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The Application of First and Second Orders of Inherent Safety in the Chemical Process Industry

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The inherent safety (IS) concept has been introduced for more than 45 years, yet its adoption into process design is still very low. As a result, similar accidents keep on occurring worldwide since a majority of the risk reduction strategies used are based on the outer layers of protection such as active engineered and procedural. To enhance the uptake of inherent safety into chemical plant design, this paper aims to outline the common inherent safety strategies that have been used by the chemical process industry (CPI) to prevent accidents. 502 cases of inherently safer design (ISD) applications in the CPI have been collected and analysed. The process changes through plant modification are grouped based on the four main ISD strategies of minimisation, substitution, moderation, and simplification. The four main ISD keywords are then further classified into a hierarchy of inherent safety order. 58 cases (12 %) fall under first order IS which is from substitution keyword. For the 2nd order IS (magnitude), the keyword minimisation gives 242 cases (48 %) while moderation gives 151 (30 %). The simplification keyword which is under 2nd order IS (likelihood) gives 51 cases (10 %). The 2nd order IS (magnitude) seems to give the biggest numbers of design changes made by the CPI. Magnitude reduction strategy is the common choice by the CPI when designing safer equipment or process.

1. Introduction

The modern accident prevention strategy basically adopts the layers of protection concept. For example, a simplified risk assessment for chemical plants which prepared by Argenti et al. (2015) applied layer of protection (LOPA) approach to access the factors that influenced the accidents occurrence. There are four basic layer of protection which begin with inherent safety. The next layer is passive engineered, followed by active engineered and lastly is procedural. To compare between four layers, inherent safety is said to be the most reliable. The concept of IS has been introduced since 1970s by Trevor Kletz as an effort of designing processes in a safe condition by its nature rather than adding on active and passive control device. A research that compiled papers from 2001 - 2011 which discusses about IS at a different perspective shows a positive rise (Srinivasan and Natarajan, 2012). Despite having attention and argument over its implementation, inherent safety concept is not practically applied yet (Mannan et al., 2015). The concept is widely believed as the most effective strategy in eliminating hazards, but the uptake is slow and similar accidents keep occurring from time to time.

There could be a list of issues that leads to a slow uptake of its implementation and the reality of its being too conceptual are related to the flaw of design process. This is mainly due to the lack of understanding on how to implement ISD in design projects. The information on the existing efforts made by companies is not easily accessible since most of the new design projects are declared as confidential. The new or latest ISD implementation in real industries is poorly disseminated to the process community. In this study, the main objective is to provide a better understanding on current status of ISD which has been implemented in the

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CPI. To be able to have a design tool, the database is to be analysed for ranking to compare with 1st and 2nd orders of inherent safety. The orders of IS concept has been mention briefly in CCPS (2008).

2. Research Approach

The methodology that will be used for this study is inherent safety database analysis. It is well known that similar problems have similar solutions; the approach used in this system is basically based on the adaptation of solved problems. The solutions referred to, are based on past experiences. The basic purpose of applying this method is to collect cases for a case library. This can be use in future applications to mine knowledge.

This methodology will be separated into two main parts specifically the establishment of database and data analysis. For the raw database collection, over 1,000 cases were collected from open journals, patents, chemical engineering magazines and accident cases. All of the cases must relate to the chemical process industry. There are 502 cases on the current status of IS implementation elected for the analysis. The case should have at least one design improvement and it should be safer than the existing design.

The next is data analysis which is frequency analysis and ranking development. There are two parts of frequency analysis to be highlighted which is the frequency for the order of inherent safety and the frequency of the ISD keywords. There is also a list of strategies that has been used for the ISD implementation. All the results will be given in a ranking to get a picture of the overall current status of the inherent safety implementation in the chemical process industry.

3. Results

The result of this study can be separated into two sections of order of IS and IS keywords. The order of IS have 3 significance elements. The elements are 1st order IS, 2nd order IS (magnitude) and 2nd order IS (likelihood) while IS keywords have 4 significance elements consisting of minimisation, substitution, moderation, and simplification.

