Jordanian Journal of Engineering and Chemical Industries

Print ISSN: 2616 - 9584 Online ISSN: 2617 - 720X

Process Safety Management Strategies and Risk Assessment

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Abstract

The benefits of achieving excellent process safety prevent or mitigate incidents. Well, the decision-making process has a benefit on risk reduction. This paper guides how an effective system can be established to develop methods and models for mandatory safety and a healthful workplace. The success of health and safety management depends on the discipline, commitment, and participation of all employees to ensure the success of management strategies and ensure the reduction of significant risks. The sustainability challenges are increasingly by evaluating risk and process safety due to the differences in the knowledge and experiences. Failure Mode and Effective Analysis (FMEA) combined with risk management principles provide an overall assessment to express the deviation that might occur in the process before failure and distinguish the importance of risk factors. This article intended to provide a method for integrating an organization's safety and health regardless of its size and work contributed to regulations and requirements. The benefits to implementing this model in the company will show returns in the investment. The main challenges include identification and discussion of the potential risks, in addition, to the collaborative of researchers between environmental protection and process system leading to the reliability and better understanding of the existing safety concepts.

Paper type: Review paper

Keywords: safety, health, environmental impact, risks, hazards, process management, ISO.

Citation: Jildeh Nina, and Mohammed Matouq " Process Safety Management Strategies and Risk Assessment" *Jordanian Journal of Engineering and Chemical Industries*, Vol. **4**, No.2, pp:52-61 (2021).

Introduction

The American Institute of Chemical Engineers (AIChE) created the Center for Chemical Process Safety (CCPS) in 1985 after the chemical disaster in Mexico and India to prevent major chemical accidents. CCPS provides a series of guidelines and essential practices for implanting process safety and risk management system to ensure the effectiveness of process safety management (PSM) (Abu Baker *et al.*, 2017). Nevertheless, many organizations are still challenged within a complex of operational processing plants and management systems. This could certainly create new risks and hazards. Weaknesses, including lack of awareness about severe chemical hazards and poor preparation of any hazards, result in victims (Fatemi *et al*., 2019). According to International Standardization and Organization ISO 45001, the Occupational Safety and Health Administration (OSHA) requires employees to comply with safety, health standards, and regulations. The management system aims to prevent work-related incidents/injuries and provide a safe and healthy workplace. The literature reviewed that European and US safety concepts are considered more advanced and comprehensive than those found in the Taiwanese construction industry (Chen *et al*., 2020). Continuously, the organization management should eliminate any hazards besides improvement of safety performance (Guntzburger *et al.*, 2017; Grossel, 2007). According to regulations and requirements, organizations and industries seek a new way to improve safety and health management in the work area. The main aim is to reduce risk and economic failure based on risk analysis and judgment on existing resources and processes. This could become more effective once consultation and expert analysis of the risks of the entire process life-cycle from the safety point of view for restructuring a new practical, safe system. Several accidents have occurred over the past decades with significant impact results directly or indirectly in the environment and human health. Different accidents reflect the efficiency and effectiveness of process safety and risk management system to prevents and reduce the severity and occurrence of these industrial accidents. It is expected to learn from these accidents and another industrial failure, reducing the potential catastrophic accidents in the future. Some notable accidents in history have been addressed in order to learn and improve the existing process safety management system or reduce the impact of the undesirable hazards:

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Received on May 7, 2021; Accepted on July 30--, 2021.

Jordanian Journal of Engineering and Chemical Industries (JJECI), Vol.4, No.2, 2021, pp. 52-61.

