Studying the relationship between inherently safer design and equipment reliability

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Abstract: Risk associated with a process depends on both likelihood and consequence of an incident. Inherently safer design is based on the use of technologies and chemicals with intrinsic properties that reduce or eliminate hazards. This philosophy is mainly focused on reducing the consequences associated with an incident. However, recent research has revealed that applying principles of inherent safety can influence the likelihood element of risk as well. One of the major drawbacks of implementation of an inherently safer design (ISD) is that it can lead to risk migration, Thus, attempting risk reduction through implementation of ISD by mitigating the consequence element of risk can undesirably lead to an increase in risk by affecting the likelihood element of risk. This likelihood element of risk is the mathematical complement of system reliability. To better understand the relationship between inherently safer design and equipment reliability, this study mainly focuses on assessing the effect of implementation of ISD principles on the reliability of a chemical process as it progresses along different stages of process design.

Keywords: inherent safety, reliability, process design, maintenance

Introduction

Inherent safety

The Flixborough disaster in 1978 served as a cornerstone for inherent design philosophy (Kletz, 1978). Inherently safer design (ISD) concept is based on the use of technologies and chemicals with innate properties that reduce or eliminate hazards (Mannan, 2002). Inherent safety has found its way in several regulations by various authoritative bodies including the UK health and safety executive. The European council directive 96/82/EC of 1996 on the control of major-accident hazards involving dangerous substances, in its guidance document states, “Hazards should be possibly avoided or reduced at source through the application of inherently safe practices.” In United States, the new jersey department of environmental protection in its toxic catastrophe prevention act and Contra costa county, California in its industrial safety ordinance have implemented the consideration of inherently safer technologies for regulation of hazardous industrial facilities. In February 2016, the US environmental protection agency (EPA) put forth a proposal to revise its risk management program to include the consideration of safer technologies and alternatives in the process hazard assessment for regulation of hazardous industrial facilities. This proposal received criticism from various industrial associations such as US small business administration and American forest and paper association primarily due to the difficulty of implementing ISD in existing facilities as compared to the design stage of grass-root facilities. However, despite this industrial opposition, the amendment was finalized by US EPA in January 2017.

Inherent safety is primarily based on the following 4 principles (Mannan, 2002) :

- Minimization: reducing the volume of hazardous materials
- Substitution: replacing a chemical in the process with a relatively safer alternative.
- Attenuation: reducing the severity of operating conditions in the process involving hazardous chemicals
- Simplicity: implementing simpler process designs with lesser equipment

Equipment reliability

Reliability is the probability that a system or a component will perform its desired function at the required time when used under the appropriate operating conditions whereas availability is the probability that a system or a component will perform its desired function at the required time when maintained or operated in the prescribed manner (Ebeling, 1997). Quantifying reliability of a system is insufficient in terms of estimating the maintenance downtime since, reliability and maintainability share a trade-off which overall contributes towards the availability (and ultimately the maintenance downtime) of the system. Various industries have manipulated this relationship to improve the profitability of their processing systems. Exxon Mobil in 1994 introduced the reliability and maintenance system program which reduced the maintenance cost by $ 30 million (Exxon Mobil, 2001). Shell in its Pulau Bukom refining facility in 1996, made design and operational modifications which resulted in a 4-year run of a long residue catalytic cracking unit with only 21 hours of downtime (Shell, 2001). British Petroleum saved over $ 1.4 million in pump repairs by increasing the mean time between failure of pumps in their facility in Lima, United States (Griffith.J, 1998).

Motivation

An analysis of the occurring process safety incidents revealed that most of these incidents occur during transient operations, such as equipment maintenance, start up and shutdown (Duguid, 1998). Therefore, a process with higher maintenance downtime can be associated with higher risk. The maintenance downtime comprises of the corrective and preventive maintenance downtime. The preventive maintenance downtime primarily depends on the procedures and safety culture adopted by the company which is generally dictated during the later stages of design of the facilities. The initial design stages of a chemical project are vital in determining the corrective maintenance downtime of system since major decisions pertaining to the number and type of different equipment involved in the process are taken during these stages.

