New Safety Evaluation Methodology; A Gold Mining Application

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ABSTRACT

Several safety assessment methods have been used to evaluate and improve safety in the process industries. Different methods have various approaches and may consider safety from different aspects and at different levels of the process design. Some methods may evaluate chemical and physical safety in the processes while some other methods analyse the failure risk associated with the processes. According to the importance of both aspects of safety, a method that can evaluate them concurrently and intervene in the early design phases would be of great importance. This paper presents a method with mentioned ability which is developed based on the inherent safety assessment and probabilistic risk analysis methods. This method is implemented on an industrial case using the Petri net modelling and safety assessment tool introduced by the authors in their previous work.

Keywords: Petri nets, Inherent safety, Probabilistic risk analysis, Indexing system, Process design.

1. INTRODUCTION

The ever-increasing importance of safety in the process industries has led to several research studies. Safety and reliability levels of a process can be evaluated and improved in any step of a plant's life cycle. Moreover, early safety consideration can lead to significant changes in the process design and make them safer and prevent hazards and catastrophic events from occurring. Investigation to develop approaches that can intervene early in the process design is on-going.

This study reviews safety assessment methods and tools that emphasise different aspects of safety and attempts to create a combined method which addresses a range of safety issues concurrently. A novel tool proposed earlier by the authors is used as the implementation tool in this study. Using this tool and according to the extent of detail information that the proposed method needs as input data it has the potential to be applied in the early design phases.

The inherent safety assessment method introduced by Kletz [1] and probabilistic risk assessment methods have been described briefly in section 2. Section 3 presents the modifications of these methodologies and outlines the new method developed by the authors. A brief background on different types of Petri nets is given in section 4 and the modified version which is used in this study as the implementation tool is described. In section 5 performance of the proposed method is demonstrated through an industrial case study followed by a discussion in section 6 and the conclusion in the final section.

2. SAFETY ASSESSMENT METHODS

The different safety assessment methods reported in the literature attempt to evaluate processes from different safety aspects and through various approaches. Two main groups are evident. The first group of methodologies emphasise the safety levels of process conditions both chemically and physically while the second group gives more weight to the equipment safety characteristics and their reliability levels [2, 3].

Chemical conditions such as toxicity, flammability and explosiveness and physical conditions such as pressure and temperature are considered as main factors influencing safety of a process in the first group. Inherent safety assessment is an example of this group [4, 5].

The second group accounts for the reliability levels of the equipment to start working or continue to work in different situations. Probabilistic risk assessment, fault tree analysis, failure mode and effect analysis, and layer of protection analysis come under this category [6, 7].

In this study one well developed technique from each group has been chosen for more detailed investigation based on their capability to intervene in the early stages of design. Inherent safety assessment can be implemented at any phase of design by using chemical and physical information of a process available at that particular level. Probabilistic risk assessment is also another method which can be employed early during design process using experts' opinions and available data bases. These two methods are described briefly as follows.

Inherent safety assessment – this method is based on the idea of making a process safer through fundamental modifications. This approach attempts to make safety as a permanent and pro-active characteristic of the processes rather than creating safety through add-on features and control procedures. The key principles of this method are: simplification to use simpler processes; minimization to reduce the amount of hazardous materials; attenuation to replace hazardous materials with non-hazardous alternatives; and finally, moderation to diminish the impacts of hazardous materials by reducing the amount of these materials available in the processes [1, 4]. Considering these principles during process design stages ensures inherently safer processes. On the other hand, in evaluation of safety in an existing process the extent of application of each of these keywords can give a measure of the inherent safety level of that process. Hence, by using this method, safety assessment is able to appropriately intervene into process design from the initial design stages [8].

The qualitative concepts applied in this approach may be quantified using a proper indexing system. Many researches have been under taken and a number of well designed index based systems have been developed to serve this purpose. These include Prototype safety index, Inherent safety index, Expert system and Integrated inherent safety index [4, 8]. Integrated inherent safety index system (I2SI) has been adapted in this study and described as follows.