- **Nypro Chemical Plant in Flixborough, 1974**: Large explosion caused 28 coworkers to be killed and injuries of 36 coworkers. Upon investigation, leakage of cyclohexane formed a flammable mixture led to an unconfined vapor cloud explosion which resulted in the ignition for 1 min (Raji, 2014).
- **Bhopal in India, 1984:** Worst industrial disaster in history, caused by accident release around 40 tonnes of highly toxic and heavier than air. This incident results in at least 16000 people were killed, and 150,000 to 600,000 suffered injuries (Raji, 2014; Hardy, 2013; Cheremisinoff, 2001).
- **Chernobyl Nuclear Disaster in Ukraine, 1986**: A Chemical explosion due to uncontrolled graphite fire led to more than 450 radio-nuclides. This accident was officially considered one of the biggest economic catastrophes in history, resulting in 125,000 people who died from cancer, and 1.7 million people were affected directly (Raji, 2014).
- **Explosion in Pennsylvania, 1999:** Explosion of a vessel containing several hundred pounds of hydroxylamine, which high chemical concentration and high temperature led to the explosion. This explosion caused four employees and managers to be killed, four people were injured, and ten buildings were damaged. Upon Chemical Safety and Hazard Investigation Board (CSB) investigation showed that the company did not collect and analyze the safety information properly before starting the process and a fault in the design plant (Hardy, 2013).
- **Explosion in Delaware, 2001:** Explosion due to leakage of sulfuric acid storage tanks resulting in the acidic vapor in the atmosphere led to the death of one maintenance coworker and injuries of eight coworkers. Upon CSB investigation, the tank had a history of leakage, and the company has failed to conduct proper identification of the presence of the leakage (Hardy, 2013).
- **Explosion and Fire in Florida, 2006:** Explosion and fire occurred in a wastewater treatment plant, results in two employees were killed, and three was severely burned. Upon CSB investigations, the coworkers were using a cutting torch to repair a roof above the methanol storage tank, igniting vapor from the storage tank and flame back into the tank (Hardy, 2013).
- **Fire in Texas, 2007:** Fire caused extensive damage to the facility due to a crack in liquid propane pipe, results in shutdown for months. This accident caused an injury for four people. Upon U.S. CSB investigated that the cracked pipe was not properly isolated (Hardy, 2013).
- **Fukushima Nuclear Disaster in Japan, 2011:** A powerful earthquake occurred under the sea about 70 km east of the Oshika peninsula, resulted in 15,854 deaths, in addition to 3,155 missing people and about 27,000 people were injured (Raji, 2014).
- **Explosion in Beirut, 2020:** Explosion occurred due to a large amount of ammonium nitrate stored at the port of Beirut, which results in over 150 were killed, more than 5000 injuries, and 2 billion dollars in property damages and leaving an estimated 300,000 people homeless (Crisis Group, 2021).

Furthermore, the main focus should be on process safety, in which the manufacturing process should be built upon regulations and customer specifications from specific materials or desired operating processes. The well-designed process was established from data information to identify the main requirements: raw materials, supplier information, by-process analysis, final product analysis, analytic equipment maintenance, calibration requirements, packaging materials (containers, labeling requirement), storage and disposal of containers. The contribution between a complete team of technical operators, engineers, scientists, management, marketing, purchasing, finance, and clients, results in reducing the likelihood of incidents in and control of process hazards to protect the workplace. Proper documentation and information about materials and equipment should always be addressed in the manufacturing area, including personal and material flow diagrams, piping and instrument diagrams (P&IDs), and material safety data sheets (MSDS). The specific information of the operating equipment should be addressed to ensure the continuity of correct operation and the presence of specific information, including datasheets for identifying the potential hazards of the process, corrosive materials, physical data, and reactivity of the process materials, stability analysis of hazardous materials. The emergency shutdown system, senor alarms, and interlocks should always be checked to ensure the safety process. Considering the catastrophic incidents, the Occupational Health and Safety Administration (OSHA) enacted in 1994 the Process Safety Management (PSM), aims to prevent incidents through the application of 14 elements based on principles and management systems for knowledge and control of the risks involved in the processes as present in **Figure 1** (Khan *et al*., 2015). The historical reason for PSM is to prevent any catastrophic accidents in chemical industries, as methyl isocyanate was released in Bhopal, India, in 1984, which led to the death of more than 3.800 people and more than 100 thousand injuries, in addition to compensation of 470 million dollars (Raji, 2014).

1 Process safety management in terms of ISO 31000

Process safety is defined as an integral part of process development and manufacturing to define risk identification, risk analysis, risk assessment, risk evaluation, and consultation for critical decision making (Khan *et al*., 2015). Process safety is expressed in terms of ISO 31000 to manage the risk/safety and economics based on decision making and design improvement, as presented in **Figure 2**

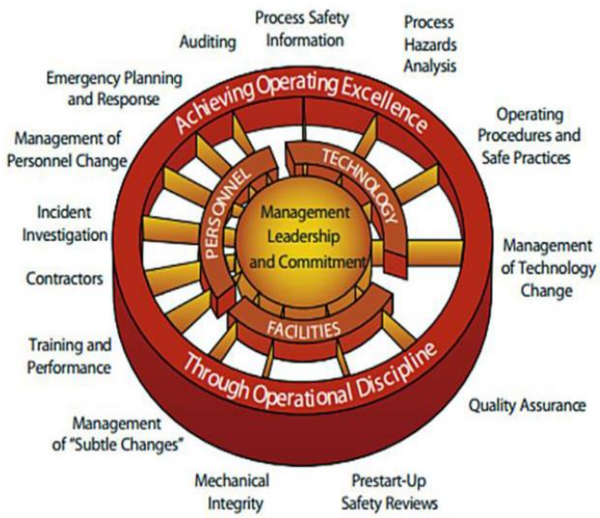

Fig. 1 Principles of management systems based on 14 elements for controlling the risks involved in the processes. *Source: Pacheco and Souza, 2018*

