DEVELOPING PROCESS SAFETY INDICATORS FOR ORGANIZATIONAL

FACTORS IN PETROCHEMICAL INDUSTRIES

A Thesis

by

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ABSTRACT

Most major process safety incidents are preventable and can be avoided as shown in several incident investigation reports. Moreover, these reports indicated that these incidents were certain to occur as shown from the related near-misses and safety control system failures that occurred prior to the incidents.

The key element to improve process safety performance is developing effective process safety leading indicators. In the past, the petrochemical industrial organizations used traditional personnel safety measures to measure process safety performance. Now, most of the current industrial facilities focus more on process safety lagging indicators. Ignoring organizational factors and lacking a systematic approach were the major deficiencies during the development of process safety indicators.

The main objective of this research is to construct a systematic technique to develop process safety leading indicators by selecting the most effective leading indicators, defining different safety metrics for each leading indicator, conducting accurate measurements, monitoring these metrics on a frequent basis, and revalidating the measures using lagging indicators and near-misses. The effects and contribution of different organizational factors were studied and analyzed within process safety performance. Process safety leadership, data collection system, and proactive monitoring

are critical factors that directly impact the development of process safety leading indicators.

DEDICATION

To my mother and father

To my wife, daughters and son

To my sisters and brothers

To my family

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NOMENCLATURE

AICHE	American Institute of Chemical Engineers
API	American Petroleum Institute
BP	British Petroleum Company
CCPS	Center for Chemical Process Safety
CSB	Chemical Safety Board
EHS	Environmental Health and Safety
HAZOP	Hazard and Operability Study
HSE	Health and Safety Executive
LOPC	Lost of Primary Containment
MI	Mechanical Integrity
MLE	Most Likely Explanation
MOC	Management of Change
OSHA	Occupational Safety and Health Administration
OECD	Organization for Economic Coordination and Development
OGP	International Association of Oil & Gas Producers
PHA	Process Hazard Analysis
PM	Preventive Maintenance
PSM	Process Safety Management
SPI	Safety Performance Indicator
VCE	Vapor Cloud Explosion

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1. INTRODUCTION

The petrochemical industries have developed significantly over the past years. This development resulted of using an advanced technologies and complex processes. The hazards and risks increased as result of these advanced technologies and complex processes. The safety management system was one of the efficient and effective ways to control the hazards and significantly reduce the incidents in the industry. The industry has focused a lot on the personnel or occupational safety performance to measure the effectiveness of their safety management system. A lot of companies were confused between personnel safety and process safety. The injury rates cannot represent the process safety performance.

The phrase “process safety” has been used a lot after the BP Texas city refinery explosion in 2005. There are several definitions for process safety available in literature that mostly shared the same meaning and contents with different words and explanations. In general, process safety can be defined as the preventions and mitigations of the risks and hazards that are associated with the industrial process activities. Process safety incidents include release of either potentially hazardous (flammable or toxic) materials or release of energy in the form of fires or explosions (Baker, Leveson et al., 2007). Process safety programs are focusing on the process design and engineering, mechanical integrity, process hazard analysis, risk assessment, management of change and other elements related to the industrial processes.

1.1 Problem Statement

Most of the major process safety incidents are preventable and can be avoided as shown in many incident investigation reports. Moreover, there are clear trends that these incidents will happen. Unfortunately, these trends are discovered after the incidents. Process safety leading and lagging indicators should be used to measure the process safety performance. There was a lot of focus on process safety lagging indicators, which were clear and easy to be defined and measured by the industrial facilities. These are after the fact measurements such as number of fires, leaks and explosions. The process safety indicators are still in nascent stages where a lot of industrial companies are struggling in measuring these indicators in a systematic and an effective way. Most of the current techniques that are used for developing process safety leading indicators are lacking of an efficient systematic approach. In addition, organizational factors have significant contributions to most of industrial incidents and these organizational factors were not included in the current techniques to develop the process safety indicators.

1.2 Motivation

Process safety leading indicators are key factors in preventing a lot of major process safety incidents. They are forward-looking and can identify deficiencies in the safety system before it grow up and cause a serious problem. Accurate measurement of these indicators are very important to prevent incidents and losses. Since there are a lot of leading indicators, it is difficult to choose which indicators shall be measured and how.

1.3 Research Objective

The main objective of this research is to develop a systematic method for developing process safety leading indicators in the petrochemical industry. The research will use different approaches to develop a well-designed systematic technique to measure the process safety leading indicators. This systematic approach will focus on continuous monitoring of the safety system as a whole structure that include lagging indicators, near-misses and leading indicators.

1.4 Research Approach

The research will focus on the development of process safety leading indicators. The research will start with a literature review about the history of the process safety and the similarities and differences between the process safety and personnel (occupational) safety including illustration of the common factors between the two types that may cause some misunderstanding in most industrial facilities. Also, the common techniques for developing process safety leading indicators will be explained briefly with main advantages and limitations of each technique.

Historical data with expert judgment will be utilized to select the critical process safety leading indicators elements. These data will be used to build a systematic method using Bayesian network to develop appropriate process safety leading indicators and metrics. The systematic method structure will focus on the selection and revalidation of the measuring metrics. The organizational factors will be analyzed during the selection and development phase. The importance of near-miss analysis and its relation to accurate development of process safety leading indicators will be discussed in details.

2. BACKGROUND AND LITERATURE REVIEW

In this section, the background of process safety and comparison between personnel safety and process safety will be clarified briefly. The literature review will include the major incident that bring attention to process safety indicators and the importance of measuring the process safety leading and lagging indicators to prevent process safety incidents. The current common techniques for developing process safety indicators will be discussed, concentrating on the advantages and limitations of each method.

2.1 Process Safety and Personnel Safety

There was a lot of confusion in the industry between personnel safety (occupational safety) and process safety. Personnel safety can be defined as prevention or mitigation of the risks and hazards that are directly related to individuals. Personnel safety mostly deals with the risks related to physical injuries including slips, falls, electrocutions, burns, and motor vehicle accidents. So, personnel safety is more related to individual workers (Hopkins, 2009).

As per the American Petroleum Institute (API), process safety can be defined as “a disciplined framework for managing the integrity of hazardous operating systems and processes by applying good design principles, engineering, and operating and maintenance practice” (API, 2010). Process safety is related to prevention of incidents that meet four criteria as defined by the Center for Chemical Process Safety (CCPS) which are (1) physical or chemical process involvement, (2) location within an industrial facility, (3) the exceedance of minimum threshold limit, and (4) acute release. The first criterion is physical and chemical processes that take place within all process equipment including tanks, piping, heat exchangers, reactors and other processes in the industry. The second criterion is that the process incident happens inside the perimeter of the industrial facility. The third criterion can be either uncontrolled releases of flammable or toxic materials above the threshold limit, or releases of any materials including non-flammable and non-toxic materials that may have the potential to cause harm to people. The fourth and last criterion for the process safety incidents is the acute release of the material that exceeds the threshold limit within a short time (CCPS, 2011).

Before the BP Texas Refinery explosion in 2005, most of the industrial facilities were focusing on the personnel or occupational safety to measure their safety system performance. This measurement will not give a correct indication of the safety level in their facility. Most of industrial facilities were using personnel safety to measure the process safety which resulted in insufficiencies in their safety system. Personnel safety can be measured by the number of injuries and fatalities in the industrial facility using different standardized formulas, such as OSHA incident rate and fatal accident rate. These indicators cannot represent how well the industrial facility is doing in process safety. Several catastrophic process incidents happened in facilities that have a low rate of fatalities and injuries.

