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SUITABILITY ANALYSIS OF CORRECTIVE ACTIONS TO PREVENT MAJOR CHEMICAL PROCESS ACCIDENTS

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Graphical abstract

Type of Accident Contributors	Inherently safer	Passive-engineered	Active-engineered	Procedural
External factors	4	3	2	1
Design errors	4	3	2	1
Technical errors	2	4	3	1
Human errors	1	2	3	4
Organizational errors	1	2	3	4

Note:

4 = Most suitable corrective actions; the root causes are successfully corrected; the hazards are mostly removed; risks are reduced by using both likelihood and consequence aspects.
3 = Suitable corrective actions; the root causes are partly corrected; the hazards are not completely removed; risks are reduce by using likelihood or consequence aspects; may require monitoring/maintenance afterwards to reduce residual risks.
2 = Less suitable corrective actions; the root causes are inadequately corrected; focus on add-on protection systems; require stringent monitoring/maintenance afterwards to mitigate risks.
1 = Not suitable corrective actions; the root causes are wrongly corrected.

Abstract

Recent accident analyses show that accident rates in the chemical process industry (CPI) are still increasing. The identified contributing factor to the scenario is poor learning from accidents which allows occurrence and recurrence of major chemical accidents. The paper examines the suitability on the recommended corrective actions to prevent accident by resolving various types of accident contributors (i.e. external factors, design errors, technical errors, human errors and organisational errors). Therefore, 468 major accident reports were retrieved from several accident databases to analyse accident contributors and their corresponding corrective actions. In this research, the suitability analysis is conducted using *accident contributor - corrective action logic matrix*. The matrix is constructed based on initial capital, operating cost, reliability, and complexity; and the ability to correct root causes, reduce risks in terms of likelihood and/consequence, and afterwards monitoring/maintenance. From the analysis, about 46% of the corrective actions are considered as unsuitable (i.e. less suitable or not suitable). As the contributors are inadequately/wrongly corrected, thus contributing to non-decreasing accident rates of the industry.

Keywords: Accident analysis, accident contributor, corrective action, major chemical process accidents, suitability analysis

Abstrak

Kadar kemalangan bagi industri kimia sentiasa meningkat. Antara faktor penyumbang kepada peningkatan ini adalah kurang mengambil iktibar dari kemalangan-kemalangan lampau. Kertas kerja ini bertujuan untuk mengenal pasti ketidaksesuaian tindakan pembetulan dalam menyelesaikan pelbagai punca kemalangan. Oleh itu, 468 laporan penyiasatan kemalangan besar telah dianalisis. Dalam penyelidikan ini, ketidaksesuaian tindakan pembetulan untuk pelbagai punca kemalangan ditentukan dengan menggunakan matrik logik yang telah dibangunkan berdasarkan kos, keberkesanan dll., keupayaan tindakan pembetulan untuk menyelesaikan punca kemalangan, mengurangkan risiko dari aspek kebarangkalian dan tahap bahaya, dan penyelenggaraan/pemerhatian selepas tindakan pembetulan. Sebanyak 46% tindakan pembetulan adalah dianggap tidak sesuai kerana tidak menyelesaikan punca kemalangan lantas menyumbang kepada peningkatan kadar kemalangan dalam industri.

Kata kunci: Analisa kemalangan, punca kemalangan, tindakan pembetulan, kemalangan proses industri, analisa kesesuaian

1.0 INTRODUCTION

Majority of recent accident analyses of the chemical process industry (CPI) have reported on the increasing major accident rates in the US and China [1, 2]. Other comprehensive analysis using the information in open literature showed non-uniform fluctuations of accident occurrences and consequences in 1988 till 2012 [3]. The most recent accident was the Tianjin chemical plant explosions and fires occurred on August 12, 2015 due to dissipation of wetting agents of nitrocellulose containers leading to partial drying and accelerating decomposition reactions. The rising temperature and pressure within the containers damaged the containers and released a large amount of nitrocellulose. The release was ignited by neighbouring sources and resulted in explosions. Then, fires ensued and caused big secondary explosions, killing 165 people and injuring 798 of others [4].