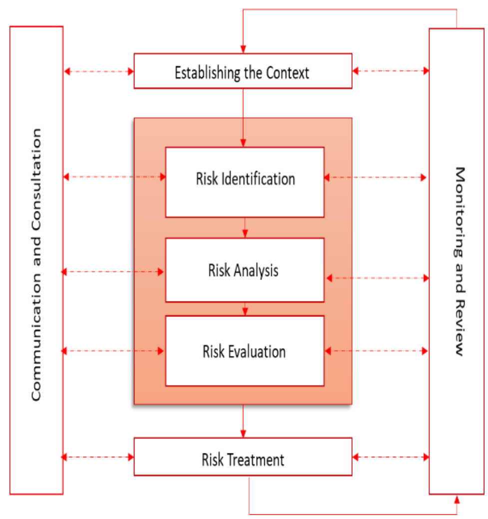

Fig. 2 Risk ISO 31000 Management Process.

By implementing the principle of risk management system, the obtained model provides organizations with an analysis of how the design process influences safety. It also provides ideas for improving the existing operating system and measuring future performance through communication with expertise. The effectiveness of regulations on process safety systems involves a complete understanding of equipment and the concept of critical hazardous systems (Halim and Mannan, 2018). Predicted accidents should be modeled and structured depends on the overall life-cycle process to prevent serious injuries and incidents. **Figure 3** shows a process flowchart for an organization focused on process-safety performance and personal behavior to identify the effectiveness of process safety the potential risks based on collecting information through observations, facts, experiences, and assumptions. The analysis of risk provides a quantitative and qualitative estimation of each identified risk. Based on identifying, analyzing, and treating the risks, the organization would make decisions depending on the situations that are subjected to change by monitoring and reviewing the effectiveness of the risk management framework.

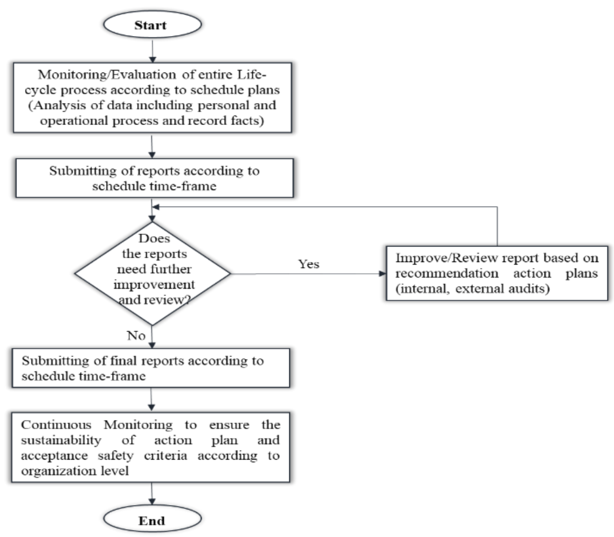

Fig. 3 Process flowchart for organization focused on process-safety performance and personal behavior to identify the effectiveness of process.

In addition, the view of compliance and consultation within rules and specifications helps resolve problems, customer satisfaction within high-quality management. Within variation of process parameter and personal behavior for continuous improvement, this variation should be anticipating and acceptable otherwise, and it is called deviation. Center for Chemical Process Safety (CCPS) mentioned that risk-based process safety provides a helpful tool and essential guidance on design process management, correcting the presence system, and improving the practices of the safety management system (ISO 45001, 2018). Good documentation is highly required to minimize the potential risk of personal and process safety of an organization. For example, a coworker falling from a ladder is not reported or an incident of a coworker falling from a juke is not reported. An incident caused by a failure in the processing unit is reported immediately. However, all the incidents should be highly reported to distinguish the safety of the equipment and materials workplace. Reporting criteria should be reported immediately to prevent any difficulty in controlling the incident. Failure to follow instructions and safety work-area results in critical safety issues summarized in **Table 1**, which presented severe incidents and corresponding consequences of the accidents as sickness, death, and disability for life.