Different organizations work to clarify the differences between process safety and personnel safety and importance of process safety after the BP Texas refinery explosion in 2005. The Center for Chemical Process Safety (CCPS) has issued multiple publications on this field. Process safety and personnel safety are totally independent and one type cannot be used to measure the other type. However, there are some common elements that have strong effects on both types, such as system safety and safety culture. Deficiencies within the safety system are the main causes for the major personnel and process incidents in the industry (Baker, Leveson et al., 2007).

Positive safety culture has a significant effect on the personnel and process safety. It encourages personnel to act safely and prevent hazards. It also puts a lot of emphasis on organizational process safety in analyzing associated risks and hazards (Reiman & Pietikäinen, 2010). Measuring the effects of safety culture on process safety is a complex process. The effect of safety culture can be seen in proactive risk assessments, frequent walkthroughs by senior management, effective communication, individual safety attitude, and safety commitment by all employees (Biggs, Dinsdag et al., 2010).

The process safety field started in the last decade after the major process safety disasters. However, the petrochemical industries started to put a lot of emphasis on measuring process safety performance after the BP Texas City Refinery explosion in 2005. The excellent personnel (occupational) safety performance for this facility didn’t represent the actual process safety performance (CSB, 2007). This was the typical attitude in most industrial facilities. There was no clear measurement guide of the process safety performance and most of the industrial facilities were using normal incident and fatality rate to measure their process safety performance. The deficiency in their process safety was one of the major findings in the incident investigation report that was conducted by U.S. Chemical Safety and Hazard Investigation Board (CSB).

2.2 Importance of Process Safety Indicators

Process safety indicators are the key elements to improve process safety performance in the petrochemical industry through measuring and monitoring process safety performance activities against requirements and objectives. The process safety indicators should identify all factors and causes that can lead to high potential process safety incidents. The process safety indicators should work also to eliminate these factors and causes to prevent process safety incidents. The process safety indicators can be classified into two main categorizations, which are leading indicators and lagging indicators.

The lagging indicators are used to measure the process safety events that already occurred including explosions, fires, and flammable or toxic material releases. The lagging indicators are considered the accurate outcome measurement of the process safety system. Lagging indicators are the most common process safety indicators that are used in the industry because they are clear and easy to be identified and measured (Wang, 2012). The lagging indicators can be analyzed and assessed to identify the potential risks and deficiencies in the process safety system. Then, the identified potential risks and deficiencies shall be rectified before a major incident occurs. One of the major advantages of the lagging indicators is that they can be normalized to have a better comparison between different industrial organizations. The normalization factors, that used to calculate the process safety lagging indicator can be either based on the total work hours or process related criteria such as production quantity (Wang, 2012).

Process safety leading indicators are forward-looking measurements of the process safety system. These indicators works to identify the deficiencies and weakness in the process safety system before an incident occurs. The CCPS defined the leading indicators as “A forward looking set of metrics which indicate the performance of the key work processes, operating discipline, or layers of protection that prevent incidents” (CCPS, 2011). The process safety leading indicators work as early indications of a new hazard developed or a failure in any protection layer. Some examples of process safety indicators include overdue preventive maintenance items, open HAZOP items, failure in management of change (MOC), and rate of completed process safety training. The leading indicator can be either positive or negative, but it should work to identify the effectiveness of each protection layer over the time. Several process safety leading indicators and metrics shall be measured in order to do an accurate evaluation of any protection layer such as mechanical integrity or process hazard analysis. Process safety leading indicators are used mainly to improve the process safety system rather than compare different industrial organizations. Measuring the process safety leading indicators is challenging compared to lagging indicators because it is the measurement for something before it occurs. However, safety cannot be granted by relying only on lagging indicators. Process safety leading indicators are a proactive approach to prevent process events and accidents before they occur.

Both leading and lagging process safety indicators are very important for measuring and improving the process safety system, and both should be used in the process safety performance assessment. There is no clear cut line between the leading and lagging indicators. Some process safety lagging indicators can be considered leading indicators to a catastrophic incident. Near-misses can be classified as leading indicators because they work as early indications of some deficiencies in the process safety system and don't have a significant sequence to be classified as lagging indicators. On other hand, near-misses can be classified also as lagging indicators because they already occurred.

2.3 Developing Process Safety Indicators Guidelines

The tragic events of BP Texas City Refinery disaster on March 23, 2005 brought the attention of the petrochemical industry to the importance of developing and maintaining process safety indicators. Several organizations started to put a lot of effort in establishing some guidance for developing process safety indicators, such as United Kingdom Health and Safety Executive (UK HSE), Organization for Economic Co-operation and Development (OECD), Center for Chemical Process Safety (CCPS) and American Petroleum Institute (API). The following section shows a brief description about the most common guidelines that currently are used to develop process safety indicators.

2.3.1 Developing Process Safety Indicators by UK HSE; HSG254

This guideline for developing process safety indicators was created jointly by the United Kingdom Health and Safety Executive (UK HSE) and the Chemical Industries Association (CIA) in 2006. The guide was designed mainly for the chemical and highly hazardous industries. The main objective of this guideline is to measure process safety indicators in order to assure that all hazards and risks are controlled correctly. The guideline uses "dual assurance" concept to measure the functionality and effectiveness of risk control systems using leading indicators for active monitoring and lagging indicator for reactive monitoring. Active monitoring should give feedback about the risk control performance before occurrence of an incident, while the reactive monitoring should give feedback about the risk control performance after the incident (HSE, 2006). Also, the guideline uses the "Swiss-Cheese" model to illustrate the leading and lagging indicators rules in discovering the deficiencies in the risk control system that are represented by multiple process safety protection layers. The leading indicators should detect the deficiencies (holes) in the risk control system during normal checks and inspections(HSE, 2006). The lagging indicators should detect deficiencies (holes) in risk control systems after the incident. The guideline establishes six major steps to measure process safety performance that are shown below:

Step 1: Set up leader and team

Step 2: Develop the scope

Step 3: Define the risk control systems and lagging indicators

Step 4: Identify critical components and leading indicators

Step 5: Collect data and information

Step 6: Review the performance result

The new main ideas of this guideline include development of process safety leading indicators, and using the “dual assurance” concept to measure the effectiveness of risk control systems. Also, the guideline identifies the immediate causes of all possible hazardous scenarios and the existing protection layers to control these hazards (HSE, 2006).

2.3.2 Guidance on Developing Safety Performance Indicators by OECD

This guidance was prepared in 2008 by the Environment, Health and Safety (EHS) Division of the Organization for Economic Co-operation and Development (OECD) to develop the Safety Performance Indicator (SPI) program. The main objectives of this program are to provide early warnings for all deficiencies in the safety system that may develop over time and define the corrective actions that shall be taken. The SPI program is represented by a process of seven steps, which are: (1) set up a team; (2) define the key issues; (3) develop lagging indicators; (4) develop leading metrics; (5) collect the data and information; (6) define the corrective action; and (7) review the safety performance indicators (OECD, 2008). The SPI program recommends identifying the main issues of concerns and potential hazards using the process hazard analysis (PHA) technique such as HAZOP, what-if analysis, and layers of protection analysis. The lagging and leading indicators should be developed based on most critical risk controls to reflect a clear measurement of safety performance (OECD, 2008).