Occurrence and recurrence of major accidents in the CPI indicate the need to learn from past accidents to improve reliability and performance of process safety and risk management in the industry [5]. Major challenges of learning from accidents are lack of methods to establish safe plant operation by identifying possible accident contributors and safety measures; and lack of detailed models to support emergency response operation and decision-making in action situations [6]. Currently, many significant risk management researches have been conducted to enhance inherent safety features using evolution matrices; and application and quantification of inherent safety for real time decision-making. Data uncertainty, information scarcity, and process systems complexity in the industry inhibit development of process safety and risk management model [3]. However, comprehensive tool to determine suitability of hierarchy of controls per accident contributors is still lacking.

In general, the contribution of process equipment failures as the direct causes of major accidents in the industry is significant. It is reported that 79% of the root causes of the failures are technical-oriented, followed by human and organizational errors (19%), and external factors (2%), respectively [7]. Technical errors are classified into general technical errors and design errors (i.e. a design error is deemed to occur if the design features or operating procedures are changed after an accident has occurred) [8, 9]. Several analyses classified accident contributors into mechanical failure, external event, human factors, impact failure, violent reaction, instrument failure, upset process condition, and service failure [10]; origin of accident contributors in the process plant design lifecycle (i.e. development and implementation, operation, and management) [11]; and technical features (i.e. safety barrier failure, barrier task failure, and, management delivery system failure) [12]. As most accidents in the CPI are caused by multiple and interrelated contributors, emphasis on individual type of accident contributors is insufficient. The industry requires comprehensive safety measures which includes both technical and management aspects to prevent accidents at the workplace. Moreover, the findings of the analyses are inappropriate as they are case-specific thus difficult to applied in the industry.

On the other hand, there is lack of analyses on the recommended hierarchy of controls in the industry to prevent accidents, resulting in limited publications available on process safety and risk management. Nowadays, most safety analyses often emphasized on general classifications of the corrective actions in terms of inherently safer, passive-engineered, active-engineered, and procedural strategies [13, 14]. The most reliable controls are inherently safer, followed by passive-engineered, active-engineered, and procedural strategies, respectively [15]. Hierarchy of controls are further grouped as preventive and corrective actions. Preventive action is the action applied to eliminate the contributor of a potential non-conformity to prevent occurrence of accidents i.e. proactive approach whereas corrective action is the action taken to fix the contributor of the non-conformity and prevent recurrence of accidents or reactive approach [16].

In the paper, major accident investigation reports were retrieved from several accident databases to determine suitability of the recommended corrective actions against different classes of accident contributors. The analysis was conducted using the developed suitability contributor-action logic matrix.

2.0 METHODOLOGY

In the research, about 1,000 major chemical accidents (i.e. fire, explosion and/or toxic release) investigation reports were retrieved [17] from the US Chemical Safety and Hazard Investigation Board (CSB) [18], US National Transportation Safety Board (NTSB) [19], US Environmental Protection Agency (EPA) [20], Japan Science and Technology Agency-Failure Knowledge Database (JST-FKD) [21], and EU Major Accident Reporting Systems (eMARS) [22] databases.

Initially, only accidents occurred in 1990 till 2014 were selected for the analysis (mean=2000). About 468 out of 1,000 accidents involving six major process equipment failures (i.e. piping systems, reactors, storage tanks, process vessels, heat transfer equipment, separation equipment) as the direct causes of accidents [7] with identified root causes and recommended corrective actions included in their investigation reports were analysed. The selection methodology is shown in Figure 1.

