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A Credit Approach to Measure Inherent Hazards Using the Fire, Explosion and Toxicity Index in the Chemical Process Industry: Case Study of an Iso-max Unit in an Iran Oil Refinery

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ABSTRACT

Objectives: Indices are extensively used for ranking various units of a chemical process industry on the basis of the hazards they pose of risk a fire, explosion and toxicity release.

Methods: This type of ranking enables the professionals to identify the more hazardous units from the less hazardous ones so that greater attention can be paid to the former. The key process subunits in the Iso-max unit were identified based on parameters such as process pressure, temperature and material value. In next step, the main parameters affecting the FETI were identified and estimated, and the Mond FETI index was calculated for each subunit. In addition, the criteria offset measures for each case were identified and their influences were studied.

Results: The results showed that the process route's potential hazardous characteristics, such as major incidents, were associated with one or more of the following dangerous phenomena: thermal radiation, blast (pressure wave) and ejection of fragments, release of toxic materials and chemical concentration in the air. Intake amount assessments and the corresponding risk of exposure were also produced. By using statistical incident data of the risks of fire, explosion and toxicity, exposure risks can be estimated more realistically as probabilities. This approach is capable of comparing alternative processes to select the one which is inherently safest.

Conclusion: Using this method, the exposure risks in a process can be identified sooner, and proper risk management decisions can be made early in the process development or predesign stages.

Keywords: Inherent Hazards, Chemical Process, Criteria Offset Measures

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Introduction: An inherently safe plant is a plant with no absolute hazards, and 'zero risk'. It may be impossible to design and operate such an inherently safe plant. Therefore, hazards and risks need to be strategically and systematically managed [1, 2].

Safer approaches to plant design and general theories on how safety can be built into the design process have been presented since the 1960s [3]. Safety indices have been applied for identifying hazards and have generated alternative designs as well [2]. Most general and traditional safety approaches have focused on the layer of operation (LOP) method, where additional safety devices and features are added to the operational process. The LOP method has been successful in analysing safety systems. However, with this approach, process hazards may remain. It also increases the complexity of the process and hence the capital outlays and operating costs; in the oil and gas industries, 15% to 30% of the operating costs go to safety issues and pollution prevention [4]. Other approaches safety studies have tended to focus on hazard identification and control. In addition to the traditional analysis methods such as Check List, Safety Review Relative Ranking and What If analyses, more advanced hazard and risk analysis methods have been developed as well, such as Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Cause- Consequence Analysis (CCA), preliminary Hazard Analysis (prHA), Human Reliability Analysis (HRA) and Hazard and Operability (HAZOP) study have been developed [5-8].

For chemical process industry loss prevention and risk management several hazard indices have been developed. The safety-eighted hazard index (SWeHI) was developed as a tool to define fire, explosion and toxic release hazards [9]. The Environmental Risk Management Screening Tools (ERMSTs) instrument was developed by Four Elements Inc. for ranking environmental hazards including air, ground water and surface water pollution [10]. The Mond Fire, Explosion and Toxicity Index (FETI) is a tool to assess these three hazards [10]. The Hazardous waste index (HWI) is used as a tool for measuring flammability, reactivity, toxicity and corrosivity hazards of waste materials [9]. The Transportation Risk Screening (ADLTRS) model is a tool for determining the risk to people and the environment posed by chemical transportation operations [9]. Heikkila (1999) developed the Inherent Safety Index at the Helsinki University of Technology. This index classifies safety factors into two categories: chemical- and process-inherent safety. The chemical-inherent safety category includes the choice of materials used in the process by looking at its heat of reaction, flammability, explosiveness, toxicity, corrosivity and incompatibility of chemicals. The process-inherent safety covers the process equipment and its conditions such as inventory, pressure, temperature, type of process equipment and structure of the process [11]. The overall inherent safety index was developed by Edward and Lawrence (1993) to measure the safety potential for different routes of reaction to obtain the same product [12].

The fuzzy logic-based inherent safety index (FLISI) was developed by Gentile (2004) [13]. The major problem in applying inherent safety indices is that safety is mostly based on qualitative principles and cannot easily be evaluated and analysed. The FLISI was an attempt to use hierarchical fuzzy logic to measure inherent safety and provide conceptual framework for inherent safety analysis. Fuzzy logic is very helpful for combining qualitative information (expert judgement) and quantitative data (numerical modelling) by using fuzzy IF–THEN rules.

The Fire and Explosion Index (F&EI) was invented by Dow's chemical exposure hazards researchers and the American Institute of Chemical Engineers (AIChE) in 1967 as a tool to determine relative rankings of fire, explosion and chemical exposure hazards. It has been revised six times since then. Its last revision (7th edition) was published in 1994 [14]. A computer program was developed to automate F&EI calculation and perform sensitivity analysis using Microsoft's Visual Basic by Etowa et al. in 2002 [15].

However, their program was not intended to determine business interruption or loss control credit factors, when conducting process unit risk analyses. Index methodologies are found to be robust, but are not able to cover all safety parameters [16]. The application of the F&EI and SWeHI as predictive tools for loss prevention and risk management in the oil and gas industry can be considered a new use for them. One of the attempts in present study is to apply F&EI to predict the safety status of an old oil refinery.

The Mond FETI index is a relatively simple technique, including a complete methodology to calculate the total risk of a given process [17]. It does not require highly qualified experts to administer and its calculations are not time consuming. The FETI is the only index that considers all safety parameters and is able to select the most critical parts of the process. It is able to calculate the values of damages and other losses using day outage, property damage, replacement value and value of lost production. These characteristics make FETI stand out among other fire and explosion risk indices. The objectives of the present study were to measure the inherent fire, explosion and toxicity hazards in the Iso-max unit of the Tehran Oil Refinery using the Mond FETI Index.