The main new contribution in this guideline includes focusing on the corrective actions by adding a separate step in the process of development safety performance indicators. Also, the guideline priorities the hazards and risk controls based on possible scenarios, contributions to potential incidents, and likely consequences (OECD, 2008).

2.3.3 Process Safety Leading and Lagging Metrics by CCPS

This guideline was initially published in 2008 and revised in 2010 to be aligned with API RP 754, "Process Safety Performance Indicators for the Refineries and Petrochemical industries". This publication introduces the concept of the "Process Safety Metric Pyramid," which consists of three main parts; lagging metrics in the top, leading metrics in the bottom, and near-misses are located in the middle of the pyramid. Failure of layers of protection and the "Swiss Cheese" model were used to develop the lagging and leading metrics. The lagging metrics are represented by the failure of multiple protection layers, while the leading indicators are represented by the failure of a single protection layer, or a deficiency "hole" within a single protection layer (CCPS, 2011). Different process safety incidents rates were introduced in this publication using a severity categorization of each indicator. The publication developed leading indicators for major elements in the safety system including mechanical integrity, management of change, action item follow-up, and process safety training (CCPS, 2011).

2.3.4 Guidelines for Process Safety Metrics by CCPS

This publication was issued in 2010. The objective of this publication was to provide guidelines for different levels with the organization on how to develop and improve process safety indicators. This publication tried to bring together all previous efforts that had been done on the development of process safety indicators including the UK HSE and OECD guidelines. This publication identifies different procedures to select the process safety leading and lagging indicators such as identifying the weaknesses in the process safety system using experience judgment or data analysis. Process hazard analysis, incident investigations, audits, and process safety system baseline surveys can be used to identify the weaknesses in the process safety system. This guideline highlighted the importance of communicating the process safety indicator measurements on a frequent basis. Different process safety indicators should be communicated to different levels of the organization depending on their responsibilities, objectives and roles (CCPS, 2010).

2.3.5 API RP 754; Process Safety Performance Indicators for the Refining and Petrochemical Industries

This recommended practice was issued by the American Petroleum Institute in 2010. The main objective of this publication is to identify process safety leading and lagging indicators in refining and petrochemical industries. The new concept in this publication is that process safety indicators are classified into four main tiers that are represented by the process safety incident pyramid as shown in Figure 1. The top of the pyramid is mostly lagging indicators, whereas the bottom of the pyramid is mostly leading indicators. The classification of the process safety indicators into four tiers was based on the level of consequence (API, 2010).

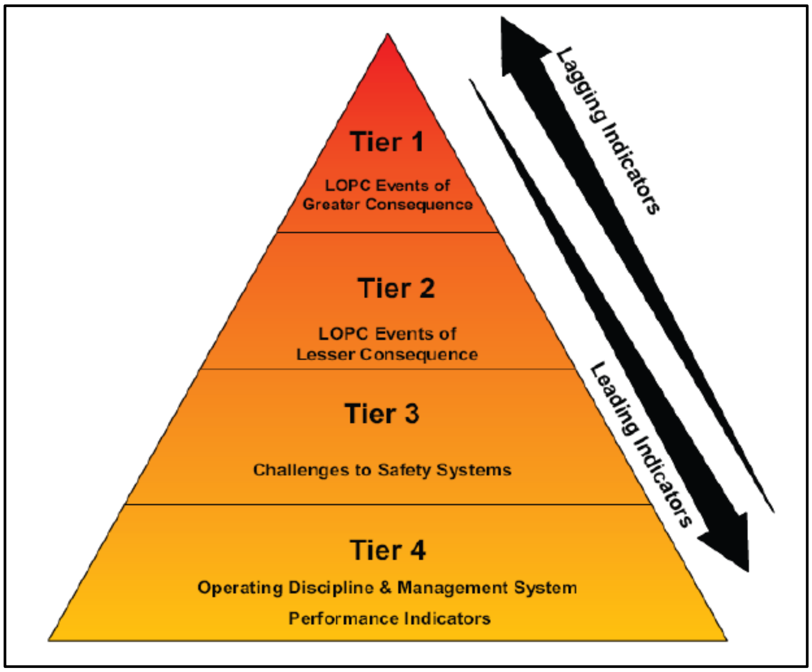

Figure 1. Process Safety Indicators Pyramid (API, 2010)

Tier 1 is represented by loss of primary containment (LOPC) with greatest consequence, while Tier 2 is represented by loss of primary containment (LOPC) with lesser consequence. Tier 3 is designed to be used internally and is represented by process safety system challenges such as exceeding the safe operating limit. Tier 4 is designed to reflect of facility-specific barriers and performance objectives. Both of Tiers 1 and 2 should be reported annually to the community and emergency management team of the specific facility. This recommended practice identified different procedures to select the process safety indicators including process hazard analysis and risk assessment, incident investigation and analysis, and shared lessons learned from outside parties (API, 2010).

3. PROCESS SAFETY LEADING INDICATORS AND ORGANIZATIONAL FACTORS

The development of process safety indicators is the key to improve the process safety system. Both leading and lagging indicators have a major contribution in measuring and improving the process safety system. It is essential for petrochemical industries to focus on leading indicators to prevent process safety incidents or to reduce the severity of these incidents. Process safety leading indicators are forward-looking and proactive indicators that can identify the deficiencies and weaknesses in the process safety system before an incident occurs.

3.1 Difficulties in Developing Process Safety Leading Indicators

The development and measurement of process safety indicators would require a lot of effort and analysis compared to process safety lagging indicators. The lagging indicators are easier to measure because they represent a measurement of specific process safety events that already occurred. On other hand, process safety leading indicators are more challenging because they are based on the prediction measurements related to the probability of process safety incidents in the future. There are several challenges to develop process safety leading indicators that include leadership commitment and support, data collections, continuous monitoring of measurements, and selecting the most effective indicators. In this section, the main difficulties of developing process safety leading indicators will be explained in detail.

3.1.1 Leadership and Management Commitment

Leadership and management support are essential in developing and monitoring process safety leading indicators. Leadership and management play key roles in the implementation and reinforcement of the process safety measurement program. Effective engagement of senior management has a major impact in encouraging the accurate reporting of the process safety data. Corporate management shall review and communicate the measurement of process safety leading indicators frequently with all levels of the organization. These measurements shall be used as a baseline measurement of the company process safety instead of using personnel injury rates or other lagging indicators. The main objective of process safety leading indicators is to identify and detect the faults and deficiencies within the process safety system of the industrial facility. However, detection alone is not sufficient and would require leadership and management support to rectify these deficiencies and verify that these faults are fixed properly (CCPS, 2010).

3.1.2. Data Collection

Collection of the process safety data and information is one of the major challenges that the petrochemical industry faced during the development of process safety leading indicators. In the petrochemical industry, there is a big variance between what can be measured and what should be measured. Most of the collection data systems were designed to collect direct information about the personnel safety system such as injuries, fatalities and motor vehicle accidents. This data collection system can be modified easily to collect the data related to process safety lagging indicators such as gas releases, fires and explosions because it is direct and simple to collect. However, the existing system is difficult to be adapted to collect the process safety leading indicator data. A lot of effort will be required to build an independent automated data collection system for process safety that includes leading indicators data and analysis. Such a data collection system shall be designed to deal with indirect data and analysis related to process safety leading indicators. It is expected to be costly and requires a lot of time and development updates. For an effective system, employees within different organizational levels should be trained on how to collect and report the process safety data. The effective training will help to communicate the right data and to keep consistency (Kenan & Kadri, 2014).