Table 1 Industrial accident and the corresponding failure identifications, evaluation, treatment, monitoring and review

Industrial Sectors	Risk Identification	Risk Analysis (Low, Medium, High)	Risk Evaluation	Risk Treatment	Monitoring and Review	References
Petrochemical and refining production	Reactors, tanks, pipes, boilers, cooling towers, refrigeration systems, spillage, interlocks and emergency shutdown systems, fire and explosion	Medium to High	Steam, hot condensate, gases, compressed air, increase of temperature, increase of pressure. Serious harmful effects on human health and environment such as respiratory distress, eye and skin irritation	Technical and continuous communications with contractors and suppliers. Continuous checking and maintenance the performance of the machinery Alarms are provided for any changes in the process Inspecting the fire protection facilities	Continuous maintenance of mechanical equipment Continues training for safety issues Continuous maintenance of emergency interlocks, emergency equipment	Mechhoud *et al*, 2016; Ebrahimi *et al*., 2021; Damnjanovic and Roed, 2016, Fatemi *et al*., 2019
Wastewater treatment plants	Contamination of surface water from excess nutrient, operational/ mechanical malfunctions, ecological hazard	Medium to High	Improper design issues/ inappropriate operational management, bacteria in an activated sludge chamber, environmental pollution with chemicals	Improve the separation process to reduce the concentrations of pollutants Improve technologies lines devices	Continuous monitoring of the operation treatment plant and review process to ensure the effectiveness in providing suitable risk migration	Analouei *et al*., 2020; Loi-Plich and Zakzewska, 2020; Carroll *et al*., 2006
Chemical Industries	Uncontrolled chemical reaction resulted in the release of toxic vapors from reactors, tanks, leakage system, fires and explosions	Medium to High	Increase of temperature, increase of pressure, gas evolution Serious harmful effects on human health and environment such as respiratory distress, eye and skin irritation	Fundamental thermochemical calculations are performed for better understanding of the hazard as oxygen balance, heat of reaction, maximum pressure/rate of pressure rise, temperature rise, reaction rate constant, computer programs, screening tests as incompatibility tests, thermogravimetric analysis, differential scanning calorimetry	Review of process safety awareness, review of employees awareness for plant hazards and safety regulations	Fatemi *et al.*, 2019; Mannan *et al*., 2015
Laboratory-scale incidents	Corrosive-vapors, electrical-contacts, exothermic reaction	Medium to High	Failure in mechanical integrity and material compatibility, lack of technician experience	Continuous training and regulations to wear safety glasses, lab coats and gloves	Review the required training of employees with respects to safety and emergency regulations	Langermann, 2009
Others	Incidents that is no direct contact to chemical or process as office building fire, earthquakes, war, floods situations	Medium to High	Injury, disabilities, loss of life, property damages results in economic losses	Emergency preparation and handling procedure	Review and evaluate the data to maintain safety and efficiency of handling procedures, review of the various active as fire hydrant, portable fire extinguishers and sprinkler	WHO, 2018; DeCoyet *et al*., 2006
Pharmaceutical Industries	Storage of active pharmaceutical ingredient and chemical components, uncontrolled temperature and relative humidity, machinery failure	Medium to High	-Improper storages condition according to the supplier specifications -Power failure to the refrigerators or conditioning system -Damage in the operational machine	Continuous checking and maintenance the performance of the machinery Alarms are provided for any changes in the set-point temperature/humidity Trained employee to keep monitoring	Review of process safety awareness, review of employees awareness for plant hazards and safety regulations	Patel *et al*., 2019; Chavda *et al*., 2015

2 Strategies to prevent and control the risks

Major regulatory elements of process safety management (PSM) as published at 29 CFR 1910.117 includes employee's, information of process safety, analysis of process hazard, operating procedures, training, contractors, pre-sat-up safety, mechanical integrity, management of change, incident investigation, emergency planning and response, compliance audits and trade secrets as presented in **Figure 4** (Langermann, 2009). Furthermore, risk description associated with a set of hazards is considered an important aspect is comprising scope, procedures, personal qualifications and successful training program, schedule and deadlines, management auditing, and review. By analyzing these risks, the approach result provides quantitative and qualitative consequences to correct/ improve activities of management process safety. Failure Modes and Effects Analysis (FMEA) is a statistical tool that identifies all the possible failures that might occur in the design, manufacturing, or assembly process and the consequences of those failures. FMEA can also analyze the history of organizational data (Nuchpho *et al*., 2014). Despite the simple concept of FMEA, the variation in the complex processes should be taken into consideration to ensure quality and safety, and this must include a complete understanding of the type of failure modes, cause or effect, risk assessment, type of control, process versus design, and interactions between structures. Each potential failure is corresponding to various scaling values related to severity, occurrence, and detection. In the later stage of FMEA, Risk Priority Number (RPN) is determined by multiplying three scaling values, which provides valuable tools to evaluate and determine risk for each risk.

Table 2 presents a simple FMEA worksheet to understand the principle of managing the risk. The actual FMEA worksheet contains more details, including several failures. The framework starts by providing all the potential risks that might occur in the unit operation, followed by evaluating each failure in severe occurrence and the potential to detect the failure before occurrence. Therefore, well-communication protocols between employees and consulting sectors maintain a well-established process safety management system.