Material and Methods:

The FETI was first presented by D. J. Lewis in 1979 [18]. The second edition of the Mond FETI Index discussed here was published in 1997 and applied to the present study of the Mond Division of ICI [19].The general procedure for using the Mond FETI is shown in Fig 1, and involves the following six steps:

The first step, as with the Dow Index, is to divide the plant into units, and it is better to start with too many than too few.

The Second step is to determine the material factor, B, which provides a numerical base for the indices. The material factor (MF), which represents the measure of the potential energy released by the material under study, is obtained first. The MF is obtained from databases, material safety data sheets (MSDS), or manual calculations. The dominant or key material upon which the material factor is based is next determined. It is defined as the compound or mixture in the unit which, due to its inherent properties and the quantity present, provides the greatest potentia1 for energy release by combustion, explosion or exothermic reaction. The material factor, **B**, is in most cases the net heat of combustion of the material in air, expressed as thousands of BTU per pound (2326 kJ/kg). For reactive combinations of materials, the heat of reaction is used if it exceeds the heat of combustion. This material factor is often the same as that given in the third edition of the Dow guide [18, 19]. The base is then modified by other considerations contained in the following sections.

The third step is to use the Mond form and manual to allocate penalty factors for the following aspects:

The **Special Material Hazards Factor (M)** is applied to take into account any special properties of the key material that may affect either the nature of the incident or the likelihood of its occurrence. Ten properties are listed, with corresponding penalties. They include any tendencies of the key material to act as an oxidant, to polymerise spontaneously, to decompose violently, to detonate, etc. One property, designated **m**, represents the mixing and dispersion characteristics of the material and also features in the aerial explosion index. The highest penalties recommended are for unstable materials that can deflagrate or detonate [19].

The **General Process Hazards Factor (P)** relates to the basic type of process or other operation being carried out in the unit. Six main types are listed, including material transfer, physical change-only processes and various types of reactions with different characteristics.

The **Special Process Hazards Factor (S)** reflects 14 listed features of the process operation that increase the overall hazard beyond the basic levels already considered. These account for operating temperature and pressure, corrosion, erosion, vibration, control problems, electrostatic hazards, etc. **S** is evaluated on the assumption that the plant has an adequate control system for normal operations. Credits for more sophisticated safety features such as explosion suppression and combustible gas monitors are applied later.

The **Quantity Hazards Factor (Q)** represents the quantity of combustible, flammable, explosive or decomposable material in the unit, which is treated as a separate factor in the Mond FETI Index. It is related to the total quantity **K** of such material in the unit. K also features in the fire index [20].

The **Layout Hazards Factor (L)** is another separate factor in the FETI Index. The normal working area N of the unit in square metres also features in the fire index, and is defined ‘as the plan area of the structure associated with the unit, enlarged where necessary to include any pumps and associated equipment not within the plan area of the structure.’ The height **H**, in metres above ground at which flammable materials are present in the unit, also features in the aerial explosion index. **L** also includes factors for the relation of ventilation rates to flammable vapours, which could escape, and ‘domino effects’ involving the spread of incidents from one unit to another. The **Acute Health Hazards Factor (T)** is not intended to reflect health hazards as such, but rather the delay caused by the toxicity of escaping materials when tackling a developing or potential fire or explosion. The factor is the sum of penalties for skin effects and inhalation.

The fourth step is to calculate indices for the following factors:

The equivalent Dow Index (3rd edition), whose formula was given earlier, is not used for interpretive purposes but features in later calculations.