This indexing system introduces one main safety index which comprises some sub-indices that account for process chemical and physical safety characteristics. Final integrated inherent safety index (I2SI) indicates the potential applicability of the inherent safety keywords to the process. This index is a ratio of inherent safety potential index over the hazard index which is calculated for each unit operation/equipment individually (Eq.1). Greater than unity index value indicates the positive respond to the inherent safety principles. The bigger the index the safer the unit operation/equipment. A less than unity I2SI indicates that the unit operation/equipment does not respond to the inherent safety guidelines which is a weakness of the process route containing that unit operation/equipment [8, 9]. These indices are explained briefly as follows:

- Hazard index (HI) – this index is calculated for the basic route and remains the same for all other options (Eq.2). HI is the ratio of damage index (DI) over the process and hazard control index (PHCI). Damage index is a function of fire and explosion, acute toxicity, chronic toxicity and environmental damage indices. The process and hazard control index takes into account existing and required add-on control measures regarding pressure, temperature, flow, level, concentration, inert venting, blastwall, fire resistance wall, sprinkler system and forced dilution.
- Inherent safety potential index (ISPI) – shows the applicability of each guide word to the process as a function of two other sub-indices (Eq.3): The inherent safety index which measures the efficiency of each guideword in the process; and process and hazard control index which is described earlier.

To calculate the total I2SI of a production route Eq.4 is suggested by Khan and Amyotte [8].

$$I2SI = ISPI/HI \qquad (Eq.1)$$
$$HI = DI/PHCI \qquad (Eq.2)$$
$$ISPI = ISI/PHCI \qquad (Eq.3)$$
$$I2SI_{system} = (\Pi\, I2SI_i)^{1/2} \qquad (Eq.4)$$

where i =1…n indicates the unit operation/equipment

Probabilistic risk assessment – this method is based on the potential major scenarios with adverse impacts on the safety of a system. These hazardous scenarios need to be investigated and the probability of their occurrence and magnitude of their consequences should be identified for each unit operation and piece of equipment. The probability of occurrence of each failure event may be calculated using released scenarios and probability data of related basic events. Severity of the consequences may be measured by considering possible loss of life and property damage and the degradation of the environment caused by the failure event [2]. Different resources may be used to obtain required information for risk/safety calculation such as experts' opinions, statistical data and experimental results. Risk/safety level can be quantified using the Bayesian probability theory [10].

A simple two term equation may be used to calculate the risk factor related to each unit operation/piece of equipment (Eq.5). Total risk associated with each process option is given through summation of risk factors of all units included in that option (Eq.6) [11].

$$Risk = failure\ rate \times consequences \qquad (Eq.5)$$
$$Total\ risk = \sum Risk\ i \qquad (Eq.6)$$

where i=0, …, n indicates the unit operation/equipment

3. METHODOLOGY DEVELOPMENT

According to the significant impacts of both groups of factors on improving the safety level of a process, methodologies that have the ability to evaluate these factors concurrently are of great importance. In this study, two safety evaluation methodologies described earlier have been adapted to develop a new combined method addressing both aspects of safety.

To assess the inherent safety, the I2SI is calculated for each unit operation/equipment existing in a production route as mentioned above: however, a new approach is suggested for calculation of the total I2SI of the system. Application of Eq. (4) in different case studies has shown the sensitivity of this method to the number of unit operations/equipment which means the greater number of unit operations/equipment results in a higher total I2SI for that system while it does not directly influence the safety level of the system. Moreover, using the square root in this formula intensifies the impact of the larger I2SI available in a system on the total value of the I2SI.

To overcome these weaknesses, it is suggested that geometric mean [12] of all I2SI values related to all unit operations/equipment in a production route is used instead of Eq. (4). It gives the average I2SI in a process option (Eq.7).

$$Average\ I2SI_{route} = (\Pi\, I2SI_i)^{1/n} \qquad (Eq.7)$$

where i = 1…n indicates the unit operation/equipment and n is the total number of unit operations/equipment

Application of a proper averaging method would diminish the impact of the number of elements contributing in a system on the final value calculated for that system. Since the geometric mean is usually used in situations in which the nature of each element is originally based on the productivity, it can be a suitable option for calculation of the average I2SI of a process option. In addition, using the n^{th} root leads to levelling the weight of all n elements of the system on the calculated average factor.

This average inherent safety factor is combined with an average risk factor to give a unique index representing the safety level of a process option considering both chemical and physical safety and reliability of that process.