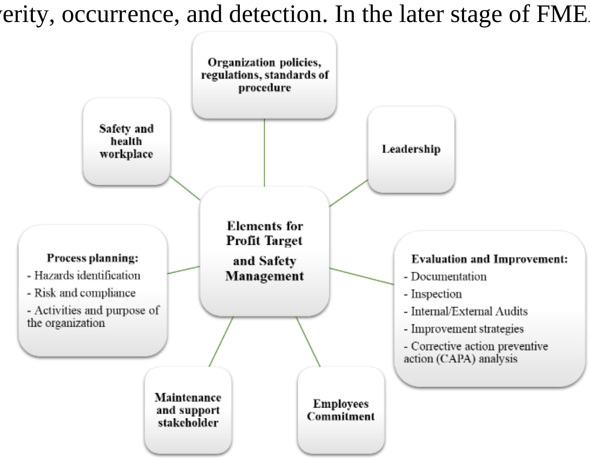

Fig. 4 Process safety management as established by 29 CFR 1910.117.

The first step in conducting FMEA is to build a model table that refers to all the possible potential failures in terms of equipment failure and functional failure (Potential Failure Modes). The second step is by describing the impact of each failure on the process (Potential Failure Modes Effects) within the severity of the failure. Identify the causes of the failure (Potential Failure Causes) within the possibility of occurrence. The third step is describing the prevention action and process control for each failure (Current Controls). In the final stage, Risk Priority Number (RPN) is measured to provide information's referring to the risks factors for implementing ideas to prevent these failures from an occurrence during the earliest conceptual design stages and continuous improvement throughout the process life-cycle (Sadaqat *et al*., 2018; Picardi *et al*., 2004). For implementing a successful model, a team of skilled people with different diverse knowledge about the process is collaborated to identify all the possible risks, including scientists, engineers, manufacturing, testing, maintenance, suppliers, marketing, and customer services.

Table 2 Typical Failure Modes and Effects Analysis (FMEA)

Number	Potential Failure Mode	Potential Failure Modes Effects	Severity	Potential Failure Causes	Likelihood Occurrence	Current Controls	Detectability	Risk Priority Number	Remarks
1									
..									
n									

Rank the failures from one to ten based on the severity of the consequences of failure
Rank the failures from one to ten based on how frequently it is likely it is to occur
Rank the failures from one to ten based on the chances that it will be detected before it occurs
Calculate the RPN for each failure by multiplication of Severity, Occurrence and Detection

Rating is usually done on a scale of ranges from 1 to 10. They depend on the severity of the failure, the probability of occurrence, and the probability of detection. The highest RPN number depending on the severity effect of the failure and the urgent correction actions.

By Applying the FMEA model for all process failures and measuring the RPN number, the detected value of potential risk helps in reducing the likelihood of a specific failure or mitigating the consequences. **Figure 5** presents how the potential occurrence of the risk failure is reduced after implementing FMEA within high severity of the risk and detectability on the process. Therefore, this model provides a knowledge's on which risk is the most serious, which has a substantial negative impact on employees and organizations, indicating that the highest risk value should be controlled first. This model also helps in reducing the impact of risks by reviewing/writing standards of procedures that cover the safety of process in terms of accidents, shutdown emergency, deviation emergency, emergency operation, emergency action plan for entire facilities including plans, maps, and assembly points. As discussed above, the essential integration of management system boundaries, as illustrated in **Figure 6,** enhances participation and engagement with coworkers and consultation sectors to provide safe and healthy working process conditions by preventing workplace injury and ill-health. This integration can be built up within the management concept of the Plan-Do-Check-Act model, which describes the organization's objectives and monitoring the performance. Management integration systems cover risk identification/awareness, risk assessment/control, emergency response, performance improvement (Yoltarelli *et al*., 2018; Patal and Deshpande, 2017; Gidey *et al*., 2014).

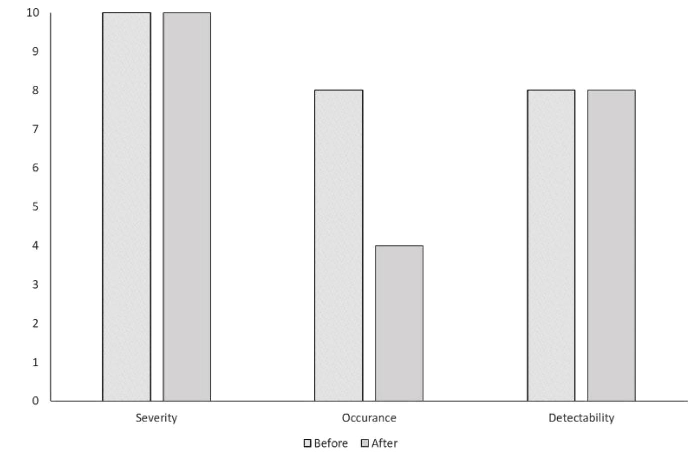

Fig. 5 Potential occurrence of the risk failure is reduced after implementing FMEA within high severity of the risk and detectability on the process.