3.1.3. Continuous Monitoring

The measures of process safety leading indicators would require continuous monitoring to ensure that all potential hazards or faults in the process system will be identified in a timely manner to take corrective actions before an incident occurs. The deficiency in the monitoring system will result in a delay in detecting potential deficiencies in the process safety system that may lead to high consequence events. There are two main types of monitoring, which are either active or reactive monitoring. Active monitoring is used to provide measures of process safety performance before an incident occurs, while reactive monitoring provides measures of process safety performance after the incidents (HSE, 2006). The petrochemical industry should rely heavily on the active monitoring of critical process safety leading indicators. The monitoring system effectiveness is expected to decrease gradually as the number of the tracked process safety indicators increase (HSE, 2006). The petrochemical industrial organizations should focus on the monitoring of limited critical process safety leading indicators that have a great impact on process safety and provide acceptable accurate measures about the status of the process safety system. Monitoring of the process safety leading indicators should be a cost-effective process by monitoring few indicators that are sufficient to provide accurate and sufficient process safety measures.

3.1.4. Indicators Definitions

Process safety leading indicators have several definitions across a wide variety of guidelines. There are more general and vague words in these definitions that are causing different understanding among the petrochemical process industry. Some of the metrics that are classified as leading indicators in some companies are classified as lagging indicators or near-misses in other companies. Each organization has different interpretations about the meaning and goal of process safety metrics. Also, additional subsystem classifications of the process safety indicators resulted in adding more layers of complexity in understanding the indicator definition. In API RP 754 guideline, a lot of petrochemical industrial organizations struggled in classifying the process safety leading indicators between safety system challenges or performance indicators (Kenan & Kadri, 2014).

3.2 Limitations of the Current Methods

The major limitation in developing process safety leading indicators is the gap between the current guidelines and their implantations in the actual process industrial fields. The implementations of the current guidelines would require a lot of effort, time, cost, and expertise, which are challenging in most petrochemical organizations. So, most of the companies try to implement these guidelines based on their limited available resources, which creates many deficiencies in their measurements of process safety leading indicators. As a result, most of these industrial companies try to develop process safety indicators that lack either systematic approaches or proactive approaches (Khawaji, 2012).

The current guidelines heavily depend on the traditional hazard analysis techniques or incident analysis techniques to develop process safety indicators. These techniques are focusing more on the technical side and component failures in the process system. Management and organizational factors are ignored normally during developing process safety indicators using these techniques (Leveson, 2015). Also, the traditional hazard analysis techniques are mostly focused in superficial causes rather than the fundamental root causes. A single series of linear events are normally assumed, which doesn't represent the system complexity of the petrochemical industry (Khawaji, 2012).

Selection of the appropriate process safety leading indicators is one of the main concerns that the petrochemical industrial facilities encountered. Most of these facilities struggled with identifying the correct number of process safety leading indicators that they should develop and monitor. This is to ensure that there are not too many or too few. The petrochemical industrial facilities have large variations in the number of developed process safety indicators, ranging from three leading indicators to 28 leading indicators as per the process safety leading indicators survey that was conducted by the center for chemical process safety (CCPS) in February 2013 (Kenan & Kadri, 2014). Too few process safety leading indicators will result in inaccurate measurement of a process safety system and several faults may not be detected, while too many process safety indicators will result in excessive monitoring and measurement of process safety indicators. However, accurate measurements of the process safety leading indicators will decrease as the number of monitored leading indicators increase because each leading indicator would require a lot of effort to be measured and monitored.

Monitoring the developed process safety leading indicators is another key concern that the petrochemical industry encountered in development of process safety leading indicators. Process safety control systems may degrade over time and process safety leading indicators should discover this degradation and weakness within the process safety system before an incident occurs. So, it is very important to keep a continuous monitoring of critical process safety leading indicators to ensure the effectiveness of the existing process safety control systems and protection against any new hazards that may develop.

Another limitation in using the current guidelines to develop process safety leading indicators is the measurement accuracy for a specific process safety indicator. The recommended equations to calculate these leading indicators have many shortages and may not represent the actual status of measured elements. Qualitative metrics of the measured process safety indicators, which are mostly ignored, are as important as the quantitative metrics that are used normally to measure the process safety indicators. For example, the quality of the conducted management of change (MOC) or process hazard analysis (PHA) are very important to perform accurate measurement of these two elements. The number of conducted MOCs or PHAs may be misleading and do not represent the true measurement of these two elements. Most of the petrochemical organizations lack accurate measurement of process safety leading indicators, which requires using several metrics to ensure accurate measurement of each leading indicator. These metrics should be both quantitative and qualitative, and should cover all parts of the measured process safety leading indicators.

3.3 Importance of Organizational Factors in Process Safety

Organizational factors have large effects on the process safety systems in petrochemical industrial facilities. These organization factors have great contributions in most of the process safety incidents. However, these organizations factors were ignored in many previous incident investigation reports. The organizational factors consist of a lot of elements, which include mechanical integrity, communication, management of change

(MOC), training program, personnel workload and safety culture. These organizational factors vary on their effects on the process safety system.

The data collected by the International Association of Oil & Gas Producers (OGP) was used to study and analyze the causal factors for the major incidents and near-misses in the oil and gas industries. The data was studied and analyzed over a period of four years, from 2010 to 2013, to evaluate the actual performance and variance of these causal factors across considerable period of time (OGP, 2014b). High potential events can be either an incident or a near-miss that has a potential to cause injuries, fatalities, or major damages. One or more causal factors were assigned to each high potential event. In 2013, 124 high potential events were investigated and analyzed to be caused mainly by 444 causal factors (OGP, 2014b).

Organizational factors were found to be on the top of the list of causal factors for the high potential events. Out of the 124 high potential events in 2013, deficiencies in the mechanical integrity organizational factor were found to be the causal factor for 57 high potential events, where failure in the standards/procedures organization factor resulted in 44 high potential events. Insufficient process hazard analysis and training/competence organizational factors caused 35 and 29 high potential events, respectively (OGP, 2014b). Due to the variations of the analyzed high potential events over the four years, the data was normalized based on 100 high potential events in order to perform accurate comparisons between different causal factors. Table 1 summarizes the common organizational factors contributed to major incidents and near-misses during the last four years based on data collected by OGP (OGP, 2014b).

Table 1. Contribution of Organizational Factors in High Potential Events

Causal Factor	Number of Organizational Factors that Assigned as Causal Factors per 100 High Potential Events			
	2013	*2012*	*2011*	*2010*
Mechanical Integrity	46.6	37.9	36.2	38.1
Procedures/Standards	35.5	32.0	29.0	38.1
PHA/Risk Assessment	28.2	36.1	34.8	48.5
MOC/Design	23.4	9.5	26.1	13.4
Training	23.4	21.3	21.7	22.7
Communication	21.0	21.7	22	19.6
Supervision	19.4	26.0	26.1	32.0

Organization factors had large contributions to the major incidents and near-misses as shown from the previous table. These organizations causal factors vary a lot in their contributions to the high potential events. These organizational factors can be ranked based on their effects in the following order: (1) mechanical integrity, (2) process hazard analysis/risk assessment, (3) procedures/standards, (4) Supervision, (5) training/competence, (6) communication, and (7) design/management of change (OGP, 2014b).