Also, it has been observed that implementing inherent safety principles (ISP) becomes more and more difficult, as the design of the chemical process plant progresses from initial stages to the later stages (Kletz, 1991). Therefore, it becomes necessary to study the effect of implementing ISPs on the corrective maintenance downtime of the system during initial design stages, to analyse the possibility of increasing the corrective maintenance downtime since an increased corrective maintenance downtime can lead to higher risk.

Methodology

To analyse the relationship between inherent safety and maintenance downtime, it is essential to quantify these parameters. Inherent safety quantification depends on the stage of design under consideration. This is mainly because the depth of knowledge pertaining to the design of the chemical process system increases along-with the progression of design stages. Therefore, it has been observed that indices like inherent safety index (ISI) and Prototype index for inherent safety (PIIS) are more suitable during the predesign stage whereas detailed safety indices like Dow fire and explosion index and Mond index are more suitable during basic engineering and detailed engineering stage (Heikkila, 1999). In 2004, i-safe index was developed primarily for the selection of inherently safer routes in the process selection stage (Palaniappan, 2004). A comparative study of the safety indices (Dow F&EI, PIIS, i-safe and ISI) revealed that ISI and i-safe indices had a strong agreement with other indices and with judgement from process safety experts in the process selection stage (Kidam, 2015). Since this study is focused on earlier stages of process design such as the process selection stage, ISI and i-safe indices are selected for the quantification of inherent safety.

The corrective maintenance downtime of the system is governed by the inherent availabilities of the equipment involved in the system, where the inherent availability of the system itself depends on the inherent availabilities of the equipment involved in the system. The number and type of different equipment involved in the process can be obtained from its process flow diagram (PFD).

The complete methodology used in this study can be described by the following diagram:

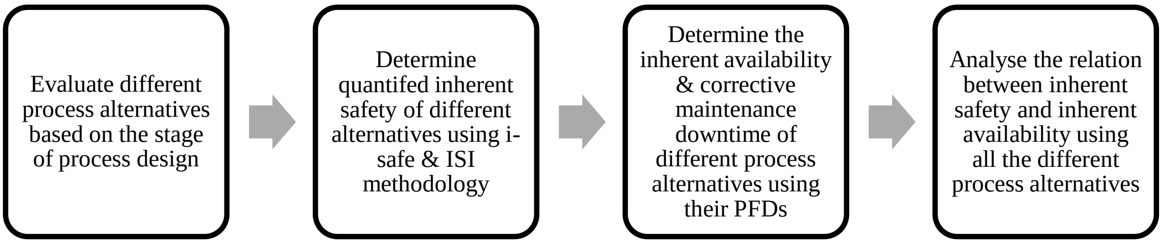

Figure 1: Methodology for analysing the relationship between inherent safety and inherent availability

Numerical calculations

Quantifying inherent safety of process systems

As mentioned previously, A process safety index based on i-safe and inherent safety indices is used in this study to quantify inherent safety of various design alternatives. The process safety index is calculated as follows:

Hazardous properties of all the chemicals (reactants and products) involved in the process such as reactivity, toxicity, flammability, and explosiveness of chemicals are converted into non-dimensional indices as per inherent safety index methodology (Heikkila, 1999). These indices are N_r (NFPA reactivity rating), N_f (flammability index), N_t (toxicity index) and N_e (explosiveness index).

Similarly, hazardous aspects of reactions such as the operating conditions of temperature and pressure and heat of the reaction are converted into non-dimensional indices as per inherent safety index methodology (Heikkila, 1999). The inventory of chemicals required for the process is indirectly considered through the yield of the chemical reactions involved. This yield is again converted into non-dimensional index as per prototype index for inherent safety methodology (Edwards, 1993). Thus, the indices characterizing a reaction involved in the process are R_t (temperature sub-index), R_p (pressure sub index), R_h (heat of reaction sub-index), R_y (yield sub-index).