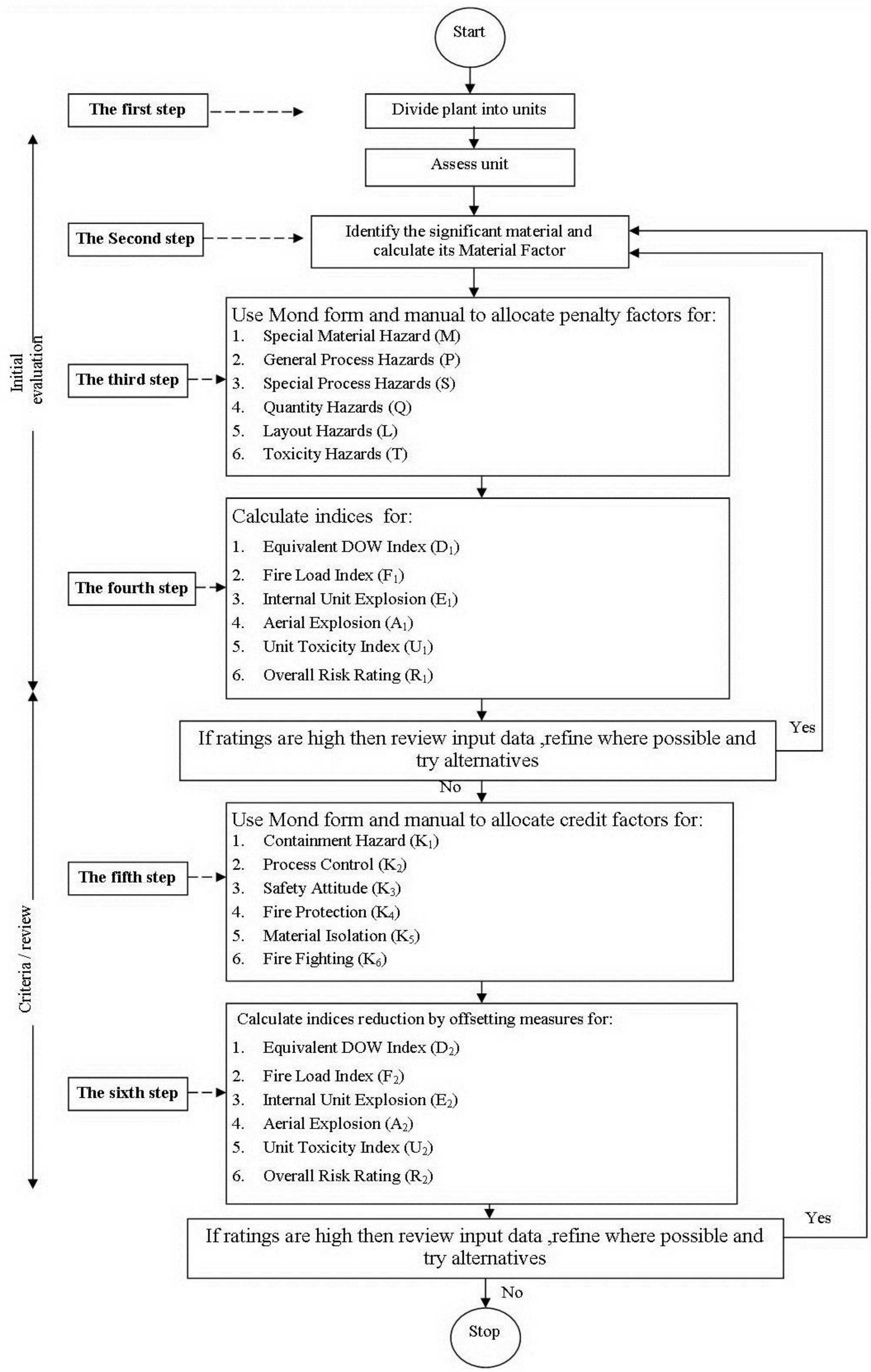

Fig 1. FETI Procedure (16)

The equivalent **Dow Index**, D1, is given by the formula:

$$D_1 = B\times\left(1+\frac{M}{100}\right)\left(1+\frac{P}{100}\right)\left(1+\frac{S+Q+L}{100}+\frac{T}{400}\right)(1)$$

The **Fire Index (F1**) relates to the amount of flammable material in the unit, its energy release potential and the area of the unit and is given by:

$$F_1 = B\times\frac{K}{N}\times 215(2)$$

F values in the range 0–2 class as 'Light', 5–10 as 'Moderate' and 100–250 as 'Extreme'. The Fire Index is related to the Fire Load, which would equal $2442\times F \text{in KJ}/\text{m}^2$ $\left(215\times F \text{in BTU}/\text{ft}^2\right)$ if all the available combustible material were consumed [18].

In practice often only 5%–10% of available combustible material is consumed before the incident is controlled. N is normal working area of the unit and is given by:

$$N = 2\times\frac{\pi D^2}{4}, D=\frac{L}{2}(3)$$

The **Internal Explosion Index (E1)** is a measure of the potential for explosion within the unit and is given by:

$$E_1 = 1+\frac{(M+P+S)}{100}(4)$$

An internal explosion index of 0–1.5 is categorised as light, 2.5–4 as moderate and above **6** as very high.

The **Aerial Explosion Index (A1)** relates both to the risk and magnitude of a vapour cloud explosion originating from a release of flammable material, usually present within the unit as a liquid at a temperature above its atmospheric boiling point. This index includes quantitative and qualitative factors, and is given as follows:

$$A_1 = B\times\left(1+\frac{m}{100}\right)\times\frac{Q\times H\times E}{1000}\times\frac{t}{300}\times(1+p)(5)$$

The **Overall Hazard Rating (R1)** is used to compare units with different types of hazards, and is given by:

$$R_1 = D_1\left(1+\frac{\sqrt{F\times U\times E\times A}}{10^3}\right)(6)$$

An Overall Hazard Rating of 0–20 is categorised as light, 100–500 as moderate, 1100–2500 as high and over 12 500 as extreme.

The **Toxicity index of unit (U1)**: it is obtained from multiplying the risk of internal explosion by hygienic risks factor:

$$U_1 = \frac{T}{100}\times E(7)$$

The Fire, Explosion and Toxicity Index is then calculated using equations 1 through 6 [21].

Criteria and review: Ranges of the six indices for different degrees of hazards are given in Table 1.The most important index is the overall hazard rating R1. Experience from applying the full method to operating plants has shown that it is uncommon for a unit, after a complete assessment, to have an R1 with a category rating greater than 'high'. It is therefore reasonable to assume that a unit assessed at this level can be operated in a satisfactory manner given full regard to the hazards indicated by the assessment. Offsetting usually reduces the overall hazard category by one or two levels and gives a clearer picture of the relative importance of the different protective measures which could be taken. When the initial assessment is unfavorable, the estimates should be refined by the use of better data [22]. The effects of possible changes in materials of construction, sizes and types of equipment and process conditions, and reduction in inventory should also be considered. When these changes have been made and all factors have been reviewed, their new values are entered in the 'Reduced Value' column of the form with a note on the reason for the change. The final stage of the index calculations in which the hazards are reduced by applying special safety features and protective measures is done on the basis of these reduced values.

