operating condition for each section. The assessment is continued by evaluating the inventory of the process. As mentioned in the earlier section, in the ISI method the total inventory is calculated based on the sum of inventories of all process vessels. Therefore, the total inventory in the gasification and purification processes is 4t/hr. Meanwhile the total inventory in the fermentation is much higher, calculated at 30 t/hr due to the high number of process vessels in this process. Next, the safety of equipment is assessed by classifying all equipment involved in the process into ISBL and OSBL as shown in Table 4 and 5. The details on ISBL and OSBL have been discussed in the earlier section. In the gasification section, fluidised bed gasifier and boilers are accounted

the most unsafe equipment whilst the fermenter reactor and blow-down system are the most hazardous equipment in the fermentation section.
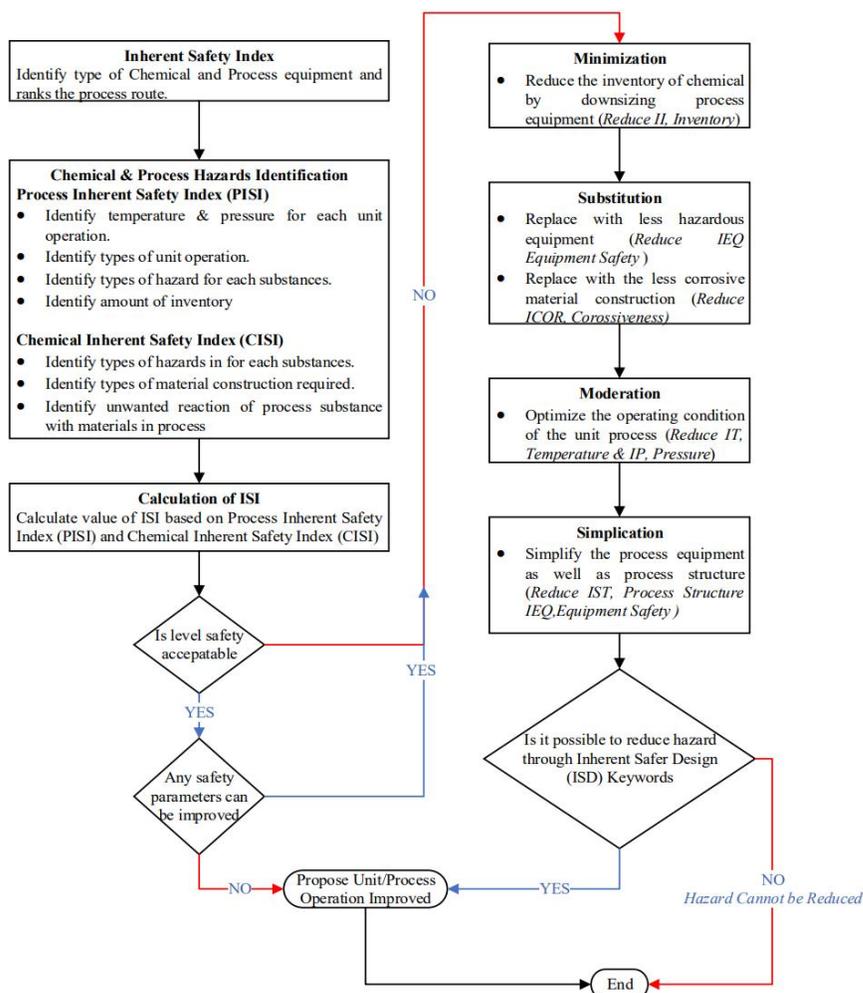

Figure 3: The Extended ISI Method for Identifying and Reducing Hazard and Risk Based on PFD

The assessment is continued by analysing all chemicals involved in this process. The most dangerous chemical in this integrated biorefineries is carbon monoxide which originally comes out from fluidised bed gasifier during syngas production. For the both sections, stainless steel is selected for construction material in this process which gives the score value 2. This is because stainless steel is the most frequently used corrosion-resistant material in the chemical industry [21]. Furthermore, the interaction between chemicals presented in this process is also considered in this assessment. The worst chemical interaction for this process is between carbon monoxide and air which results in explosion, which gives the score 4. The analyses of data as well as results from the assessment are presented in Table 4 for the gasification and purification process and in the Table 5 for the fermentation process. The total inherent safety index for thermochemical section is higher than for the fermentation section. As a result, the fermentation section is inherently safer than the gasification section. This could be attributed to:

i.　A toxic chemical, carbon monoxide, CO is present in the gasification and not in the fermentation section.