The process reaction and chemical index (PRCI) is a measure of the hazards relating to chemicals and reactions involved in the process and is computed as follows:

Individual chemical index (ICI) = $N_r + N_t + N_f + N_e$ (ICI is computed for all chemicals involved in the process)

Individual reaction index IRI) = $R_t + R_p + R_h + R_y$ (IRI is computed for all reactions involved in the process)

Hazardous chemical index (HCI) = max (ICI)

Hazardous reaction index (HRI) = max (IRI)

Overall chemical index (OCI) = max (ICI)

Overall reaction index (ORI) = ∑ IRI

Overall safety index (OSI) = ∑ (OCI + ORI)

Worst chemical index (WCI) = max (N_r) + max (N_t) + max (N_f)+ max (N_e)

Worst reaction index (WRI) = max (R_t) + max (R_p) + max (R_h) + max (R_y)

Total chemical index (TCI) = ∑ ICI

Process reaction and chemical safety index (PRCSI) = ∑ (OSI + WCI + WRI + TCI)/4

Note: a) OSI, WCI, WRI and TCI are considered for the calculation of PRCSI to also evaluate the hazards associated with the worst-case scenario possible in a chemical process. b) Hazardous chemical index (HCI) and overall chemical index (OCI) are numerically identical.

Apart from considering the hazards with respect to chemicals and reactions in a process, it is essential to consider the hazards with respect to the equipment involved in the process. Equipment like furnaces can act as ignition sources leading to fire and explosion, similarly failure in reactors handling toxic chemicals can lead to release of hazardous chemicals to the environment. The scoring of equipment in this study is based on inherent safety index methodology (Heikkila, 1999).

Equipment	Score (I_{EQ})
Equipment handling non-flammable, non-toxic materials	0
Heat Exchangers, pumps, towers & drums	1
Air-coolers, reactors & high hazard pumps	2
Compressors & high hazard reactors	3
Furnaces & fired heaters	4

Table 1: Scoring of equipment

The process equipment safety index (PESI) is calculated as,

PESI = ∑ N_j x $I_{EQ,j}$ for all j

Where j represents the different types of equipment and N_j represents the number of a specific type of equipment involved in the process.

Finally, the overall process safety index (OPSI) is calculated as,

OPSI = PRCSI + PESI

A higher value of OPSI indicates a more hazardous (i.e. less inherently safer) process.

It should be also noted that the quantification of inherent safety through OPSI involves relative weighing of hazards and thus introduces an inbuilt judgement that may not be consistent with other safety indices and expert judgments.

Since OPSI is used for comparing the inherent safety of design alternatives from hazards with respect to involved reactions, chemicals and equipment in the process, it is important to understand the effect of different inherent safety principles on OPSI, which is illustrated in the following diagram:

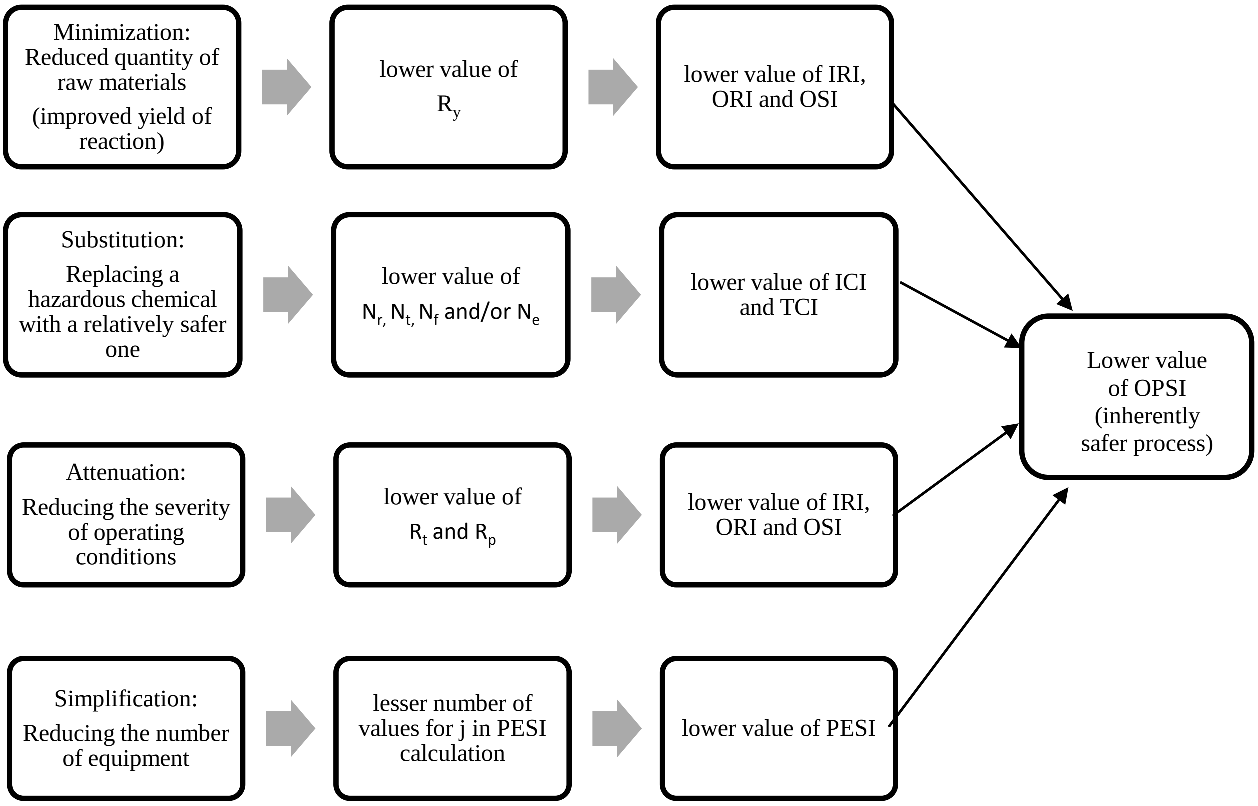

Figure 2: Effect of inherent safety principles on overall process safety index

Computing inherent availabilities of process systems

As mentioned before, inherent availabilities are used in this study to quantify the corrective maintenance downtime of process systems. The advantage of analysing inherent availability is that it is the steady state availability (i.e. it doesn't vary with time) and it is an equipment design parameter. The inherent availabilities of the equipment themselves are based on their mean time to failure (MTTF) and mean time to repair (MTTR) of the equipment. The inherent availability of an equipment is given by:

$$\boldsymbol{A_{inh} = \frac{MTTF}{MTTF+MTTR}}$$

The MTTF and MTTR values for general process equipment can be obtained from center for chemical process safety (CCPS) and offshore reliability equipment data (OREDA) databases.

In the earlier stages of design, redundant equipment are generally not considered. Thus, the equipment in the process system can be assumed to be in series with respect to their reliabilities and availabilities. Therefore, the inherent availability of the system can be expressed as:

$$\boldsymbol{A_{inh,sys} = \prod_{i}^{n} A_{inh,i}}$$

Where,

$A_{inh,i}$ is the inherent availability of i^{th} equipment,

n is the total number of equipment in the process system,

& $A_{inh,\ sys}$ is the inherent availability of the process system.

Thus, from the process flow diagrams (PFDs) of the process designs, different types and number of equipment involved in the process design can be known and the inherent availability of the system can be estimated from the inherent availabilities of equipment involved in the process. The corrective maintenance downtime for the system is computed using the following expression:

$$\boldsymbol{A_{inh,sys} = 1 - \frac{corrective\ maintenance\ downtime}{total\ process\ time}}$$

Finally, by computing OPSI and $A_{inh,sys}$ for all process design alternatives, the required relationship between these parameters can be established.