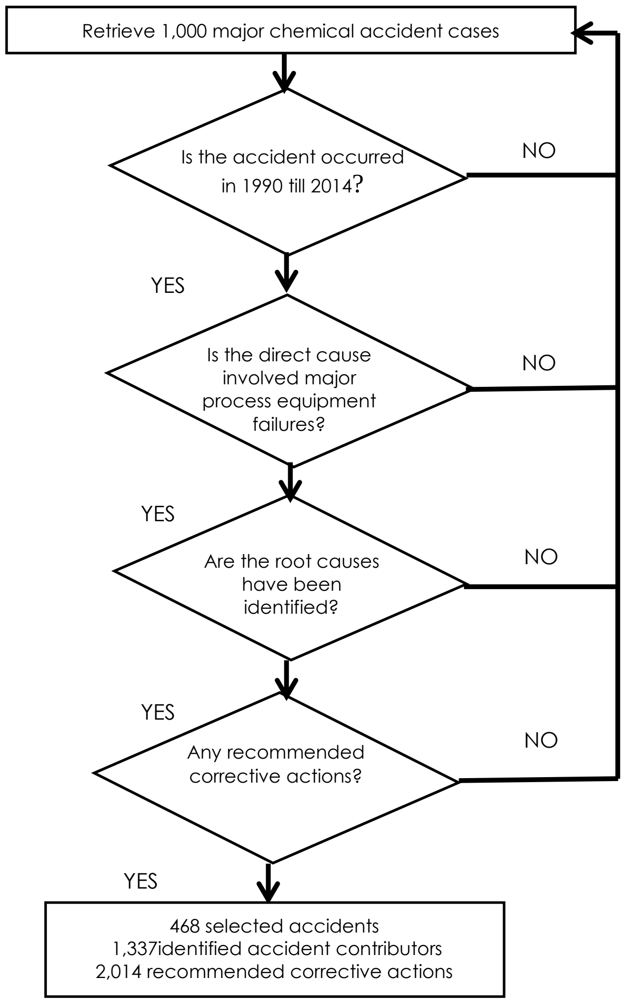

Figure 1 Selection of major accident cases

Lately, several accident analyses have reported on significant impact of technical errors in leading to accidents in the CPI [7, 23, 24]. Other studies emphasized on design errors [8, 9] and natural hazards [25]. Human errors [26-28] and organizational factors [29] also play major roles as accident contributors in the CPI. Comprehensive accident contributor classifications are needed to identify all hazards in the design and operation of chemical installations to prevent accidents in the CPI. Therefore, the identified accident contributors are classified into external factors, design errors, technical errors, human errors, and organizational errors using procedural HAZOP deviations which incorporate both management and technical system failures. Hence, the developed classifications are suitable for detailed assessments and coarse preliminary assessments throughout process plant lifecycle. The classifications are summarized in Table 1.

Table 1 Classification of accident contributors

Errors	Descriptions	Examples
External Factors	Errors related to nature and sabotage.	-Seawater -Cold -Heavy rain -Lightning -Flood -Earthquake etc.
Design Errors	Errors related to lack of hazard analysis, lack of risk assessment, inadequate safeguards, improper layout/procedures, and utilities.	-Safety/contingency -Wrong components -Wrong composition -Instrumentation -Procedure not applicable -Relief -Startup/shutdown
Technical Errors	Errors related to deviations from normal operating condition.	-Loss of containment -High temperature -Overpressure -Overfill -Shock/fatigue -Friction -Stress corrosion -Vibration -Reverse flow -Low temperature -Underpressure -Water hammer -Less agitation -Dispersion -Low flow
Human Errors	Errors due to tasks beyond the physical/mental ability, poor training/instructions, violations, and unintentional actions.	-Procedure not followed -Lack of competence -Insufficient/incorrect information -Unclear responsibilities
Organiza-tional Errors	Errors in planning, organizing, leading, and controlling management functions to achieve desired tasks.	-Not fitted for purpose -Procedure not available -Interference effects from others -Too many personnel -Too few personnel

Then, the recommendation section of the reports were analysed to determine current corrective action recommendations in the CPI. The actions are classified into their respective hierarchy of controls (i.e. inherently safer, passive-engineered, active-engineered, and procedural strategies). Inherently safer strategies are primary strategies for hazard avoidance and control at its source through use of less hazardous materials and process conditions using minimization, substitution, moderation, and simplification principles. Passive and active-engineered strategies are add-on hierarchy of controls installed to further reduce risks in terms of likelihood and consequence. Passive-engineered strategies employ systems that remain static and do not perform any fundamental operation such as dikes, containment, and firewall. In contrast, active-engineered strategies utilize safety devices (i.e. relief valves, controllers, detectors, and alarms) that respond to process changes. Procedural strategies only require personnel to perform an action to avoid hazards, reduce risks, and ensure safe plant operation by incorporating adequate training, supervision, procedure, work instructions, inspection, and maintenance [15].

Accident investigation reports generally list the recommendation for corrective actions. Therefore, to determine suitability of the actions per specific accident contributor, contributor-corrective action mapping were carried out using brainstorming. Three scenarios of the mapping are: (1) a corrective action is able to resolve an accident contributor; (2) a single corrective action is able to resolve multiple accident contributors; and (3) multiple corrective actions are required to resolve an accident contributor. For example, in scenario (1), an accident caused by the use of a lot of flexible hoses that led to wrong hose connection is recommended to install fixed connections wherever possible. For scenario (2), substitution an air opening portion of a process vessel with an inert gas is able to prevent accident due to spontaneously ignition of materials, inadequate design, and incorrect judgment in operation. In contrast, scenario (3) is depicted in a storage tank accident due to inadequate storage of explosives (i.e. design error) whereby eight corrective action are needed such as reducing size of the container, providing a deadline for storage of explosives, installing temperature and humidity recorders, enhancing monitoring systems, enhancing safety knowledge, establishing instruction system for manufacturing manager at the site, strengthening safety management system through double checks, and conducting stability tests for explosives.