Furthermore, the Center for Chemical Process Safety (2011) has reported that sleeping disorders, alertness, and physiological fatigue have a huge impact on decision-making, resulting in potential risk. In addition, extended working shifts and overtime are also assigned as a cause for risk. Industries should implement operational regulation strategies to prevent any catastrophic incidents through audits, inspections, coworker training, safety culture, and system improvement (Fatemi *et al*., 2019). An adequate process safety could indicate the performance of process safety when an accident is most likely to occurs, which enables the organizations to implement corrective actions by:

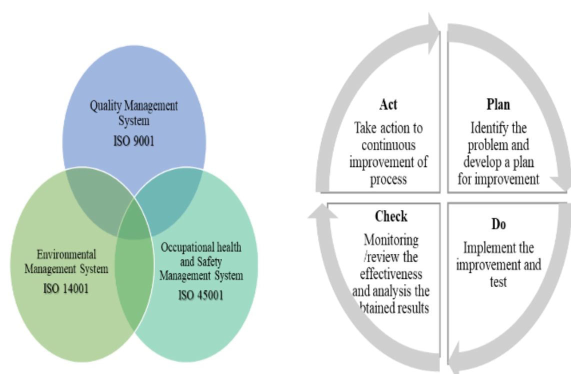

Fig. 6 Typical integration between management systems and typical Plan-Do-Check-Act model.

- Schedule annual audit and define the scope of the annual audit policy
- Discuss the annual audit report with expertise to ensure an adequate atmosphere for safety
- Define the procedures to resolve hazards related to risk and the time frame to resolve the problem
- Reduce the potential risk of accidents in the workplace, claims, business reputation, and costs
- Define the restart-up of the unit operation after resolving the issue or restart portions of the unit operation related to the safety phases
- Review and checkout the process after resolving the hazards
- Commitment to protect employees, clients, and visitors from any presence of incident
- Continuous and successful training demonstrating skills and knowledges for process safety management to prevent any significant hazards and recovery from accident circumstances
- Learning from experiences and learning from other industrial failures provide an opportunity for improvement by monitoring practical internal and external resources of information

Companies who would commit to the above engagement system firm a severe and successful environmental protection for employees, clients, and visitors, which demonstrates the success of the company in the competitive market.

3 The framework of industrial accidents and the prevention mechanisms

In order to control and prevent the presence of accidents and hazard risks during the processing plant, a feedback model on the process control is determined by continuous observation and data evaluation to maintain the safety of the process management system. Every chemical process has a certain amount of risk associated with its specific activity; usually, risks may be too high in the presence of additional factors as fire and multiple exposures. However,’’Acceptable Risk’’ should be identified during the design stage to minimize the process's economic constraints and acceptable regulatory risk standards. **Figure 7** describes the overall identifications for estimating the risk. The concept is used to define risks based on the information and frequency of predicted incidents. Several questionnaires should be applied through the design stage based on knowledge’s and previous industrial failure related to the process. What is the factor of a safe work environment and resources? The acceptability of the final framework model depends on all the parameters that directly and indirectly affect the process. A lack of resources and understanding of science and engineering through risk assessment could lead to incidents. Implementing training and teaching workers on managing and controlling the presence of any risks during the operations of machines and equipment will be an essential step in controlling the risk of dangers, with a continuous inspection and validation of the machines to ensure the safety of the used machines. Applying safety regulations in industries is intended to prevent any major incidents that might cause danger to human/environmental during industrial activities in various procedures and methods. By maintaining the safety and effectiveness of the process control, the desired target is efficiently stable, corresponding to the safety policies as recommended from Occupational Health and Safety Management System ISO 45001 and ISO 14001. This significantly helps to improve the overall safety performance. The assessment structure proposed on safety management, which attempted to characterize the relationship between physical/technical elements (equipment, facilities, guard’s protection, helmets, shoes, safety glasses), community element (education, skills, knowledge’s, expertise, managers, leaders), and external relative/social element (law/regulations, safety, budget). This model utilizes the relationship between various elements among the vital success of constructing safety professionally.