Table 1. Mond Index ranges for various degrees of hazard

Potential hazard category	Fire load in BTU / sq. ft of Normal Working Area (effective value) F	Range of DOW / ICI Overall Index D	Internal Unit Explosion Index E	Aerial Explosion Index A	Unit Toxicity Index U	Overall Risk Factor R
Mild	0-2	0 – 20	0-1	0-10	0-1	0-20
Light		20 – 40				
Low	2-5	-	1 – 2.5	10-30	1-2.5	20-100
Moderate	5-10	40 – 60	2.5 – 4	30-100	2.5-5	100-500
Moderately Heavy	-	60 – 75	-	-	-	-
Heavy	-	75 – 90	-	-	-	500-1100
High	10-20	-	4 – 6	100-400	5-12	1100-2500
Very High	20-50	-	Above 6	400-1700	12-30	2500-12500
Intensive	50-100	-	-	-	-	-
Extreme	100-250	90 – 115	-	Above 1700	Above 30	12500-65000
Very Extreme	Above 250	115 – 150	-	-	-	Above 65000
Potentially Catastrophic	-	150 – 200	-	-	-	-
Catastrophic	-	Over 200	-	-	-	-

The scope for reductions in the indices by design changes is greatest before the design is 3finalized. In existing plants, most improvements result from the incorporation of the safety features and preventative measures contained in the offsetting section. However, reducing inventory has a significant effect on fire potential and can usually be achieved in new and existing plants [23].

The fifth step: Use the Mond form and manual to allocate credit factors for:

Safety features and preventative measures may reduce the probability or magnitude of an incident (sometimes both). The Mond manual classifies them in gested by which the values of the appropriate index should be multiplied when a safety feature or preventative measure (which is additional to the basic standard) is introduced. Before such measures can be evaluated, the basic standards that would apply to the design, construction, operation and personnel training have to be defined. As examples, the basic standard for pressure vessel design is taken as Pressure Vessel Construction Category 3 of BS 5500, and the basic standard for process control instrumentation is the minimum compatible with operation under normal design conditions (i.e. without alarms or trip systems).

Three broad categories of safety features and preventative measures reduce the probability of an incident, and the symbols used for the product totals of their sub-factors are:

A. Features that improve containment of process materials (K1)

B. Features that improve the safety of process control (K2)

C. Features that improve safety awareness of personnel (K3)

There are several possibilities in each category. The factor for each category is the product of the suggested values for the features and measures that apply. Three more broad categories of safety features and preventative measures are considered to reduce the magnitude of any incident. These are:

D. fire protection (K4)

E. isolation of process materials (K5)

F. firefighting (K6)

The factor for each category is obtained in the same way as for the first group. Brief descriptions of the features and measures considered in each category are given in the calculation sheet. Where only the basic standards apply, a factor of 1 is used. The factors K1 through K6 are calculated for the actual or proposed protective features.

The sixth step: Calculate indices reduction by offsetting measures

The offset indices are then obtained by multiplying the original (reduced) indices by the appropriate offsetting factors.

The equivalent **Offset Dow Index** (**D_2**) is given by the formula:

$$D_2 = D_1 \times K_1 \times K_2 \times K_3 \times K_4 \times K_5 \times K_6 \quad (8)$$

The equivalent **Offset Fire Index (F_2)** is given by the formula:

$$F_2 = F_1 \times K_1 \times K_4 \times K_5 \quad (9)$$

The equivalent **Offset Fire Index (F_2)** is given by the formula:

$$E_2 = E_1 \times K_2 \times K_3 \quad (10)$$

The equivalent **Offset Aerial Explosion Index (A_2)** is given by the formula:

$A_2 = A_1 \times K_1 \times K_5 \times K_6$ (11)

The equivalent **Offset Overall Hazard Rating (R_2)** is given by the formula:

$$R_2 = D_2\left(1+\frac{\sqrt{F_2 \times U_2 \times E_2 \times A_2}}{10^3}\right) \quad (12)$$

The equivalent **Offset Toxicity Index of unit (U_2)** is given by the formula: $U_2 = U_1 \times K_1 \times K_2 \times K_3 \times K_5$ (13)

The benefits given by the protective features are assessed by comparing the degrees of hazard for the original and the offset indices. These benefits apply only when the protective hardware is maintained and is in proper working order and when the management procedures upon which the benefits depend are followed. Neglect of either will cause the indices to revert to their original values. The importance of maintaining special protective features was clearly demonstrated by the Bhopal disaster (14).

In the final step, business interruption (BI) is calculated. BI is estimated based on the FETI Index calculated. The FETI calculation determines the radius and the area of exposure using equation [13]. Any equipment and facility in this area will be exposed to hazard [24]. $R = 0.256 \times D_1$ (14)

The damage factor that represents the overall effect of the fire and blast damage is then estimated. This is the damage to the unit equipment produced by fire, blast, release of fuel or reactivity energy.

By having the original equipment costs and value of production per month (VPM) as inputs, the actual minimum probable property damage (MPPD) can be determined, and BI is then calculated from equation [14] [25].

$$BI(\$US) = \frac{MPDO}{30} \times VPM \times 0.7 \quad (15)$$

A calculation spread sheet in Excel was developed for the present study. Its validity was tested using step-by-step validation of the calculation process, comparing the results with hand calculated results. Total validation of the calculation sheet was implemented by comparing the results with benchmark data. Tests for total validation were run prior to the final calculation.

Studied Case: The case for the present study involves an oil refinery established in 1968. The Iso-max unit consisting of the reactor and distillation units is one of the main units in this refinery. The flow diagram of the Iso-max unit is shown in (Fig 2). In the reactor, the Iso-feed is broken down through a hydro-cracking process in high temperature and pressure using hydrogen in a catalytic bed. In the distillation unit, the reaction product from the distillation tower is separated and stabilized in stabilizing towers. Light flammable hydrocarbons handling in very high operating pressures of up to 2750 psi and temperatures of up to 980°F, with exothermic reactions inside the reactors, categorize the Iso-max unit as engaging in a high-risk process [26]. The FETI was determined for eight sub-units of the reactor and distillation units, including: the reactor feeding oven, catalytic reactor, high-pressure separator, low pressure separator, distillation feeding container, distillation oven, distillation tower and diesel sputter tower in their existing status. The offset index was also predicted following the measurement of the inherent hazards of fire, explosion and toxicity for each of these sub-sections.