3.1 Order of inherent safety

According to CCPS (2008), the order of inherent safety can be classified into 1st Order IS and 2nd Order IS. The 1st order IS is related to the risk reduction strategy of avoiding hazard. This is also applicable to the strategy of elimination. Next is 2nd order IS which is separated into specific reduction strategy of magnitude reduction and likelihood reduction. Magnitude reduction strategy can be briefly described as a way to prevent an escalation of event due to poor control of hazardous sources at the plant. Magnitude reduction can be used as a severity control. Likelihood reduction can be defined as reducing the possibilities of occurrence of events.

As seen in Table 1, from total of 502 cases, only 12 % applied the 1st Order of Inherent Safety (hazard avoidance or elimination), 78 % of the 2nd Order of Inherent Safety (magnitude or severity reduction) and only 10 % for the 2nd Order of Inherent Safety (likelihood reduction). The order of implementation is as follows: magnitude reduction > hazard avoidance > likelihood reduction. Hazard avoidance as the 1st Order IS is quite difficult to apply compared to the magnitude reduction type of strategy. As for the likelihood reduction (2nd order), the low percentage of application is perhaps due to the very common, general strategy and simple ISD application (i.e. use of safer valves, gravity flow etc.) which is not reported in the open literature.

Table 1: Total number of database

Order of Inherent Safety	Inherent Safety Keywords	Total	Percentage
1st Order, 12 %	Substitution	58	12 %
2nd Order (magnitude), 78 %	Minimisation	242	48 %
	Moderation	151	30 %
2nd Order (likelihood), 10 %	Simplification	51	10 %
Total		502	100 %

CCPS (2008), highlighted that the 2nd order of inherent safety can be used for hazard reduction intrinsically but it cannot be as powerful as the 1st order of inherent safety. The hazard avoidance under 1st order IS has the largest safety benefit since process hazard is totally avoided from the process. The distribution of databases over the IS order is as shown in Figure 1.

3.2 Inherent safety keywords

From Table 1, it can be seen that the application of ISD keywords is unbalanced. With reference to the ‘substitution’ keyword (1st order of inherent safety), 58 cases were recorded with the percentage of 12 %. The 'minimisation' keyword represented 242 cases (48 %) while the keyword 'moderation' (under the same magnitude reduction group) signified 151 (30 %). The 'simplification' keyword contributed to the least number of cases with only 51 (10 %). Based on the percentage, the popular ranking of Inherent Safety application keywords can be summarised as: minimisation > moderation > substitution > simplification. The percentage of all four inherent safety keywords were presented in Figure 2.