Finally, the suitability analysis was conducted using the developed accident contributor-corrective action logic matrix as shown in Table 2. In the research, four levels (i.e. most, suitable, less, and least) of suitable contributor-action logic matrix are developed per each class of accident contributors using initial capital, operating costs, complexity, and reliability of hierarchy of controls. As shown in Figure 2, the initial capital and operating costs required for process plant modifications are cheaper for inherently safer than other layers. At the latter stages, the modifications are difficult as the complexity increases throughout process plant lifecycle. Although the costs for procedural strategies are the cheapest, the reliabilities are the lowest [30]. Thus, expert judgements are used to balance the ability of each layer of hierarchy of controls to correctly eliminate hazards, reduce risks in terms of likelihood and consequence, and monitoring/maintenance requirements afterwards in the industry.

Logically, the most suitable solutions for external factors and design errors are inherently safer design changes (e.g. design facilities which eliminate unnecessary complexity, make operating errors less likely, and forgiving errors). The suitable corrective actions for external factors and design errors are passive-engineered, followed by active-engineered and procedural strategies. In the industry, passive-engineered strategies are prioritized before active-engineered strategies in case of inability for hazard avoidance and in need of protective measures whenever possible; and procedural strategies are the last resort for controls [30]. Thus, design errors are corrected using electrical tracing instead of steam tracing to easily control and prevent hot spots; installing protection such as fencing or barricades to protect aboveground pipes from damage from vehicles; installing automatic shutoff valves or remote control valves in high consequence areas; and establishing corporate requirement for written freeze protection programs (i.e. in decreasing suitability). For technical errors, the most suitable controls are passive-engineered, followed by active-engineered, inherently safer, and procedural strategies. On the other hand, the most suitable controls for human errors and organizational errors are procedural, followed by active-engineered, passive-engineered, and inherently safer strategies, respectively (Table 2).

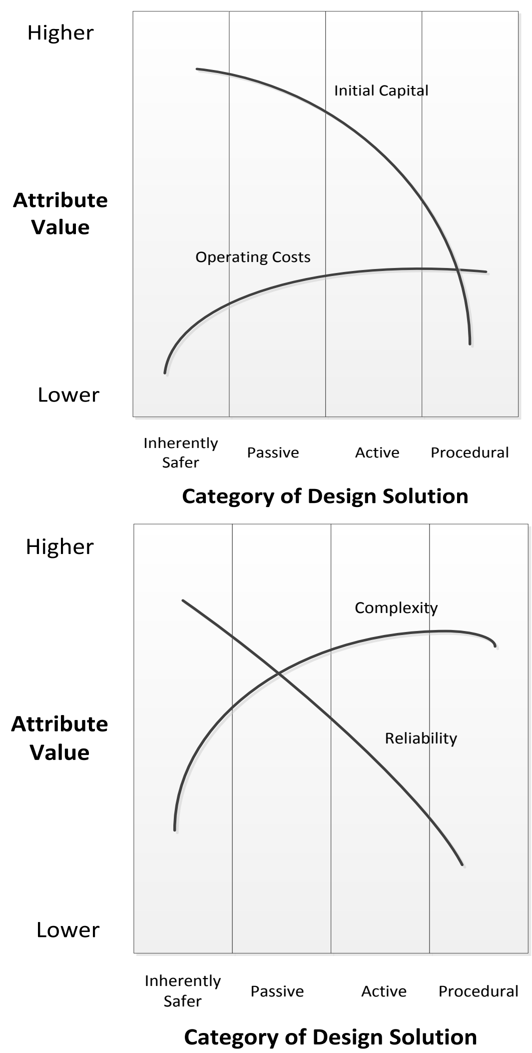

Figure 2 Comparison of cost and functional attributes for design categories (typical trends) [30]

Table 2 Suitability contributor-action logic matrix

Type of Accident Contributors	Hierarchy of Controls			
	Inherently safer	Passive-engineered	Active-engineered	Procedural
External factors	4	3	2	1
Design errors	4	3	2	1
Technical errors	2	4	3	1
Human errors	1	2	3	4
Organizational errors	1	2	3	4

Note:

4 = Most suitable corrective actions; the root causes are successfully corrected; the hazards are mostly removed; both likelihood and consequence aspects of the risks are reduced.