Reliability and probability of failure associated with each unit operation/equipment in the production route is calculated using the probabilistic risk assessment method and is based on the available data from different sources and the experts' opinions. In order to obtain a dimensionless risk factor the ratio of failure rate of a unit operation/equipment to the total possible failure rates of all unit operations/equipment is considered as the failure probability. The magnitude of consequences in each case of failure is converted into a numeric index using Table 1. Decisions about the proper index should be made based on expert opinion. The total risk factor needs to be compatible with the inherent safety factor described earlier in order to be combined with that to form a new index. Hence, instead of using Eq. (6) to calculate the total risk of a process the average risk associated with that process can be used. According to the productivity nature of the risk factor, again the geometric mean can be a suitable option (Eq.8).

Table 1. Guideline to decide magnitude of consequence of failure

Description	**index**	**Description**	**index**
Extremely high	10	Reasonable	5
Very high	9	Low	4
Not greatly high but noticeable	8	Significantly Low	3
Noticeable	7	Ignorable	1…2
Moderately noticeable	6		

$$Average\ risk_{route} = (\Pi\ risk_i)^{1/n} \quad (Eq.8)$$

where i = 1…n indicates the unit operation/equipment and n is the total number of unit operations/equipment

Finally, the average risk factor representing lack of safety in a system can be extracted from the average inherent safety factor which shows the degree of safeness of that system (Eq.9). The result is a safety factor in which both major groups of safety evaluation criterion have been considered. This new safety index is called the average safety index in this study.

$$Average\ safety\ index_{route} = Average\ I2SI_{route} - Average\ risk_{route} \quad (Eq.9)$$

The other index which is used in this method to assist decision-making process is the total number of the unit operations/equipment not responding to the inherent safety keywords (with I2SI less than unity) which is called the penalty factor in this study. Greater penalty factor shows safer process option.

One of the major advantages of the proposed method is that the input data which is used to calculate the final safety factor introduced in this method does not need to be highly detailed. Hence, this method can be appropriately applied during the preliminary design phases. It would provide designers with a safety decision-making factor which is of great importance for surviving in today's extremely competitive market and can be used in conjunction with the other important factors, such as cost factors to compare different production alternatives and choose the optimal option. The simple concept of this method is the other strength which makes it easy to understand and use in the different industries and different situations.

This safety evaluation method needs to be implemented via a suitable tool. An appropriate tool has been developed by the authors [13] which is introduced briefly in the following section.

4. SAFETY EVALUATION TOOL

To implement safety assessment during any phase of the process design a reliable tool is required. These methods and tools may differ from one stage of design to another stage depending on the specific requirements of each stage and the type of data available at that stage. Some methods can be applied after process design completion as they need the process information to an extent which can be provided only when all steps of design have been carried out. While some other methods are suitable to be used earlier in the design stages as they do not need very specific information [2, 14]. Layer of protection method and inherent safety are two examples of these categories, respectively.

As mentioned earlier, the main concern of this study is to integrate safety assessment into the early design stages. To serve this purpose the implementation tool has to be able to model process in the conceptual design decision-making phase. In order to carry out safety assessment simultaneously with process design it needs to have the capability of processing different types of information at the same time. Moreover, an effective tool has to be easy to understand and use, be able to generate the reliable results and be flexible enough to be used in the different situations [15].

Several researches show that the Petri net modelling tool is a suitable option which can meet these requirements. Petri net is a graphical-mathematical modelling tool with significant flexibility so that it is able to model different systems. Being graphic based, this modelling tool has great potential to be easily understood and applied via different groups of specialists and experts as a common modelling language. In addition, Petri net has crucial ability and flexibility in process modelling and carrying out simultaneous safety evaluation and calculation. This tool has been adapted by the authors in their previous work as an appropriate tool for process modelling and concurrent safety calculations [13].

In general, Petri net is a directed, bipartite five-tuple;
$PN = (P,T,F,W,M_0)$ where
$P = \{p_1, p_2, \ldots, p_m\}$ is a finite set of places shown as circles.
$T = \{t_1, t_2, \ldots, t_n\}$ is a finite set of transitions represented by bars.
$F \in (P\times T) \cup (T\times P)$ is a set of arcs connecting places to transitions and vice versa.
$W: F \rightarrow \{1, 2, 3, \ldots\}$ is a weighting function. Weight may be defined for any type of nodes to introduce specific attributes related to that node.
$M0: P \rightarrow \{0, 1, 2, \ldots\}$ is the initial marking defining the number of tokens (represented as dots inside places).