Table2. The important process units regarding fire and explosion risk and operating condition

Row	Process unit	Code of the process unit	Operating temperature (℃)	Operating pressure (pound per square inch)	Process unit materials	Material Factor
1	Reactor feed heater	2H-432	389	2497	Gas oil	16
2	Catalytic reactor heater	2V-432	444	2498	Gasoline , kerosene, Diesel, Methane, Ethane, LPG	21
3	High Pressure Separator	2V-433-(H.P.S)	60	2500	Gasoline , kerosene, Diesel, Methane, Ethane, LPG	21
4	Low Pressure Separator	2V-436-(L.P.S)	60	500	Gasoline , kerosene, Diesel, Methane, Ethane, LPG	21
5	Recycle Splitter Feed Flash Drum	2V-437	205	80	Gasoline , kerosene, Diesel, Methane, Ethane, LPG	21
6	Heater of distillation section	2H-433	388	30	Gasoline , kerosene, Diesel, Methane, Ethane, LPG, Hydrogen sulfide	21
7	Recycle Splitter	2V-439	374	28	Gasoline , kerosene, Diesel	21
8	Diesel Stripper	2V-444	260	25	Diesel	16

Table3. The physical and chemical properties of materials in process units

Row	Combinations	MF	IT(c)	Boiling Point	Flash Point	NFPA Classification		
						NR	NH	NF
1	**Hydrogen**	21	500	-252	gas	0	0	4
2	**Gas oil**	10	257	166	56	0	1	2
3	**Gasoline**	16	420	121	-42	0	1	3
4	**Kerosene**	10	210	115	43	0	1	2
5	**Diesel**	10	257	157	55-38	0	0	2
6	**Methane**	21	357	-162	<38	0	1	4
7	**Ethane**	21	472	-89	<38	0	1	4
8	**LPG**	21	468	-43	<38	0	1	4
9	**Hydrogen sulfate**	21	450	-76	gas	0	4	4

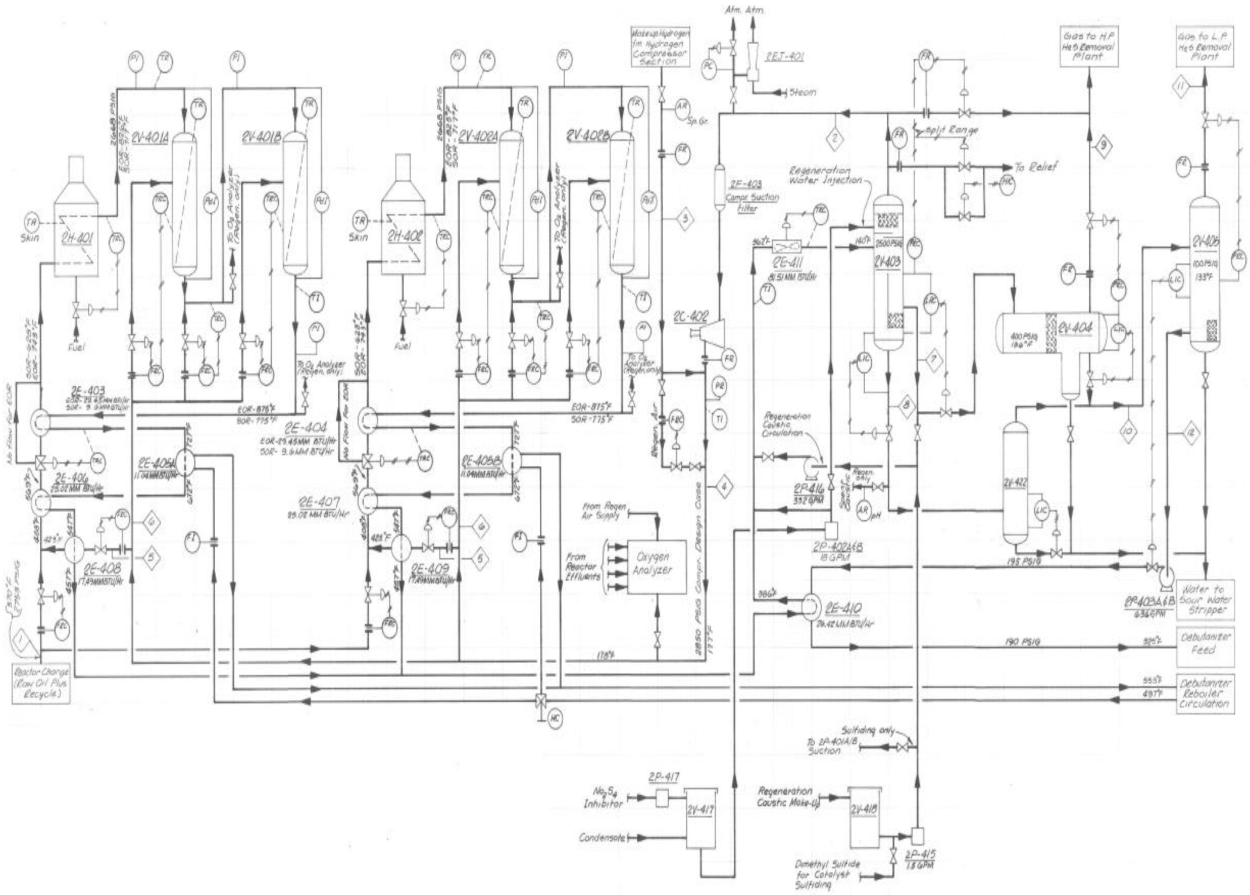

Fig 2. Iso-max process flow diagram (27)