Case studies

The described methodology is applied to the case of Acetic acid manufacturing in the process selection stage. Various processes which utilize different chemicals, reactions and equipment have been developed for Acetic acid manufacture. The processes considered in this study are Ethylene oxidation, Acetaldehyde oxidation, low pressure carbonylation, Ethane oxidation and Butane oxidation.

Similarly, the described methodology is applied to the case of Hydrodealkylation of Toluene to Benzene in the conceptual stage of design. In this stage, different process design alternatives that are similar in terms of reactions and chemicals but utilizing different number and type of equipment (i.e. different process configuration or process flow diagrams) are evaluated in terms of economic feasibility. The processes considered are described by Douglas – 1988, Bouton - 2008, Konda – 2006 and Mata – 2003.

Results

The results obtained by applying the described methodology on the mentioned case studies are as follows:

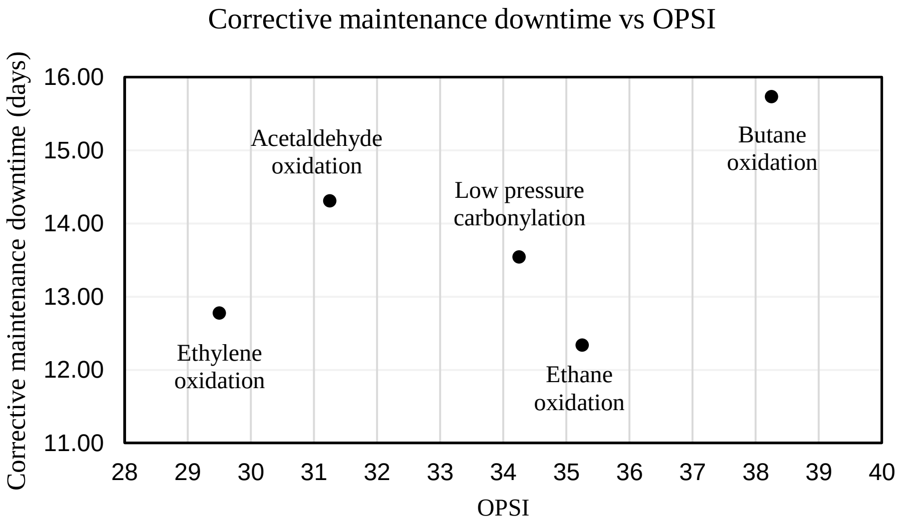

Figure 3: Results for applied methodology in process selection stage for Acetic acid manufacture

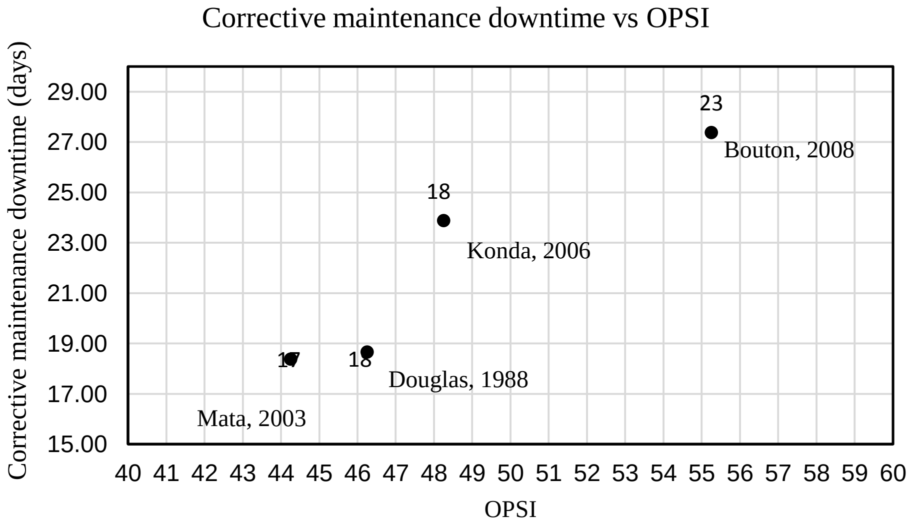

Figure 4: Results for applied methodology in conceptual stage for Hydrodealkylation of Toluene to Benzene