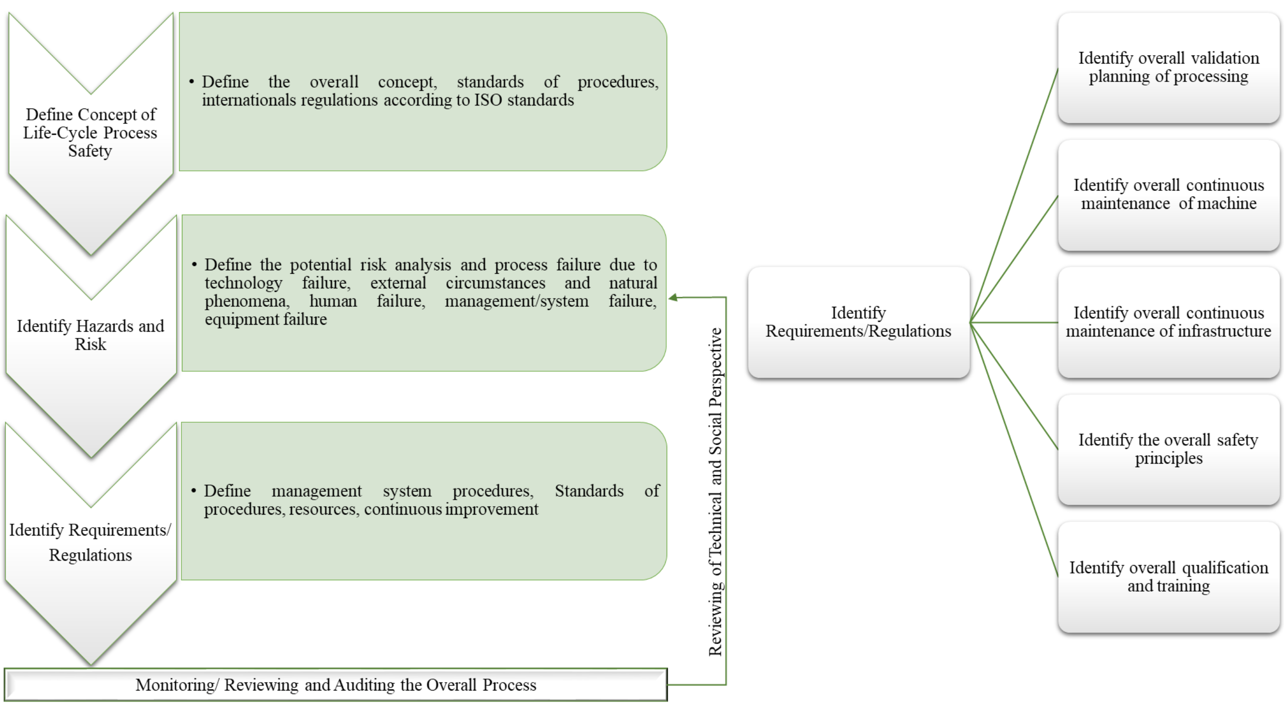

Fig.7 Overall identifications for estimating the risk.

Figure 8 shows a model process in which engineers and quality assurance workers measure the actual quality of the entire process, starting from the input to the actual desired output. A variation or deviation between the actual target and the desired target is highly dependent on the processing system, skills, knowledge’s, regulations, and economic aspects. The primary role of collaborations between various industrial sectors is to provide a sustainable workplace and equilibrium state coupled with safety policy regulations. Therefore, continuous training and education of workers and managers regarding safety performance increase the ability to undertake any presence of accident, hence protecting the lives of workers in industrial accidents and reducing costs as mentioned at center for chemical process safety in the year 2011.