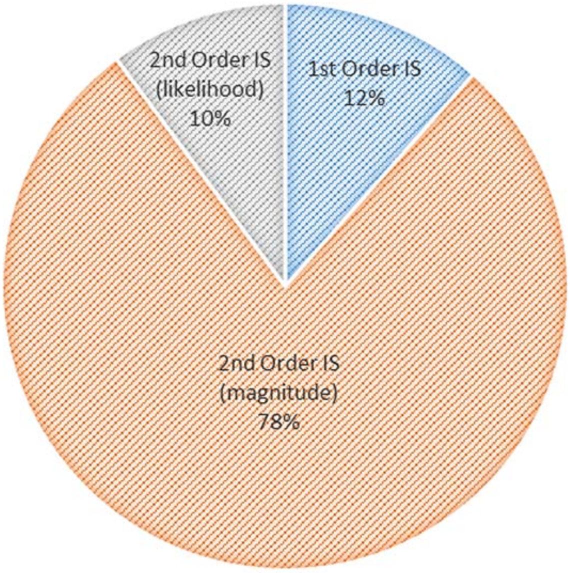

Figure 1: Percentage distribution of order of inherent safety

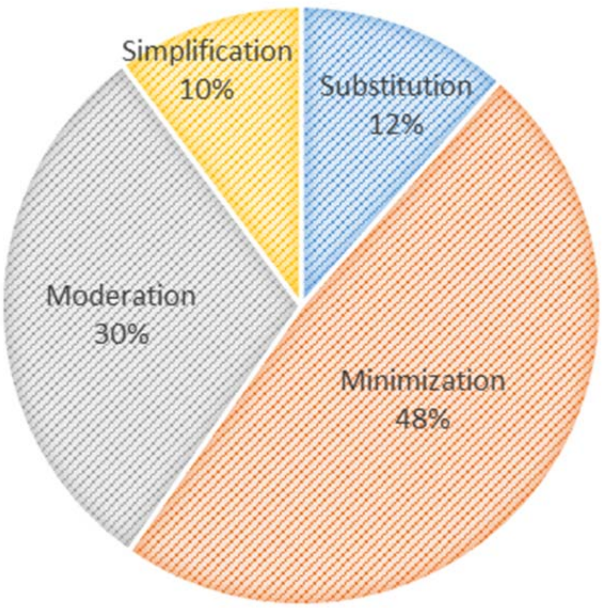

Figure 2: Percentage distribution of inherent safety keywords

An early conclusion that can be drawn from this particular analysis is that the 'minimisation' keyword seemed to be the preferred IS keyword to be applied in a process. The frequency of its application is considered high in the 502 cases analysed mainly due to its relation in improving equipment design. From the inherent safety keywords, there is a strategy that defines its category which lies under the inherent safety keywords.

Inherent safety is different compared to strategy which is about the approach that has been done to the equipment or process changes to achieve the criteria for the IS keywords category. Design changes could have one or more strategies and overlapping between that but for this study, only the superior strategy was chosen to eliminate the overlapping data between each other.

The substitution keywords are related to the replacement of a hazardous material of process control with an alternative of material less hazardous in order to eliminate or reduce hazards. There are 3 main strategies that fall under substitution keywords. There are change material (66 %), change process (19 %) and change system (16 %). Minimisation is focusing on the reduction of inventory or quantity of any hazardous material which releases energy or causes harm to the manufacturing plant (CCPS, 2008). The strategy that indicates the minimisation keywords is improve mixing (32 %), distillation efficiency (19 %), micro mixing efficiency (9 %), mass transfer rate (8 %), just in time (7 %) and heat transfer rate (6 %).

The third keyword is moderation that refers to the use of hazardous materials in a less hazardous condition so that the process is operating under less severe condition. The strategy from this keyword is containment (34 %), robust design (26 %), change form (15 %), dilution (7 %) and low operating condition (5 %). The last is simplification which refers to the elimination of process complexity. The related strategy is energy supply (16 %), flowrate control (14 %), simple separation (12 %), eliminate equipment (12 %), error proofing (12 %), change system (8 %) and change process (6 %). The description for each strategy that is mentioned above is listed in Table 2.

Table 2: Description of the strategy used for the inherent safety keywords

Strategy	Description
Change materials	The change of hazardous materials to the less hazardous materials. Example: toxic, flammable, corrosive
Change Process	The change at reaction part of the process Example: BMA process changed into Andrussow process
Change systems	The change at a part of a process besides the reaction part Example: Hydrocarbon refrigerant system changed into liquid nitrogen
Improve mixing	The improvement of chemical reaction that is initially slower to be more effective by enhancing the contact of the materials Example: Stirring, shaking
Distillation efficiency	Distillation process that incorporates the reaction process to help the separation process Example: Reactive distillation
Micro mixing efficiency	The improvement of contact between materials for reaction process at micro level Example: High gravity reactive precipitation
Mass transfer rate	Provides an effective condition that can improve the mass transfer for the particular reaction Example: A spinning disk reactor provides thin film that promotes high mass transfer rate
Just in time	The production or storage of hazardous material is made just when it is demanded in the process Example: On site generator
Heat transfer rate	The improvement of the thermal distribution so that the reaction will be more effective Example: Compact heat exchanger inside distillation column
Containment	Single or double protection that prevents materials from leaking Example: Double wall piping or storage tank
Robust design	Use of correct or tough materials that are prone to damage when designing an equipment Example: Stainless steel piping, composite materials
Change form	The change to the form of materials to make it less reactive Example: Solid phosgene is less hazardous than phosgene gas
Dilution	Materials that are not concentrated can be much less hazardous than the concentrated ones Example: Anhydrous ammonia is more hazardous than aqueous ammonia
Low operating condition	The change of process condition that is near to the ambient condition is preferable Example: Low temperature, low pressure