If all required resources are available, a transition is called enabled transition. An enabled transition changes to a fired transition if the tokens from its input places are removed into the output places [16].

Various types of the Petri nets have been developed with different characteristics and abilities to be applied in the different situations. Place weighted Petri net and Stochastic Petri net are two types of Petri nets which showed great compatibility with the proposed safety assessment methods. A combination of these two types has been used in this study.

In place weighted Petri net, places represent unit operations/equipment, transitions show start and end of operations and events, tokens are raw materials, semi-finished or final products and arcs illustrate process flow. Safety and risk information associated with each part of the process are allocated as weight factors into the related places.

Stochastic Petri net is an extended version of the original Petri net in which random firing time is associated with each transition. It has the ability to model the stochastic processes and describe the future state of a system based on the provided stochastic data. The random time spent in each state before firing the next transition is determined by the distribution function defined for each transition. Stochastic Petri nets have been used widely in performance evaluation, identifying bottleneck work station, verifying timing constraints, obtaining production rate, average delay, resource utilization, and reliability measures [17-20].

In this study, stochastic behaviour is used to address the probability of failure of each unit operation/equipment in a production route. Firing time or firing delay of each transition in stochastic Petri net can be replaced with the firing probability or on the other hand the probability of failure to fire. Firing probability of transitions shows the probability of equipment running properly or failure to run when needed. This probability can be based on the predefined probability distribution function. If a density function is used as the risk function, a discrete risk oriented system such as stochastic risk manufacturing system can be described. The concept of the total delay in a production system simulated with a stochastic timed-Petri net is equivalent to the total risk associated with the production route modelled with the risk based stochastic Petri net. This risk is accumulated from the beginning of the simulation.

These two types of Petri nets are used together to take into account both inherent safety characteristics of the processes and probabilistic behaviour of the unit operations/equipment in terms of reliability and failure. Inherent safety factors of each unit operation/equipment are considered as weight factors of related place, while failure probability data is defined as firing distribution function related to each transition showing the start of operation of each unit operation/equipment.

Using the described Petri net modelling tool all process alternatives come together and form a super-net model. This super-net is divided into some sub-nets based on similarities and differences of contributing production routes. Similar unit operations or groups of similar unit operations form the common sub-nets while different parts of processing routes are represented by the individual sub-nets.

Some significant achievements of the proposed tool are:

- Flexibility of implementing different safety evaluation methods.
- Minor complexity level to be learned and applied.
- Simultaneous process modelling and safety assessment.
- Providing comparative base for decision-making.
- And above all, providing the opportunity of automatic generation of all possible production alternatives by creating an integrated super-net [13].

5. CASE STUDY

In order to demonstrate the performance of the proposed safety evaluation methodology and tool, an industrial case is investigated. The claimed ability of the automatic generation of all possible production routes is shown through including three different production routes as base cases in a super-net model. All other possible combinations are obtained using the proposed Petri net tool. The developed methodology provides designers with a safety index associated with each option as a decision-making factor.

Gold mining is one of the major industries around the world. From the various technologies applied to recover gold ore into gold bullion, three methods are chosen as the basic routes in this study: carbon oxidation (Fig.1), roasting (Fig.2) and bio oxidation (Fig.3). These production routes are described briefly as follows:

Carbon oxidation - this method uses carbon in oxidation process for gold recovery and contains the following steps: crushing, grinding, froth floatation, carbon oxidation, carbon in leach/carbon in pulp, stripping, electrowinning and smelting [21].

Roasting – this method applies roasting technology in gold recovery phase and includes different steps: crushing, grinding, froth floatation, roasting, carbon in leach, elution, electrowinning and smelting [22, 23].

Bio oxidation – bacterial oxidation is used in gold recovery step in this method while the other steps are: crushing, grinding, bio oxidation, clarifying, vacuum de-gassing, zinc dusting and smelting [24].

Some unit operations are common in two or all three process options while each option contains some unique steps. These similarities and differences form the basis of the super-net model which includes common and individual sub-nets. The developed Petri net super-net model and associated sub-nets are illustrated in Fig. (4) , the description of the sub-nets is given in Table 2. The place numbers parallel to unit operations/equipment are shown in Figs. (1) to (3).