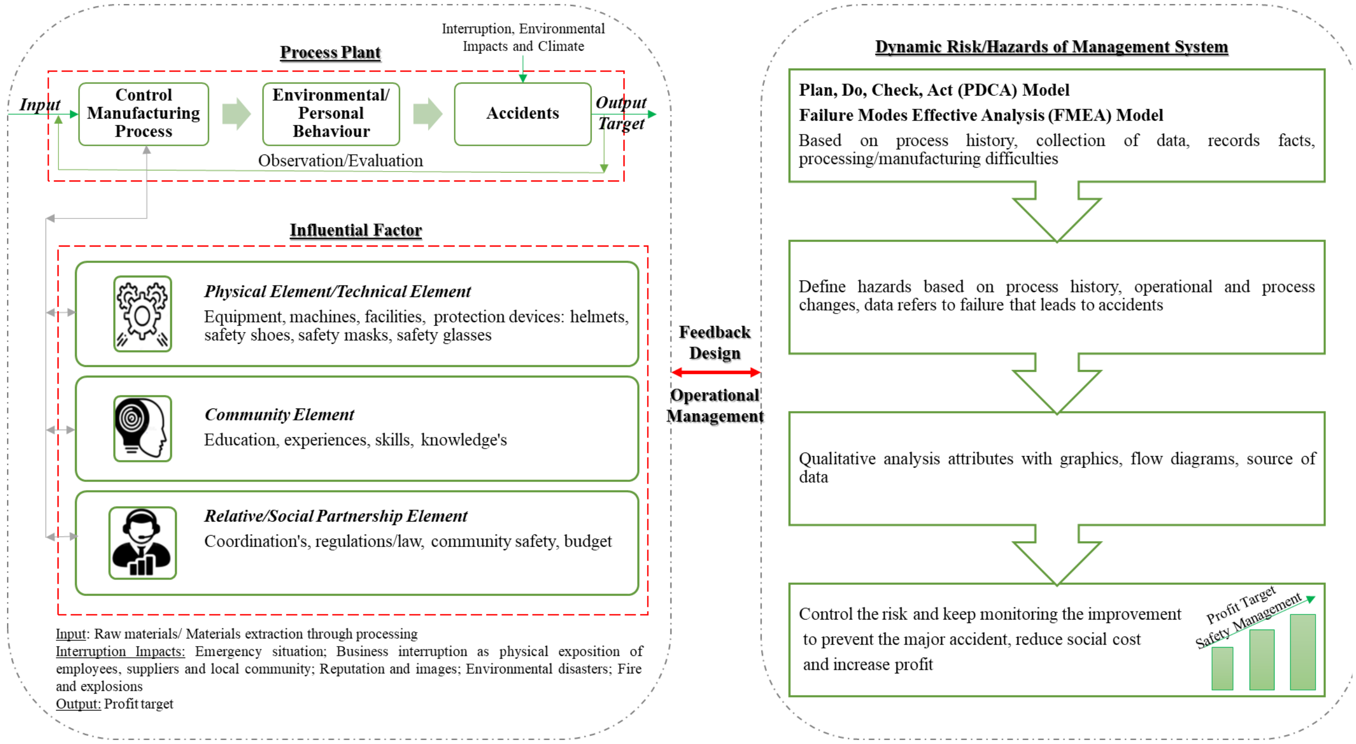

Fig. 8 Schematic methodology diagram designed for proposed dynamic industrial accident associated with influential factors to prevent risk and enhance the productivity and safety management

The ‘’Key success factor’’ term is considered a unique element to complete the organization's goal. Chen *et* al. (2020) defined KSF as a ‘’set of positive activities and results which signifies that a manager has realized their goals and objectives’’. Commitment to project safety management through comprehensive communications between sectors, which display a significant impact in implementing and measuring the effectiveness of the quality and professional training process planning (Chen *et al.*, 2020). Ismail *et al.* (2012) stated that safety management and personal protection equipment are based on the awareness of workers. In addition, the improvement principle and update of the current safety system based on the overall point of view of consultation and engineers, process life-cycle analysis, external climate to ensure the sustainability of the process (Mannan *et al*., 2015). **Figure 8** presents the methodology framework in understanding the scope and target of the process cycle from the impact of raw materials, manufacturing process, maintenance, disposal/recycling, and distribution of the final product and the external environmental interpretation on the significant improvement of the safety process. The uncertainty of identifying the potential risks in the process resulted in management failure and personal errors. For reducing such failure and losses, a contribution between various principles and management approaches as PDCA and FMEA provides a fundamental framework to ensure control and improve continuous safety system. This assessment structure methodology defines the concept of life-cycle process identifies the potential risk of process failure due to technology failure, human failure, management system failure, equipment failure, external circumstances, and natural phenomena. The provided information and data analysis would support the managers for strong decision-making by minimizing the real estimation time. Hence, reducing the possible losses and maintain the stability of company investment.

Conclusions

Failure Mode and Effects Analysis (FMEA) and Plan-Do-Check-Act (PDCA) cycle models could be conducted in any organization, which adds quantitative and qualitative value for improving the process life-cycle and protecting organizations from the organization any possible hazards. Analysis of these hazards in the processing unit is evaluated based on different criteria through visualization and experiences that aimed to identify the source of failure regardless of workplace complexity. This approach enables the organizations to implement all the required corrective actions to eliminate these risks, increase the profit investment, and ensure workplace safety. The incorporations between management systems and various sectors assure a successful, strong decision-making by reviewing and monitoring the action plans.

Nomenclature

AIChE	=American Institute of Chemical Engineers	[-]
CCPS	=Center for Chemical Process Safety	[-]
CSB	=Chemical Safety and Hazard Investigation Board	[-]
FMEA	=Failure Modes and Effects Analysis	[-]
RPN	=Risk Priority Number	[-]
OSHA	=Occupational Safety and Health Administration	[-]
PDCA	=Plan-Do-Check-Act	[-]
PSM	=Process Safety Management	[-]

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