Table 4. Potential hazard categories of Iso-max unit before and after a criteria offset

Process unit	Before Criteria offset		After Criteria offset	
	DOW Index D_1	Potential hazard categories	Offset DOW Index D_2	Potential hazard categories
Diesel sputter tower	134.8	Very Extreme	101.5	Extreme
Reactor feeding furnace	124.8	Very Extreme	101.2	Extreme
Distillation tower	214.2	Catastrophic	173.8	Catastrophic
Catalytic reactor	232.4	Catastrophic	194.4	Catastrophic
Distillation furnace	181	Potentially Catastrophic	145.9	Very Extreme
High pressure separator	228.6	Catastrophic	187	Catastrophic
Low pressure separator	217	Catastrophic	170.8	Catastrophic
Distillation feeding container	191.1	Potentially Catastrophic	155.1	Potentially Catastrophic

Results: The predicted DOW/ICI Overall Index $\mathbf{D_1}$ for the eight sub-units showed that the maximum, minimum and mean values of $\mathbf{D_1}$ were 232.4, 124 and 190.4 ± 38.6 respectively. With the application of criteria offset measures they were reduced to 194.4, 101.2 and 95.4 ± 24.1 respectively (Fig 3). The statistical paired t-test showed that the application of the criteria offset measures significantly ($p < 0.001$) reduced the $\mathbf{D_1}$ mean value.

According to the results, the catalytic reactor, with a maximum $\mathbf{D_1}$ of 232.4, is the most critical sub-unit.

At the present conditions, 6 sub-units have severe risks, while the diesel sputter tower and reactor feeding furnace both contain very extreme risks (Table 4). The implementation of the criteria offset measures reduced the potential hazard categories significantly (Table 4).

In the event of a crisis, the plant's distillation tower would experience the highest outage, with a Maximum Probable Day Outage (MPDO) of 280 days), while a failure at the reactor feeding furnace would shut down the plant for at least 115 days. After the implementation of the criteria offset steps, the plant would be expected to experience highest and lowest outages of 79 and 47days in the event of a fire and explosion at the catalytic reactor and reactor feeding furnace, respectively (Fig 4). The mean value of the MPDO is 204 ± 65.2 days with existing conditions. It would be expected to be reduced to 84.6 ± 45.8 days if the criteria offset measures were applied (Fig 4).

A statistical paired t-test showed that there is a significant difference ($p < 0.001$) between the MPDO mean values at existing conditions and after the proposed control measures were applied. The application of criteria offset measures is expected to reduce the mean MPDO by 51.2%.

The Iso-max unit would experience a maximum Fire Load (**F**) of 270 BTU/sq. ft and a minimum **F** of 105 BTU/sq. ft with failures at the catalytic reactor and distillation furnace, respectively (Fig 5). The plant would experience the highest **F** of 85 BTU/sq. ft and the lowest **F** of 49.6 BTU/sq. ft with failures at the distillation furnace and diesel sputter tower, respectively, following the implementation of the criteria offset measures (Fig 5).

The results also showed that the mean **F** value of the eight sub-sections considered was 66.5 ± 12.8 BTU/sq. ft. The application of the criteria offset measures would reduce it to 41.2 ± 7.6 BTU/sq. ft (Fig 5), which significantly differs ($p < 0.001$) from the present value.

The predicted Toxicity Index U for the eight sub-units showed that the maximum, minimum and mean values of U1 were 16.1, 5.6 and 11.4 ± 3.9 respectively. With the application of the criteria offset measures they would be reduced to 9.7, 3.4 and 6.9 ± 1.5 respectively (Fig 6). The statistical paired t-test showed that the application of the criteria offset measures significantly ($p < 0.001$) reduces the U1 mean value.