3 = Suitable corrective actions; the root causes are partly corrected; the hazards are not completely removed; either likelihood or consequence aspects of the risks are reduced; may require monitoring/maintenance afterwards to reduce residual risks.

2 = Less suitable corrective actions; the root causes are inadequately corrected; risk controls focus on add-on protection systems; require stringent monitoring/maintenance afterwards to mitigate risks.

1 = Not suitable corrective actions; the root causes are wrongly corrected.

3.0 RESULTS AND DISCUSSION

In total, 468 major chemical accidents were selected for further analyses. The accidents resulted in 307 fatalities and 2,002 injuries. About 56% of the accidents occurred in Europe; 28% in Japan; and 16% in US. From the analysis, the highest process equipment involved in the accidents are piping systems (25%), followed by storage tanks (21%), process vessels (17%), heat transfer equipment (16%), and reactors (15%). The least process equipment involved is separation equipment (6%).

3.1 Accident Contributor Analysis

Based on the analysis, design errors (45%) are the highest accident contributors in the CPI, followed by human errors (23%), technical errors (22%), and organizational errors (9%). The least significant accident contributors are external factors (1%). Further details on the accident contributor ranking are listed in Table 3.

Design errors are errors related to lack of hazard analyses and safe guards; and improper layout/procedures and utilities. In the research, the errors are classified as safety/contingency, wrong equipment/parts, wrong composition, instrumentation, procedure not applicable, relief, and startup/shutdown. Safety/contingency errors are errors related to lack of process analyses and risk assessments during operation and emergency preparedness. Examples of safety/contingency errors are inappropriate design of tank without adequate safety controls in-place, inadequate anti-flooding measures, and inappropriate sitting of the establishment. Wrong equipment/parts and wrong composition are normally considered in terms of material compatibility with process chemistry design corrosion allowance and material quality per specifications [31]. 'Procedure not applicable' is included as a design error as design errors are deemed to occur if any changes are done on the design or procedure [8, 9].

Table 3 Accident contributor ranking

Type of Accident Contributors	Percentage
Design Errors (45%)	
• Safety/Contingency	11.3%
• Wrong components	10.4%
• Wrong composition	9.5%
• Instrumentation	5.4%
• Procedure not applicable	4.1%
• Relief	3.6%
• Startup/shutdown	0.9%
Human Errors (23%)	
• Procedure not followed	8.1%
• Lack of competence	7.6%
• Insufficient/incorrect information	6.2%
• Unclear responsibilities	1.2%
Technical Errors (22%)	
• Loss of containment	5.7%
• High temperature	4.2%
• Overpressure	4.0%
• Overfill	3.8%
• Shock/fatigue	1.5%
• Friction	0.7%
• Stress corrosion	0.4%
• Vibration	0.4%
• Reverse flow	0.2%
• Low temperature	0.2%
• Underpressure	0.2%
• Water hammer	0.2%
• Less agitation	0.2%
• Dispersion	0.2%
• Low flow	0.1%
Organizational Errors (9%)	
• Not fitted for purpose	5.2%
• Procedure not available	2.0%
• Interference effects from others	1.2%
• Too many personnel	0.4%
• Tow few personnel	0.2%
External Factors (1%)	
• Seawater	0.3%
• Cold	0.1%
• Heavy rain	0.07%
• Lightning	0.07%
• Flood	0.07%

In most research, human errors are commonly classified as unintentional action/mistakes/slips or lapse of attention; intentional but mistaken action/violations; mismatches between the mental/physical abilities and the job requirements; and poor training/instructions. However, in the research, human errors are classified as 'procedure not followed', lack of competence, insufficient/incorrect information, and unclear responsibilities. Examples of human errors are an operator disregarded the regulated procedures; an operator did not have a specific preparation for the tasks; lack of communication between formulation and conditioning teams; and top managers failed to detect and hold refinery management accountable for deficiencies.