3.4. BP Texas City Refinery Explosion Case Study

A catastrophic explosion destroyed a considerable part of BP Texas City Refinery on March 23, 2005, where 15 workers were killed, 180 injured, and financial losses were estimated to be more than 1.5 billion dollars. A large quantity of flammable liquid and gas was released through an open blowdown drum vent during the startup operation of the isomerization unit, which resulted in a massive vapor cloud explosion (VCE). Incident investigation report highlighted several deficiencies in the process safety system of BP Texas City Refinery that lead to this disaster (CSB, 2007).

Most of organizational and safety system deficiencies that lead to this disaster existed several years before the incident. These deficiencies could be detected easily if there were an effective process safety indicator system. There was no appropriate system or program to measure the process safety performance in BP Texas City Refinery. The existing safety system focused mainly on injury rates to measure the effectiveness of the process safety system. The low personnel injury rate was a misleading indicator for the process safety performance (CSB, 2007). One of the major Baker Panel investigation report recommendations was to develop process safety leading and lagging indicators program (Baker, Leveson et al., 2007).

The unsafe location of the occupied trailers next to the isomerization unit that was handling hazardous and flammable materials indicated insufficient management of change (MOC) process and failure of the hazard identification program (CSB, 2007).

Most of the fatalities were inside or around the occupied trailers and they were not aware about the startup of the isomerization unit which showed a failure of hazard communication element. Major flammable material releases occurred eight times during the recent years prior to the incident without a proper investigation and analysis (CSB, 2007). The cost-cutting preference by the management resulted in less investment in process tools development and more dependence on the operators' interactions. Also, the number of operators was reduced significantly to satisfy the cost-cutting objectives. The board operator was handling two major process units in addition to the isomerization unit which all required a close attention. The board operator was working in a 12 hour shift for the last 29 consecutive days prior to the incident. The lead operator was in a 12 hour shift for 37 consecutive days and was overloaded with several activities including following-up with contactors, training new operators, and working on the startup of the isomerization unit. There were clear indications of operator excessive workloads that resulted in the operators' fatigues. The management cost-cutting plan had a direct negative impact on training, staffing, and mechanical integrity. The management worked to achieve the cost-cutting goals discarding their effects on the process safety performance (CSB, 2007).

The startup procedure for the isomerization unit was outdated and not followed which resulted in several mistakes which lead to overfilling of the raffinate splitter tower of the isomerization unit. Deviations from the written operations and maintenance procedures were the normal practice in the BP Texas City Refinery facility (Baker et al., 2007).

The unit supervisor left early in the day of the incident without an experienced personnel or adequate supervision at the site during the critical startup operation. Also, there was a failure of communicating critical startup process activities during the shift handover. The day lead operator left early and the night shift supervisor arrived late which indicate that face to face shift turnover was not conducted and shift log book was lack to a critical process information (CSB, 2007).

There were several deficiencies in the design of the isomerization unit that include the raffinate splitter tower and blowdown drum. The level and quantity of the flammable material inside the raffinate splitter tower was unknown due to the limitation of the installed level indicator and lack of flow indicators on the inlet and outlet of the splitter tower (CSB, 2007). Two redundant level indicators with alarms should be installed in such critical splitter tower in case of failure or malfunction of one of them. Also, the raffinate splitter tower should be provided with ab automatic interlock to prevent overfilling of the splitter tower. Releasing of flammable material into the atmosphere through the blowdown drum vent was a hazardous action and an indication of a design deficiency in the pressure relief system. The relief valves should be connected to a proper flare system. An effective process hazard analysis would discover such hazards and would work to eliminate them with proper controlling measures (CSB, 2007).

There were several deficiencies in the mechanical integrity of BP Texas City Refinery facility where some instrumentations and equipment were not working properly. The pressure control valve of the raffinate splitter tower was malfunction, and level indicator was not calibrated. The facility was lacking to a preventive maintenance program and there was a total dependence on responding to failures only. In addition, the repair integrity was inadequate where the same repaired components failed several times within short time (CSB, 2007).

In conclusion, there were several deficiencies in the process safety system can be detected and rectified prior to the incident. An efficient process safety indicator system would be able to detect and fix these deficiencies and faults. The leadership safety culture and competence would have a high impact on the process safety performance. Releases of flammable material from the blowdown drum were reported several times but the incident and near-miss investigations failed to prevent reoccurrence of this hazardous event. The incident investigation report highlighted deficiencies in several organizations factors that include mechanical integrity, operational procedures, management of change, process hazard analysis, communication, training, safety culture and personnel workload (CSB, 2007).

4. PROCESS SAFETY DATA COLLECTION AND ANALYSIS

There were several difficulties in collecting the process safety leading indicators data for various reasons that will be discussed in this section. A cost-effective method will be developed by selecting a limited number of leading indicators that have a great impact on the process safety performance. An effective near-misses investigation and analysis play important role in measuring the process safety performance. Bayesian network technique will be used to study the probability reasoning of different organizational factors that cause an incident. Numerous quantitative and qualitative metrics will be used to perform accurate measurements of the most effective leading indicators.

4.1 Data Collection Difficulties

The collection of process safety leading indicators data is a difficult task. Most of the petrochemical industrial companies do not have a sufficient data collection system to analyze process safety measures. The process safety leading indicators would require a lot of time and effort to be measured (Kenan & Kadri, 2014). A large database would be required to do a proper research to analyze process safety data. There were two main types of difficulties in collection these data. The first type of difficulties is the process safety data unavailability. The second type of difficulties is the willingness of petrochemical industrial companies to share their process safety data.

A new developed collection data system would be required to conduct an effective collection of process safety data. Most of the current safety data systems are dealing with both process safety data and personnel safety data at the same time. This will make it very difficult to accurately analyze and discuss process safety data. A standalone process safety data collection system would be required in order to achieve a correct measurement and analysis of these data. The survey conducted by the Center of Chemical Process Safety (CCPS) in 2013 indicated that the industrial facilities are still in the experimental phase of collecting process safety data and development of process safety leading metrics (Kenan & Kadri, 2014).

Many petrochemical industrial facilities are not willing to share their process safety leading indicators data with the public. These companies may think that the releasing some of these data may have direct effects on the integrity of these data which used mainly for improvement purposes. Also, these process safety leading indicators may be incorrectly interpreted by the public, where these data are used as an improvement tool rather than a measuring tool. In addition, most of petrochemical industrial companies started to put some attention on collecting the process safety data in 2010 after releasing of API RP 754, *Process Safety Performance Indicators for the Refining and Petrochemical Industries*. There have only been a few years of implementations for most of the companies where a lot of audits and updates involved in the process safety leading indicators systems. These continuous changes and updates to the system make it difficult to report the variable data of process safety leading indicators. In addition, API RP 754 only requires all petrochemical industrial companies to report the lagging indicators to the public (API, 2010).

4.2 Alternative Data Collection Method

The process safety leading indicators can be developed through three main techniques which are hazard analysis, incident investigations, and shared lessons learned (CCPS, 2010). In the case of a lack of reported process safety leading indicators, a comprehensive incident investigation and analysis database would be a good replacement procedure to analyze the process safety leading indicators data. The incident investigation and analysis data base should be focused on the real causes rather than superficial causes. Also, the incident investigation should look for the process safety control system that degraded over the time. The effective incident investigation and analysis should provide adequate data that required to perform a proper analysis and study of leading indicator variables. The only negative property with using this technique is the lack of a proper mathematical relation between leading indicators events and lagging indicators events, where several leading indicators events would not cause incidents or near-misses.