Table 2: Description of the strategy used for the inherent safety keywords (continue)

Strategy	Description
Energy supply	The change of the method of using the energy source in the safest way possible Example: Steam is better than fired heater
Flowrate control	The flow needs to be limited and controlled so that only a small and reliable amount is transferred to the next process Example: 3-way valve, orifices
Simple separation	The separation process that uses a simple mechanism without any difficult equipment design Example: membrane separation
Eliminate equipment	The changes of utilising less equipment by using the law of nature Example: gravity flow instead of pump
Error proofing	A way to differentiate certain equipment handling to prevent confusion Example: colour coding, different size connection

The full research has about 36 strategies for all the IS keywords but this paper only mentions 19 strategies. These 19 strategies are the top strategy for each respective IS keywords which is more than 5 %. The strategies of change system and change process can be found at both minimisation and simplification therefore it can be said that these two strategies can be significant for both keywords.

The result of IS keywords can be compared to the work that have been done by Kidam (2010) and Amyotte (2011). Kidam (2010) investigated around 364 cases reported in the Failure Knowledge Database located in the Japan Science and Technology website. Amyotte (2011) studied the U.S Chemical Safety Board (CSB) report that had around 200 cases. These two studies have classified the approach into four main and common ISD keywords namely minimisation, substitution, moderation and simplification but Kidam (2010) separated the error tolerance and limitation of effect in their own categories. The keywords distribution has a slight difference but the generalisation of it can take CCPS (2008) to be a reference which clearly generalises the error of tolerance and limitation of effect into the four main keywords. The difference in the results can be compared and tabulated in Table 3.

Table 3: Result from different research on inherent safety keywords implementation

	Kidam, 2010	Amyotte, 2011	This research, 2016
Minimisation	8 %	25 %	48 %
Substitution	21 %	22 %	12 %
Moderation	56 %	25 %	30 %
Simplification	15 %	27 %	10 %

For overall interpretation, only Amyotte (2011) has the result of near to equal for distribution among the keywords while Kidam (2010) has the biggest gap between the lowest and the highest keyword.

For minimisation keyword, Kidam (2010) has only 8 % while Amyotte (2011) has 25 %. There is a big difference in this research because 48 % is the biggest number compared to theirs. The substitution which is under 1st order IS is nearly similar between Kidam (2010) and Amyotte (2011) with 21 % and 22 %, while this research has about 12 %. The moderation keyword is very high at Kidam (2010) with 56 % but nearly the same as for Amyotte (2011) and this research with 25 % and 30 % respectively. The simplification keyword did not give too much gap between these three researches with 15 %, 27 % and 10 %.

4. Conclusions

From this research, it is well known that 1st order IS is the superior order compared to 2nd order (magnitude) and 2nd order (likelihood). Although it is well known to be superior yet its application in design changes is still low. The problem is due to the limited design knowledge as most of the research are just discussing it at the conceptual level rather that preparing a method as a tool to help design work. The significance of this research is to have the knowledge on distribution of design changes according to IS keywords. From the result, it can be pointed out that the targeted design changes at CPI are mostly towards magnitude reduction. This is

because, by controlling the severity of an accident, a catastrophic event will not happen. The 1st order IS seems to be slow to be adopted because it needs deep research which is related to the reaction mechanism and the changes for the certain equipment require much effort.
An extended research for the next project can focus more on how to educate designers to consider 1st order IS at the first instance for design project.

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