Deviations from normal operating conditions are considered as technical errors. Among the identified technical errors are loss of containment, high temperature, overpressure, overfill, shock/fatigue, stress corrosion, vibration, reverse flow, low temperature, underpressure, water hammer, less agitation, dispersion, and low flow. Oxygen entered into the originally inertized centrifugal machine, contamination of foreign materials, drying systems was running very close to thermal decomposition temperature, exothermic runaway decomposition reaction, and overpressurization due to formation of carbon dioxide are examples of technical errors.

Organizational errors are described as errors in planning, organizing, leading, and controlling management functions of a chemical plant to achieve desirable tasks. Organizational errors are 'not fitted for purpose' errors, procedure not available, interference effects from others, too many personnel, and too few personnel. Among the errors are safety management oversight system did not detect or correct serious deficiencies in the execution of maintenance and review of process changes; inadequate process and equipment integrity procedures or training; ignition by neighbouring welding sparks; nonessential personnel were not removed from areas in and around the process unit; and no personnel was present in the immediate area of the oven who could detect the fire.

3.2 Corrective Action Analysis

Procedural strategies are the highest recommended corrective actions in the research, indicating that management corrective actions (MCA) are preferred by the industry (i.e. 56%) although inherently safer and add-on strategies are more reliable in eliminating hazards and reducing risks. Examples of MCA are development and revision of standard operating procedures (SOPs), management system guidance, and national/international regulations or standards. For safer and healthier work environment, safety management systems are also developed, reviewed/revised, and implemented. Additionally, proper training and education are established to improve work mechanism, emergency preparedness, knowledge on chemical and process hazards, and safety research or learning evaluation. Only 44% of the actions are engineering corrective actions (ECA). The highest ECA are inherently safer (18%), followed by active-engineered (14%), and passive-engineered (12%) strategies, respectively. Table 4 lists the corrective action details in terms of ranking.

Table 4 Corrective action ranking

Hierarchy of Controls	Percentage
Procedural (56%)	
• Safety guidance and regulation	6.7%
• Training and education	6.7%
• Inspection/monitoring	5.6%
• Safety management system	5.6%
• Communication	5.1%
• Safety analysis/assessment	5.1%
• Documentation	3.9%
• Emergency preparedness	3.9%
• Maintenance	3.4%
• Human resource	2.8%
• Work mechanism	2.2%
• Safety culture	1.1%
• Enforcement	1.1%
• Management of change	1.1%
• Cooperation	1.1%
• Contractor control	0.5%
Inherently Safer (18%)	
• Moderation/attenuation/limitation of effects	8.8%
• Substitute	5.0%
• Simplify/error tolerance	3.8%
• Minimize/intensification	0.4%
Active-engineered (14%)	
• Instrumentation	6.2%
• Protective system	5.0%
• Automation	1.5%
• Alarms/notification system	1.5%
• Mitigation systems	1.0%
• Equipment improvement	1.0%
• Redundant systems	0.6%
Passive-engineered (12%)	
• Design change	5.9%
• Layout	2.4%
• Protective system	2.0%
• Proper ventilation	0.6%
• Earth connection	0.5%
• Thermal insulation/sealing	0.5%

Four main principles in inherently safer strategies are moderation, substitution, simplification, and minimization. As premier strategies in eliminating hazards and reducing risks, improvements in process operating conditions and physical forms such as facilities, as well as substituting substances/materials, equipment/parts or processes/procedures with less hazardous options are required for inherently safer strategies. To reduce possibilities for accident recurrence, simple and user-friendly facilities/equipment, human-to- process systems, and human-to-machine systems are incorporated. In the research, minimization (i.e. limiting energy generations during chemicals production) is the least applied inherently safer principles compared to moderation, substitution, and simplification.

To further reduce risks from hazards, add-on protection systems are incorporated in chemical process plants. Based on the findings, active-engineered strategies such as instrumentation (i.e. flow, pressure, pH/concentration, and others) protective systems, automation (i.e. process and emergency controls), alarms/notification systems (i.e. on-site and off-site systems), equipment improvements, redundant systems, fire mitigation systems and other mitigation systems are more prevalent than passive-engineered strategies. Emphases of passive-engineered strategies include design changes, layout, protective systems, ventilation, grounding, and thermal insulation/sealing. Changing of the facilities layouts to create smooth production and worker flows in the process areas by installing additional safety barriers and relocating potential hazardous equipment to safer zones is an example of passive-engineered strategies.

3.3 Suitability Analysis of the Recommended Corrective Actions

For each recommended corrective action, suitability analysis was carried out using the developed accident contributor-corrective action logic matrix. After contributor-action mapping, almost 6,000 corrective actions are required to solve 1,337 accident contributors (Table 5).