Note: Numbers above data points represent the number of process equipment in the process

Analysis of results

Process selection stage for Acetic acid manufacture

Analysing the graph obtained between OPSI and corrective maintenance downtime for process selection stage (Figure 3), it can be observed that a process that is inherently safer in terms of involved reaction, chemicals and equipment may not necessarily have the least corrective maintenance downtime. This is primarily because, in process selection stage OPSI is governed by the inherent safety principles of minimization, substitution, attenuation and simplification (Figure 2), whereas corrective maintenance downtime depends only on the number and types of equipment present in the process system and thus, only depends on the principle of simplification. Therefore, implementing a process that's inherently safer in terms of involved reaction, chemicals and equipment might lead to an increase in the associated risk of the system by increasing its corrective maintenance downtime.

In 1972, around 10% of the Acetic acid manufacture was carried out by low pressure carbonylation. However, due to the economic superiority of this process, its dominance has increased over the years and currently more than 90% of Acetic acid manufacture is achieved using low pressure carbonylation (Cheung, 1990). Prior to the dominance of low pressure carbonylation process, major proportion of the Acetic acid was produced by Acetaldehyde oxidation (Hintermann & Labonne, 2007) . Thus, if regulations to enforce the consideration of inherently safer designs are imposed, upcoming facilities might need to reconsider the potential of Acetaldehyde oxidation for Acetic acid manufacture over low pressure carbonylation due to its higher associated inherent safety. This can lead to implementation of process that has a higher corrective maintenance downtime and thus ultimately higher associated risk.

Conceptual stage for hydrodealkylation of Toluene to Benzene

From the graph obtained for the conceptual stage (Figure 4), it can be observed that the corrective maintenance downtime of process systems increases with increase in OPSI. A detailed analysis reveals that the number of equipment involved in the process systems increases as we move from a process with lower OPSI and lower corrective maintenance downtime to a process with a higher OPSI and a higher corrective maintenance downtime. Due to similarity of process systems in terms of reactions and chemicals in the conceptual stage, inherent safety principles of minimization, substitution and attenuation become redundant, Therefore OPSI is essentially governed by the principle of simplification where in a process with lesser number of equipment will have a lower value of OPSI and thus will be inherently safer. Similarly, corrective maintenance downtime of a process is dictated by the number and type of equipment involved in the process and generally, increases with the number of equipment involved in the system. This explains the trend observed in the results for conceptual stage (Figure 4).

Conclusion

In process selection stage, it is vital to analyse the processes in terms of their corrective maintenance downtime apart from the involved reactions, chemicals and equipment to reduce the possibility of risk transfer, since a process that is inherently safer in terms of these process parameters might be associated with higher corrective maintenance downtime and thus, higher risk. In conceptual stage, a process that has lesser number of equipment might be inherently safer (however, this depends on the relative weighing of hazards inbuilt in OPSI calculation) and this process might have relatively lesser corrective maintenance downtime as well. It can be concluded from this study that, there exists a complicated relationship between inherent safety and corrective maintenance downtime (and thus, system reliability) and this relationship varies with the progression of the design of the process system. The different trends in this relationship during various stages of design can be attributed to the variation in impact of the inherent safety principles towards the overall quantified inherent safety of the process (and the associated judgment of relative weights of hazards involved in the calculation). This drawback can be eliminated by using a risk-based inherent safety approach for quantification rather than a hazard-based inherent safety approach to accurately judge these impacts rather than estimating them using non-dimensional safety indices.

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