The database collected by the International Association of Oil & Gas Producers (OGP) was used to study and analyze the process safety leading indicators events using the incident investigation of process safety incidents and near-misses. The database includes causal factors of high potential events for a four-year period, from 2010 to 2013. The investigations were conducted for the high potential incidents and near-misses that may result of harm to people or equipment. These investigations analyzed these high potential events and assign one or more causal factors for each event. The database was collected from around 50 industrial companies around the world representing OGP members.

The causal factors data were classified into two main classifications, which are act and process causal factors. First, the act causal factors include mistakes, slips and lapses related to human actions, e.g. an operator did not perform the required action or did a wrong action. The causal factors related to the act causal factor classification are more categorized into the human error related to following procedures, using equipment/tools, lack of attention and protective method failure. Second main classification is the process causal factors which involve equipment/tools failures, organizational deficiencies, physical hazards, and defective protection system (OGP, 2014a).

In 2010, about 97 high potential events were caused by 400 causal factors. The top causal factors were process hazard analysis, mechanical integrity, procedures/standards, supervision, and training/competence, respectively (OGP, 2014b). Around 69 high potential events were caused by 317 causal factors in 2011. The top causal factor was mechanical integrity, followed by process hazard analysis, procedure/standards, management of change, and supervision, in that order (OGP, 2014b).

In 2012, about 169 high potential events were caused by 603 causal factors. The top three causal factors were the same as in the previous year. The fourth and fifth causal factors were training/competence and communication, respectively (OGP, 2014b). In

2103, there were 124 high potential events were investigated and analyzed. These high potential events were caused by 444 different causal factors. The top five causal factors were mechanical integrity, procedures/standards, process hazard analysis, training/competence, and management of change, respectively(OGP, 2014b). Table 2 below summarizes the most common causal factors that lead to high potential incidents and near-misses during the four-year period as per OGP data base.

Table 2. Top Causal Factors from 2010 to 2013

Causal Factor	Number of High Potential Events per Causal Factor			
	2013	*2012*	*2011*	*2010*
Mechanical Integrity	57	64	25	37
Procedures/Standards	44	54	20	37
PHA/Risk Assessment	35	61	24	47
Competence/Training	29	36	15	22
MOC/Design	29	16	18	13
Communication	26	36	15	19
Supervision	24	44	18	31

4.3 Analysis of Most Effective Causal Factors

Monitoring large number of leading indicators would require a lot of time and effort. So, it is very important to do a cost-effective analysis by studying the most effective leading indicators that have great impacts on the process safety performance. The collected database in the previous section should be normalized due to the different number of investigated high potential events across the four-year period. Table 3 below shows the top causal factors per 100 high potential events.

Table 3. Most Effective Causal Factors of High Potential Events

Causal Factor	Number of Organizational Factors that Assigned as Causal Factors per 100 High Potential Events			
	2013	*2012*	*2011*	*2010*
Mechanical Integrity	46.0	37.9	36.2	38.1
Procedures/Standards	35.5	32.0	29.0	38.1
PHA/Risk Assessment	28.2	36.1	34.8	48.5
Competence/Training	23.4	21.3	21.7	22.7
MOC/Design	23.4	9.5	26.1	13.4
Communication	21.0	21.3	21.7	19.6
Supervision	19.4	26.0	26.1	32.0

The most effective causal factors can be listed in the following order:

(1) Mechanical integrity (MI)

(2) Process hazard analysis (PHA) and risk assessment

(3) Procedures and standards

(4) Supervision

(5) Training and competence

(6) Communication

(7) Management of Change (MOC) and design

Each causal factor had different effects on causing high potential events. The effect of each factor varies from one year to another, but the top three causal factors are the same over the four-year period. The three most effective causal factors are mechanical integrity, procedures/standards, and process hazard analysis organizational factors.

4.4 Importance of Near-misses Analysis

A process safety near-miss can be defined as any event that has the potential to cause a process safety incident but does not meet the definition and criteria of process safety lagging indicators or process safety incidents. A process safety near-miss can be either a release of hazardous material below the threshold limit or a failure of a protection system (CCPS, 2011). An example of a near-miss is when a flammable gas leak resulted in the release of flammable gas in quantities below the threshold limit and there is no harm caused by the gas leak. Another example is a failure of a safety protection system, such as relief devices, emergency shutdown system, or gas detection system, that does not result of a process safety incident (CCPS, 2011).

Near-misses can be classified as leading and lagging process safety indicators at the same time because there are some common factors between near-misses and both types of indicators. A near-miss can be classified as process safety lagging indicator because it describes an event that already occurred. Also, a near-miss can be classified as a process safety leading indicator because it works as an indication for a more serious event. In both classifications, near-misses shall be investigated and analyzed properly to identify all associated hazards, risks and causal factors that may have the potential to cause high potential process safety incidents. So, an appropriate analysis of process safety near-misses can be the main reason to avoid a lot of process safety incidents (CCPS, 2010).

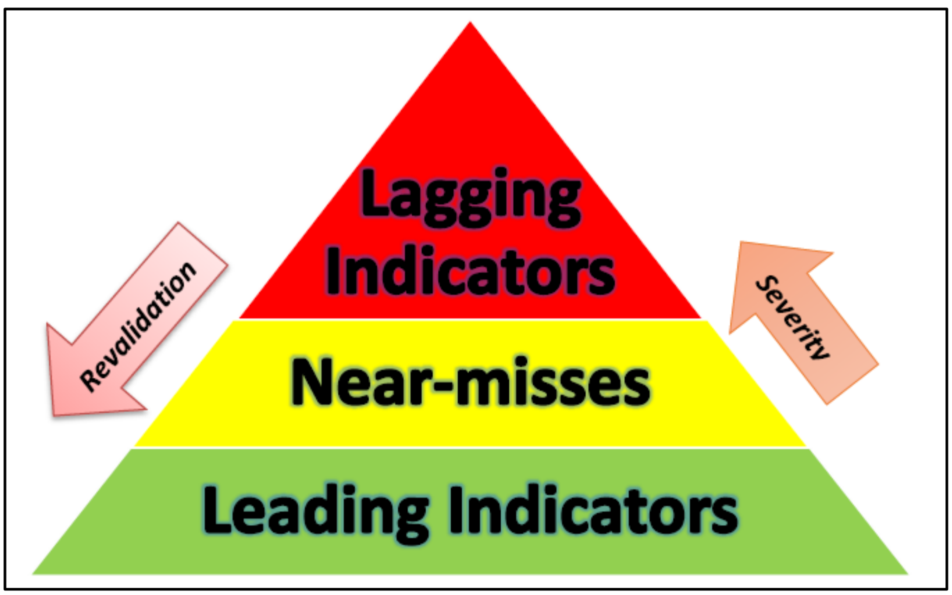

Figure 2. Severity and Revalidation of Indicators in Process Safety Pyramid

Major incidents could be prevented by tracking, analyzing and reducing near-misses and low-consequence process safety events (Prem, 2010). The near-miss analysis is a critical element in an effective process safety system. A single process safety incident is normally proceeded by multiple near-misses that share the same causal factors and process safety deficiencies (Oktem, Seider et al., 2013). Near-misses are located in the middle of the process safety pyramid between the lagging and leading indicators as shown in Figure 2. The severity of process safety events increases as one goes from the bottom of the pyramid to the top. So, it is easier to detect a near-miss than it is to detect a leading indicator because near-misses have higher severity.