Table 5 The recommended corrective actions against accident contributor classifications

Type of Errors	No. of Controls				
	Inherent-ly Safer	Passive	Active	Procedural	Total
External (9)	6	7	3	17	33
Design (606)	461	397	374	1,479	2,711
Technical 295)	250	167	206	501	1,124
Human(308)	155	118	141	933	1,347
Organi-zational (119)	54	40	36	573	703
Average	185	146	152	701	1,184
Total	**926**	**729**	**760**	**3,503**	**5,918**

In average, procedural strategies (701) are the highest recommendations for resolving external factors, design errors, technical errors, human errors, and organizational errors. The second highest corrective actions are inherently safer strategies (185), followed by active-engineered (152) and active-engineered (146) strategies, respectively. Based on the research, the extracted accident reports were made by both governmental agencies and industry players. The governmental agencies such as the CSB, NTSB, and JST emphasized on inherently safer implementation throughout plant lifecycle but the industry players only focused on procedural strategies to correct accident contributors during operation. However, multiple procedural strategies were recommended to avoid human unreliability in leading to improper problem-solving, inappropriate actions, and ill-timed response.

According to Table 5, technical errors are commonly resolved using procedural strategies which are not suitable to correct the root causes of accidents. Technical errors are most suitably be resolved by passive-engineered strategies such as increasing the retention basins capacity, improving overpressure protection of the acetylene compressors, and adequate grounding to prevent the buildup and discharge of static electrical charges. Active-engineered corrective actions are considered suitable to resolve technical errors by installing spray nozzles at the socket of the suction pipe, temperature sensors in critical area to detect exothermic reactions, an automatic release to flood piping system at a threshold temperature, and extinguishing system that automatically activated by a temperature sensor. The less suitable solutions for technical errors are inherently safer strategies. Table 6 lists other accident contributors and their respective corrective actions in terms of their suitability.

The summary of the suitability analysis is shown in Table 7. In the research, the most suitable and suitable corrective actions are considered as 'suitable' controls to prevent accidents. The suitable corrective actions correct the root causes by eliminating hazards and reducing risks in terms of likelihood and/or consequence. However, less suitable and not suitable corrective actions are considered as 'unsuitable'. The corrective actions are unable to eliminate hazards and reduce risks as the root causes were not/inadequately corrected.

Overall, 54% of the recommended corrective actions are considered suitable and 46% are considered unsuitable. In average, 40% of the corrective actions are considered as the most suitable, 14% are suitable, 12% are less suitable and 34% are not suitable. Most recommended corrective actions for resolving accident contributors such external factors, design errors, and technical errors are considered unsuitable. However, for human errors and organizational errors, the recommended actions are considered suitable as highlighted in Table 6 (i.e. 79% and 87%, respectively).

Table 6 Accident contributors and their corresponding corrective actions (in decreasing suitability)

Errors	Corrective Actions	Examples
External Factors	Inherently safer	Limit the chlorine deposition to only 50% of original capacity.
	Passive-engineered	Place the containers into special construction to prevent movement.
	Active-engineered	Install an automatic monitoring with a signalizing screen.
	Procedural	Retrain employees on the necessity to report abnormalities.
Design Errors	Inherently safer	Use electrical tracing instead of steam tracing to prevent hot spots.
	Passive-engineered	Install fencing to protect aboveground pipes from possible damage.
	Active-engineered	Install automatic shutoff valves or remote control valves in high consequences areas.
	Procedural	Establish corporate requirements for freeze protection programs.
Technical Errors	Passive-engineered	Increase the retention basins capacity.
	Active-engineered	Improve the automatic control system.
	Inherently safer	Change the material of the piping to a corrosion-resistant material.
	Procedural	Patrolling during first shift with event recording.
Human Errors	Procedural	Cooperation to improve overall response and mitigation time.
	Active-engineered	Install valves with an air flow meter.
	Passive-engineered	Separate operations by adequate distances.
	Inherently safer	Use inherently safer fuel gas piping cleaning methodologies rather than natural gas blows.
Organiza-tional Errors	Procedural	Conduct an audit of the safety program.
	Active-engineered	Enable controlled shutdown from safe distance.
	Passive-engineered	Suitable separation distances between hazards categories.
	Inherently safer	Control changes to batch recipes i.e. quantities, reaction, temperature etc.