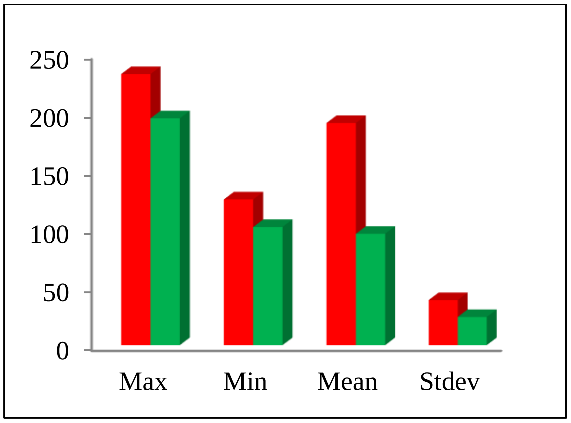

Fig 3. DOW / ICI Overall Index D_1 Iso-max unit before and after Criteria offset

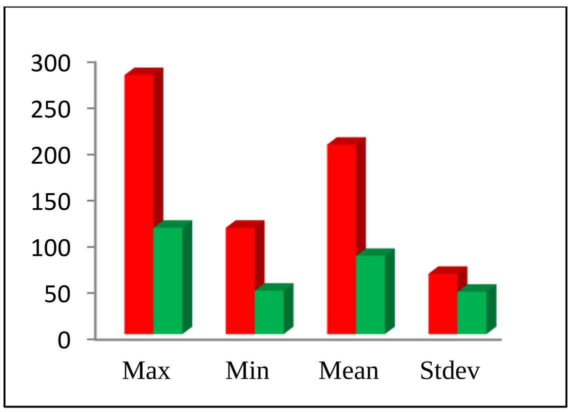

Fig 4. MPDO(day) of the Iso-max unit before and after criteria offset

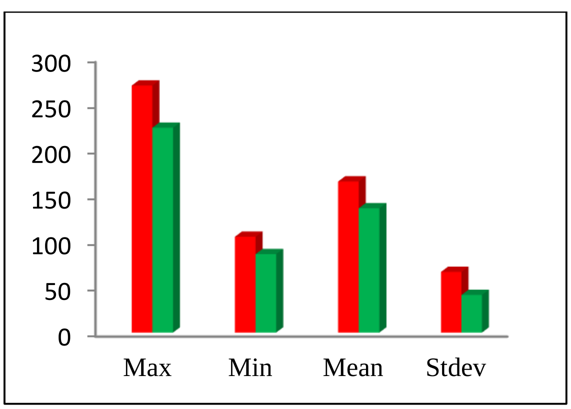

Fig 5. Fire Load (F) of the Iso-max unit before and after criteria offset

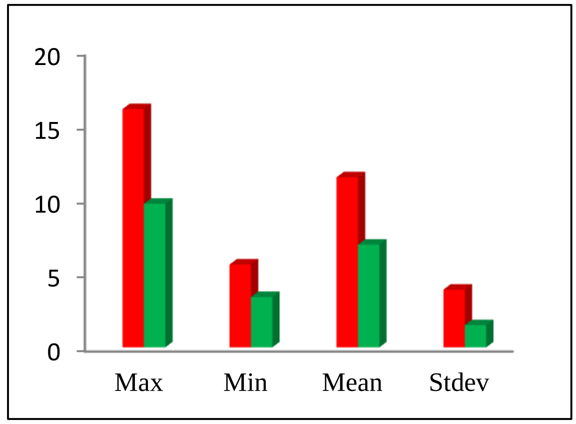

Fig 6. Toxicity Index (U) of the Iso-max unit before and after criteria offset

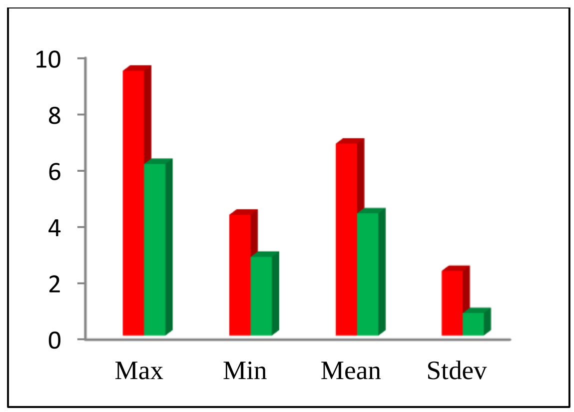

Fig7. Internal Unit Explosion Index **(E)** Iso-max unit before and after Criteria offset

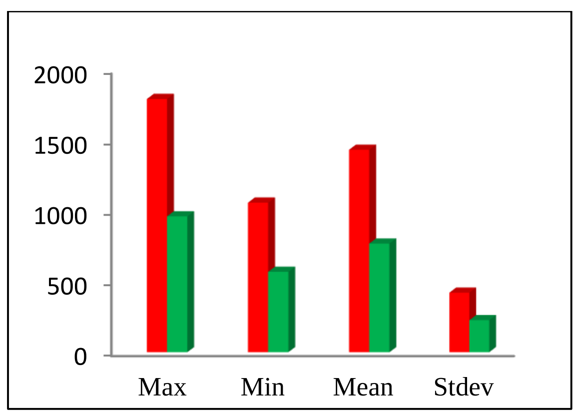

Fig 8. Aerial Explosion Index (**A**) Iso-max unit before and after Criteria offset

According to the results, the distillation feeding container with a maximum **U** of 232.4 is the most critical sub-unit. The Iso-max unit calculations for the Internal Unit Explosion Index (E) for all eight sub-units showed that the maximum, minimum and mean values of E were 9.4, 4.3 and 11.4 ± 3.9 respectively. With the application of the criteria offset measures they were reduced to 9.7, 3.4 and 6.8 ± 0.8 respectively (Fig 7). The statistical paired t-test showed that the application of the criteria offset measures significantly ($p < 0.001$) reduced the mean E value.

According to the results, the catalytic reactor with a maximum E of 9.4 is the most critical sub-unit.

The predicted Aerial Explosion Index (A) for all eight sub-units showed that the maximum, minimum and mean values of A were 1794, 1062 and 1435.1 ± 423 respectively. With the application of the criteria offset measures they were reduced to 964.7, 571 and 771.6 ± 227.4 respectively (Fig 8). The statistical paired t-test showed that the application of the criteria offset measures would significantly ($p < 0.001$) reduce the A mean value. According to the results, the catalytic reactor with a maximum A of 1794 is the most critical sub-unit.

The Iso-max unit Overall Risk Factor, I, for the eight sub-units showed that the maximum, minimum and mean values of R were 9800, 4021 and 5620 ± 1800 respectively. With the application of criteria offset measures they would be reduced to 5233, 2033 and 2860 ± 789 respectively (Fig 9). The statistical paired t-test showed that the application of the criteria offset measures would significantly ($p < 0.001$) reduce the mean value of R. According to the results, the catalytic reactor with a maximum I of 9800 is the most critical sub-unit.