This Petri net model is implemented in the Visual studio environment using the C++ codes and resulted in the generation of twelve different production routes which illustrate all possible combinations. The proposed safety evaluation method described earlier is applied to assess the safety and reliability level of each generated process alternative. All results are presented in Table 3 and are discussed in the following section.

6. DISCUSSION

Table 3 shows the results of the application of the proposed safety and risk assessment method in this study. The application of the proposed methodology and Petri net tool has resulted in generation of twelve routes with the final safety factors between 0.40 and 0.55, and the total numbers of not responding unit operations/equipment, penalty factors, between 8 and 13. Routes number 8 and 12 prove to be the safest options in this method with the final safety factors and penalty factors of (0.55, 10) and (0.54, 8), respectively. The final safety factor for route 8 is slightly higher than the final safety index of route 12: however, route 12 contains the smallest number of not responding unit operations/equipment to the inherent safety keywords.

The safety assessment methodology and tool proposed in this paper provide designers with the opportunity to generate all possible production alternatives based on the similarities and differences between some initial base cases. Furthermore, several quantitative and qualitative safety characteristics of all these generated production routes are evaluated and converted into a pair of quantitative factors for each option simultaneously with the route generation process. It is shown that these combined methodology and applied tool would result in easier, faster and more accurate decision-making process. In addition, automatic route generation and safety calculations in this method minimize the need for human involvement and therefore human errors during the design process.

7. CONCLUSION

This paper has proposed a new safety assessment methodology based on two well known methodologies: the inherent safety assessment and the probabilistic risk analysis. Some important modifications have been made to these methods and the modified methods have been combined to create a new approach which can address safety issues related to the chemical and physical process conditions and risk of failure associated with the unit operations/equipment in the process options. This approach automatically generates all possible production options and calculates two factors for each route concurrently. One of these factors shows the safety level, while the other one gives the total number of unit operations/equipment not responding to the inherent safety principles in each route. These factors may be used as the appropriate safety indicators along with the other decision-making factors to enhance the decision-making process and choose the optimal production route.

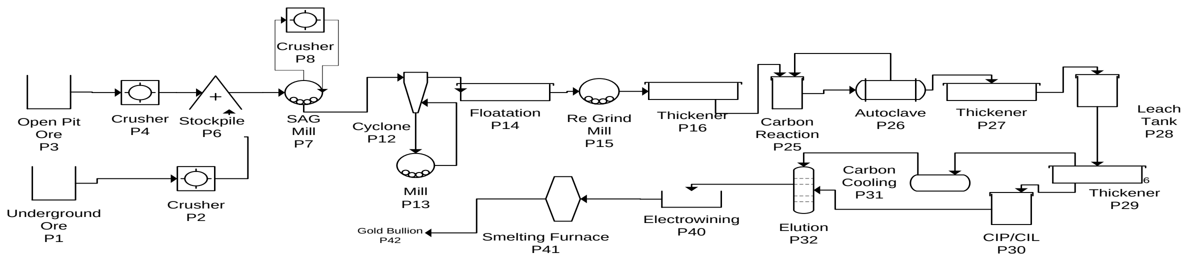

Fig.1 Carbon oxidation method [21].

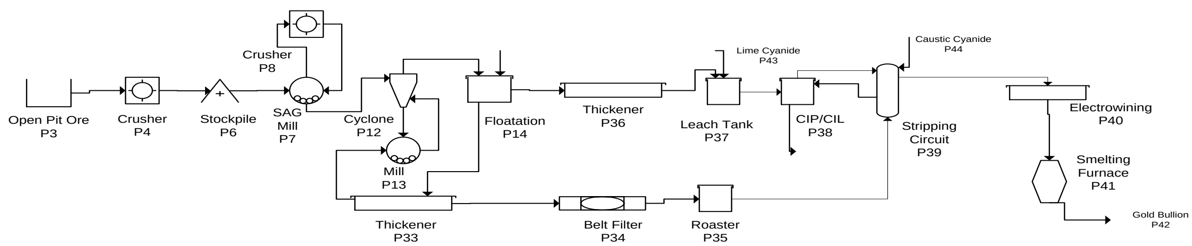

Fig.2 Roasting method [22].