Table 7 Summary of the suitable and unsuitable corrective actions against accident contributors

Errors	Suitability			
	Most Suitable	Suitable	Less Suitable	Not Suitable
External Factors	18%	21%	9%	52%
Design Errors	17%	15%	14%	55%
Technical Errors	15%	18%	22%	45%
Human Errors	69%	10%	9%	12%
Organizational Errors	82%	5%	6%	8%
Average	40%	14%	12%	34%
Suitable	54%			
Unsuitable			46%	

In the research, suitability analysis of the recommended corrective actions against various accident contributors was conducted to prevent major accidents in the CPI. As the tools for accident contributor-corrective action safety assessments are lacking, the research developed the contributor-action logic matrix by harnessing accident data, extracted from several accident databases such as the CSB, NTSB, and FKD etc. The logic matrix is basically developed based on capital costs, operating costs, reliability, and complexity of layers of hierarchy of controls for accident prevention throughout process plant lifecycle. The logic matrix also emphasized on the ability of the corrective actions to correct root causes, eliminate hazards, reduce risks (i.e. likelihood and/or consequence), and requirements for afterwards monitoring/maintenance.

The established logic matrix is tested on 468 major accident cases, involving five contributor classes of process equipment failure accidents (i.e. external factors, design errors, technical errors, human errors, and organizational errors) which are also derived in the research. The classifications are made by incorporating both engineering and management-related errors. As design errors and human errors are significant accident contributors in the industry, separate classes are developed to distinguish them from technical and organizational errors, respectively. Previously, safety studies only classify accident contributors in the CPI as nature, technical errors, and human and organizational errors.

In theory, inherently safer strategies are considered as the most suitable actions for correcting external factors and design errors, followed by passive-engineered, active-engineered, and procedural strategies, respectively. Unfortunately, the analysis shows that procedural strategies are the most recommended corrective actions to deal with external factors and design errors, exposing the industry to potential major chemical accidents. About 52%-55% of the recommended corrective actions for the mentioned contributors are procedural strategies which are considered as unsuitable hierarchy of controls.

The decreasing suitability levels for technical errors are passive-engineered, active-engineered, inherently safer, and procedural strategies. Only 15% of the recommended actions for technical errors are passive-engineered strategies. Almost 45% of the actions are procedural-based, 22% are inherently safer strategies, and 18% are active-engineered strategies. In short, the technical errors are unsuitably corrected as deviations from normal operating conditions require more reliable strategies to avoid human dependency. By installing, both passive-engineered and active-engineered systems, the issue of human flaws during operation could be avoided.

For human errors and organizational errors, procedural strategies are the most suitable corrective actions, compared to active-engineered, passive-engineered, and inherently safer strategies. Although the industry could design and install various protection systems, the resource would be wasted as both errors require management-based corrective actions. Fortunately, the industry has already emphasized on the need for procedural strategies in encountering the errors. Based on the analysis, about 69% of the recommended corrective actions for human errors are procedural-based. Likewise, about 82% of the recommended actions for organizational errors are also procedural-based. Thus, the recommended corrective actions are considered suitable to resolve both management-related errors (i.e. human errors and organizational errors) and able to prevent major accidents in the industry.

Based on the suitability analysis, 46% of almost 6,000 corrective actions recommended for resolving 1,337 contributors are considered unsuitable. As majority of the corrective actions are on the outer layers of protection, the accident prevention is less reliable and ineffective especially for external factors, design errors, and technical errors. Therefore, the root causes are not/insufficiently corrected. The hazards were not completely removed, emerging residual risks that increase the load to manage process safety during process plant operation.

4.0 CONCLUSION

As a conclusion, it is reported that a large majority (56%) of the recommended corrective actions in the accident investigation reports are based on procedural strategies which are less reliable to prevent accidents in the CPI. Moreover, about 46% of the corrective actions are considered unsuitable to correct the identified accident contributors. The corrective actions are unsuitable as the hazards and risks resulting from accident contributors are not/inadequately eliminated and/or reduced. Most of the CPI players are unaware on the unsuitability of hierarchy of controls implemented due to lack of communication, documentation and cooperation in disseminating accident knowledge among members. To improve the situation, more reliable and suitable hierarchy of controls such as prevention through design strategies should be promptly recommended and implemented in the industry for safer, simpler, robust, and user-friendlier chemical process plant establishments through enforcement of inherently safer design and safety awareness among the industry players by relevant governmental authorities.

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