ii.   The process temperature in gasification is higher than in the fermentation section.
iii. There is possibility for gas explosion to occur in biomass gasification facilities when a mixture of combustible gases consisting of CO, hydrogen, higher hydrocarbon and oxygen within the flammability limits meets an ignition source [1].

Table 4: Safety Analysis for Gasification and Purification Process

Inherent Safety Index (ISI)		Score
Chemical Inherent Safety Index (CISI)		
Flammability (I_{FL}), Explosiveness (I_{EX}), Toxicity (I_{TOX})	Maximum Sum for Carbon Monoxide	10
Corrosiveness (I_{COR})	Stainless Steel	2
Chemical Interaction (I_{INT})	Carbon monoxide- air	4
Total CISI		16
Process Inherent Safety Index (PISI)		
Inventory (I_I)		1
Process temperature, max (I_{Tmax})	675	4
Process pressure (I_P)	1 Bar	0
Equipment (I_{EQ})	ISBL: Fluidized Bed Gasifier (High Hazard Reactors) = 3 OSBL : Boilers = 3	6
Total PISI		11
Total ISI (CISI + PISI)		27

Table 5: Safety Analysis for Succinic Fermentation and Purification Process

Inherent Safety Index (ISI)		Score
Chemical Inherent Safety Index (CISI)		
Flammability (I_{FL}), Explosiveness (I_{EX}), Toxicity (I_{TOX})	Maximum Sum for Sodium Hydoxide,Potassium Hydroxide, Hydroclouric Acid	5
Corrosiveness (I_{COR})	Stainless Steel	2
Chemical Interaction (I_{INT})	Sodium Hydroxide, Potassium Hydroxide, Heat formation	3
Total CISI		11
Process Inherent Safety Index (PISI)		
Inventory (I_I)	30 tonne/hr	2
Process temperature, max (I_{Tmax})	180	2
Process pressure (I_P)	5 Bar	1

Equipment (I_{EQ})	ISBL: Fermenter (Reactor) = 2 ISBL : Blowdown Sytems= 2	4
Total PISI		9
Total ISI (PISI + CISI)		20

In this case study, there are no possibilities to reduce the total index for the gasification section. As can be seen from the Table 4.14 fluidised bed gasifier received high score due to high operating temperature, 675 °C compared to other unit operations for the both sections. The range of temperature to be operated by fluidised bed gasifier is between 600°C-1000°C [6]. Therefore, reducing less than 600°C may affect the presence of oxidising agents to decompose biomass into lighter molecules and permanent gas (CO, H2,CH4) as stated by Kumar et al. [6]. A further point is by reducing temperature from 675 °C to 600 °C, it does not make a marked difference in the total score for the gasification section. It can be observed that at 600 °C and 675 °C the difference in the respective scores, 3 and 4 is unity. It can be concluded that in term of ISD applications, this case study revealed that, there are no possibilities to implement any keywords to reduce the calculated index in the gasification section. This is because it requires a wide range of operating conditions in order to accommodate changes and does not affect the yield of products.

4.   CONCLUSION

In summary, all the research objectives outlined earlier in the beginning of this study have been met with the completion of this study. There are several research outcomes that have been gained out of this study as summarized below :

  i.   The framework is successful in providing comprehensive guideline to user for selecting the most appropriate method(s) for their assessment according to their needs, scope, nature and constraints of the assessment.
 ii.   The demonstration of the designed framework on case study has highlighted that the decisions made in selecting chemical substances and process condition during PFD development are very important as it may affect the latter safety performance of the process.
iii.   Early of hazards and risk assessment enables for early consideration of alternative design and technical controls to either eliminate hazards or mitigate their consequences as demonstrated by the designed framework.

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