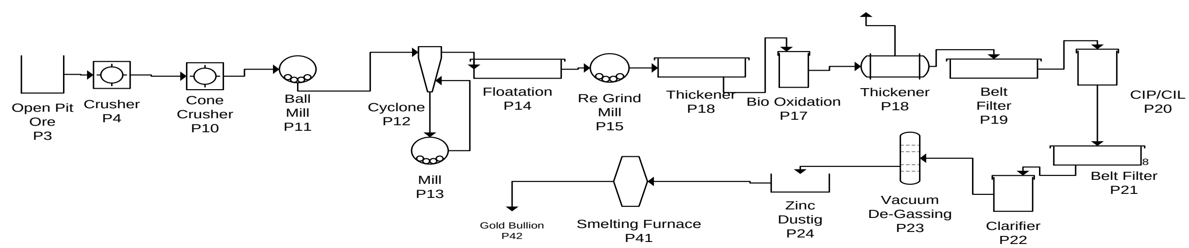

Fig.3 Bio oxidation method [24].

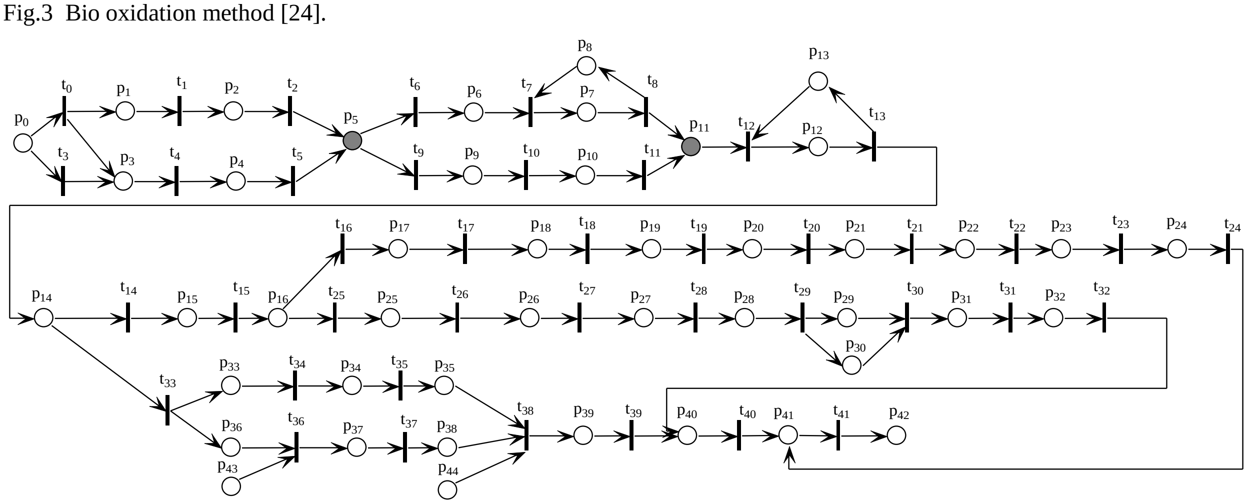

Fig.4 Super-net model

Table 2. Definition of sub-nets included in super-net model

Sub-net	Place(s)	Sub-net	Place(s)
Sub-net 1	P1, P2	Sub-net 6	P16, P17, P18, P19, P20, P21, P22, P23, P24
Sub-net 2	P3, P4	Sub-net 7	P25, P26, P27, P28, P29, P30, P31, P32
Sub-net 3	P6, P7, P8	Sub-net 8	P33, P34, P35, P36, P37, P38, P43, P44
Sub-net 4	P10, P11	Sub-net 9	P41, P42
Sub-net 5	P12, P13		

Table 3. Summary of results using average safety method

Route number	**Route1**	**Route2**	**Route3**	**Route4**	**Route5**	**Route6**
Average safety index	0.40	0.42	0.42	0.44	0.47	0.49
Penalty factor	11	10	10	9	13	12
Route number	**Route7**	**Route8**	**Route9**	**Route10**	**Route11**	**Route12**
Average safety index	0.52	0.55	0.45	0.47	0.51	0.54
Penalty factor	11	10	11	10	9	8

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