According to the results, in case of a failure, the highest, lowest and mean value of the actual MPPD in the eight sub-units were $10.1, $3.8 and $7.3 ± 1.4 million US dollars respectively. With the application of criteria offset measures they were expected to be reduced to $3.8, $1.3 and $2.8 ± 0.5 million US dollars respectively (Fig 10). The statistical paired t-test showed a significant difference ($p < 0.001$) between the actual MPPD mean values at existing conditions and following the interventions.

A failure in the distillation tower would lead to the largest business interruption cost, totalling up to $856 million US dollars in the Iso-max unit. The BI cost would be reduced significantly ($p < 0.001$) by 64.2% (Table 3) with the criteria offset measures applied. After the implementation of the criteria offset measures, a failure in the catalytic reactor would lead to the highest BI cost, $232.6 million US dollars (Table 5).

Table 5. Business Interruption costs due to fire, explosion and toxicity in the Iso-max unit (million US$)

BI	before Criteria offset	after Criteria offset
Max	10.1	3.8
Min	3.2	1.3
Mean	7.3	2.8
Stdev	1.4	0.5

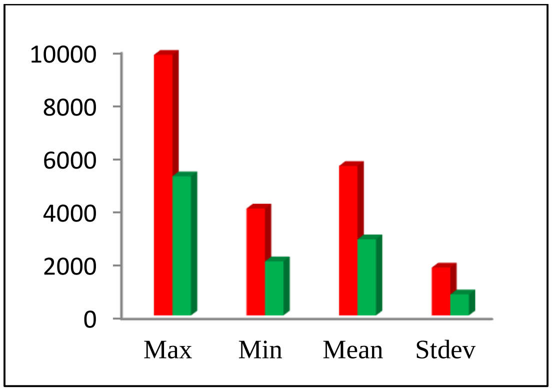

Fig 9. Overall Risk Factor I Iso-max unit before and after Criteria offset

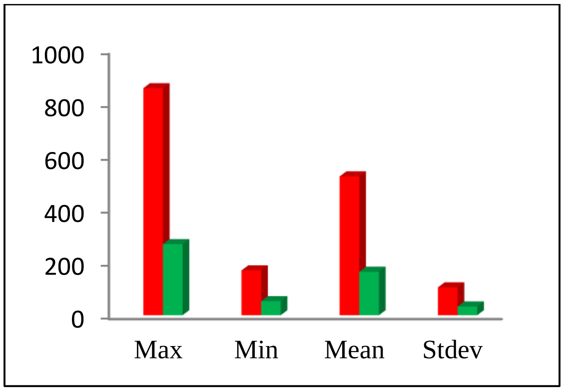

Fig 10. MPPD(million US$) Iso-max unit before and after Criteria offset

Discussion and Conclusion: Different studies including Gupta et al. (1997), F. I. Khan (2001) and Suardin et al. (2007) [23,24] showed that reducing the amount of material used in chemical processes leads to a lower F&EI, which agrees with the results of the present study. The application of criteria offset measures would be expected to reduce the mean values of FETI by almost 56.2%. The implementation of a drainage system, as the most effective and applicable criteria offset, was expected to reduce the mean value of FETI by 26.4%.Jensen and Jorgensen (2007) obtained a similar F&EI of 238 for the methyl isocyanate container in the Bopal incident [20]. With Gupta's suggestion considered for the modification of BI, the mean value of BI would be expected to be modified by 49.8% [21].

The high volume of liquids pumped from three reactors to the high pressure separator, the high amount of heat released, liquidity of the material, improper drainage system, process temperatures higher than the liquids boiling point, the application of hot fluid in heat exchangers, high corrosive potential and the leakage potential from the sight glasses are the main reasons for the high FETI in the high pressure separator subunit [23].

High operating pressure was the main specification for the high pressure separator in present study, while the high material factor of methyl isocyanate was the main reason for the larger F&EI calculated in Jensen and Jorgensen's study [14].

B. J. Tylor (1985) suggested a modification of a 50% overestimate in the Mond FETI Index parameters for developing countries due to the international nature of large projects which involve multinational funding, as well as the licensing of technology, design, fabrication, erection, commissioning and/or training to foreign companies [24].

A method for estimating the measure of inherent hazards was proposed, using a fire, explosion and toxicity risk evaluation during the development and design stages of chemical processes. The credit approach to measure inherent hazards can be performed through chemical concentration- or intake-based methods. Both the General Process Hazards Factor (P) and the Special Process Hazards Factor (S) can be calculated by standard process module-based approaches in the PFD stages. To depict a realistic exposure scenario, the present study used an oil refinery as its case example. The results of this assessment may be used to characterize the exposure risk and to compare design concepts based on their potential health impacts.

The Mond FETI method was tested with eight process subunits for the Iso-max unit. The results suggest that one sub-unit had a catastrophic risk, while one had a very extreme risk for fire, explosion and toxicity; these sub-units posed the most potential harm for health and safety. The catalytic reactor at high pressure was the most critical subunit of the Iso-max, with a DOW/ICI Index of 232.4. These figures provide an idea about the relative exposure levels of the process concepts considered. The high pressure separator was the least dangerous subunit, with a DOW/ICI Index of 222.6. The method developed is simple and flexible enough for use by large scale continuous plants using volatile compounds, such as petrochemical plants and oil refineries, and can be performed for any process development or design phase (preliminary PFD, PFD or PID stages). The calculation of this method of measuring inherent hazards varies; however, depending on which design stage is considered. The method allows the potential fire, explosion and toxicity risks of competing processes or the risk level of a process already in the development stage to be foreseen. This, in turn, enables early actions to be taken with process route selection or choices of dedicated technology , such as leak-proof valves or hermetic pumps to reduce fire, explosion and toxicity risks.

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