A near-miss investigation and analysis system should be part of a process safety management system. The near-miss investigation system should include the identification and reporting of all near-misses within the industrial facility. This important step will require specific training and establishing a good safety culture. After the reporting, near-misses should be filtered out to identify the high potential near-misses that require further analysis. These high potential near-misses should be analyzed by a knowledgeable and experienced team to identify the causal factors of each near-miss. A list of action items should be generated to resolve all deficiencies within the system and prevent the recurrence of a similar high potential process safety event. A follow-up should be conducted to ensure that all recommendations and action items are properly completed (Muermann & Oktem, 2002).

4.5 Bayesian Network to Measure Process Safety Performance

The Bayesian network technique is used to study the reasoning probability between different related variables in a complex system. It is an excellent technique to study the relations between different causal factors and their likelihood to cause high potential incidents or near-misses. The Bayesian network will be built based on the OGP database of most effective causal factors of high potential events. The database of previous incidents and near-misses will be used as weighting factors of the probability of a high potential event. The AgenaRisk software will be used to study the effects of different organizational factors on the probability of a high potential incident. When all organizational factors are maintained in a good condition, the probability of having a high potential event will be very low, around 2% as shown in Figure 3 below.

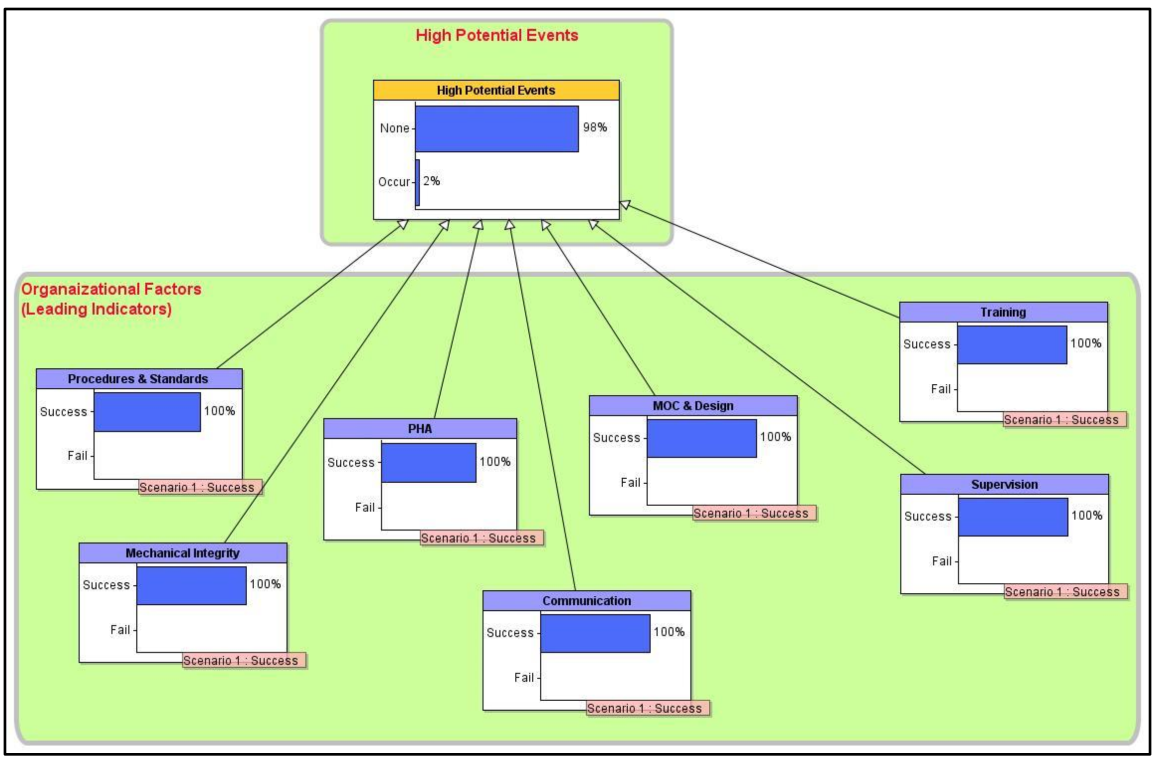

Figure 3. High Potential Events Caused by Organizational Factors

The previous AgenaRisk diagram shows that there is still a very small percentage (2%) of having a process safety incident due to standard deviations and the effects of other causal factors. Failure of one or more of these major causal factors will result in increasing the probability of having a process safety incident.

The BP Texas City Refinery explosion can be illustrated and studied using the previous AgenaRisk model. There was a failure of process hazard analysis where the major consequences of the high liquid levels in the raffinate splitter tower and the blowdown drum were not identified. Also, there was a major failure in the mechanical integrity system where many instrumentations were malfunctioning and not calibrated. The startup procedure was not updated and not followed by operators. Siting of the occupied trailers was an indication of a failure of the management of change (MOC) factor. The absence of a qualified supervisor during critical startup operations led to a failure of the supervision protection layer. The communication system failed due to shift turnover deficiencies. All these failure can be represented in the AgenaRisk model to calculate the process incident probability as shown in Figure 4.

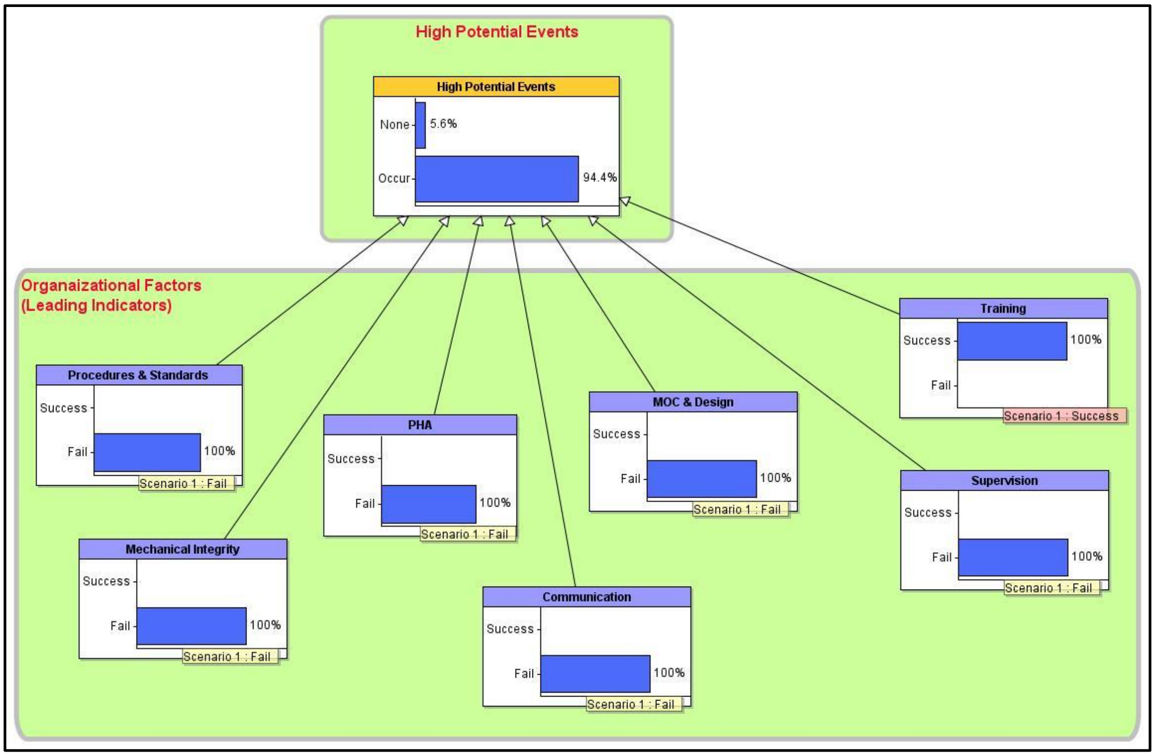

Figure 4. Failure of Organizational Factors Lead to BP Texas City Disaster

The probability of having a process safety incident has increased from 2% to be more than 94%, which is a very high probability indicating a certain occurrence of a major process safety incident. Failure of most of these organization factors could have been noticed and observed prior to the explosion.

Organizational factors have different effects on the probabilities of high potential events. Some of the organizational factors contribute more than the other to cause process safety incidents. The different effects can be studied using the developed AgenaRisk model. The model should be updated to reflect the occurrence of high potential events with 100% probability to observe the organization factors' probabilities as shown in Figure 5.

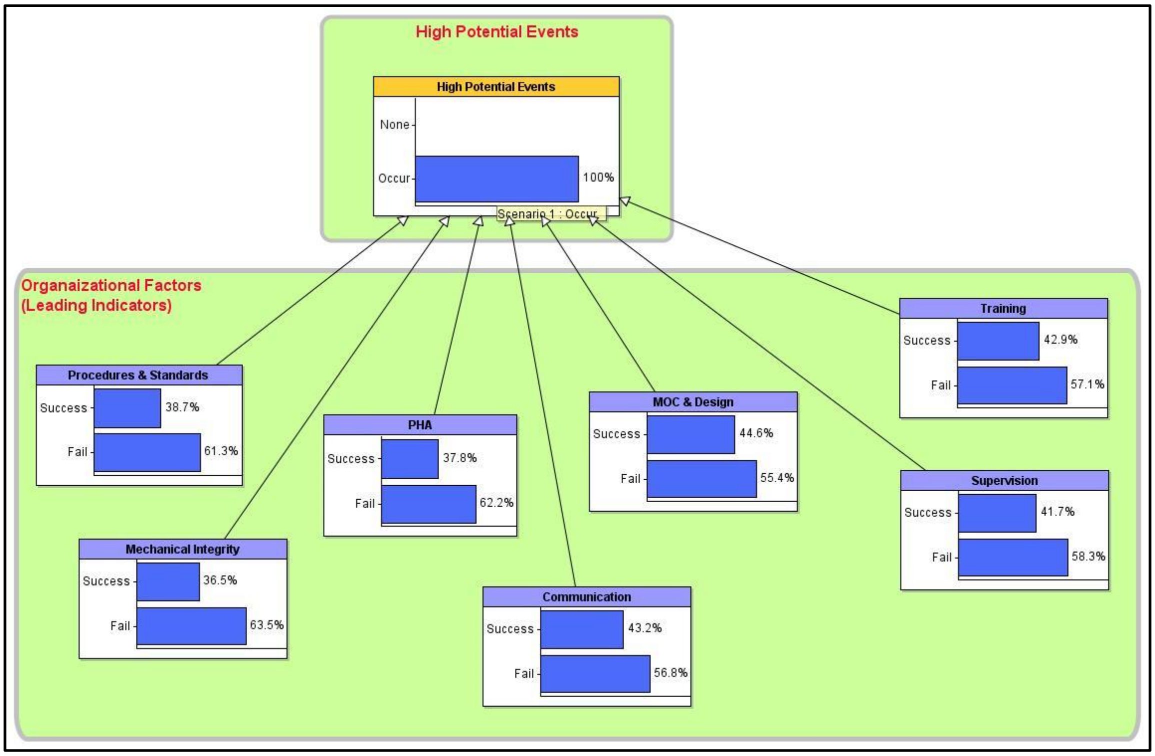

Figure 5. Most Likely Explanation of Having High Potential Events

The most likely explanation (MLE) of having a high potential incident is the mechanical integrity organizational factor with 63.5%. It is followed by the process hazard analysis and procedures/standards organizational factors with probabilities of 62.2% and 61.3%, respectively.

The previous analysis technique can be used also to select the most effective leading indicators. Cost-effective selection of leading indicators is an important factor during the development of process safety measures. Maintaining one effective leading indicator can be more efficient than maintaining two less effective leading indicators, as shown in Figure 6 and Figure 7. Failure of the mechanical integrity organizational factor would result in increase of the probability of high potential events to be 11.4%, as shown in Figure 6. On the other hand, the failure of two leading indicators, which are MOC/design and communication organizational factors, would result in only 10.4%, as shown in Figure 7.

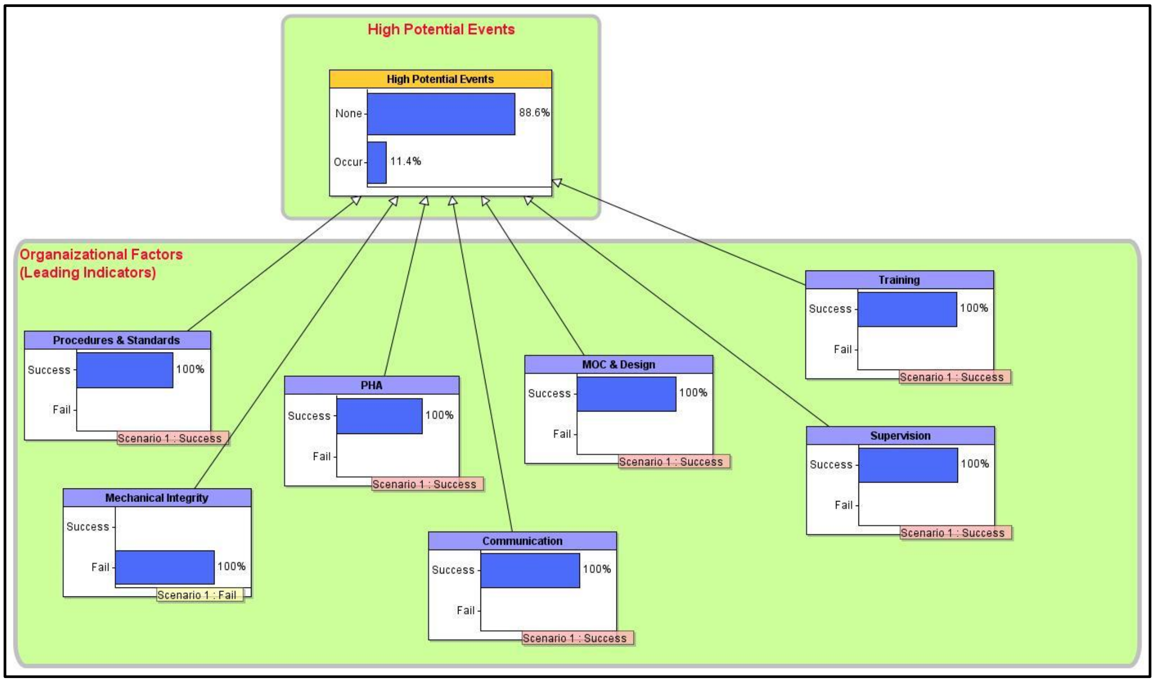

Figure 6. Effect of Mechanical Integrity Failure on High Potential Events

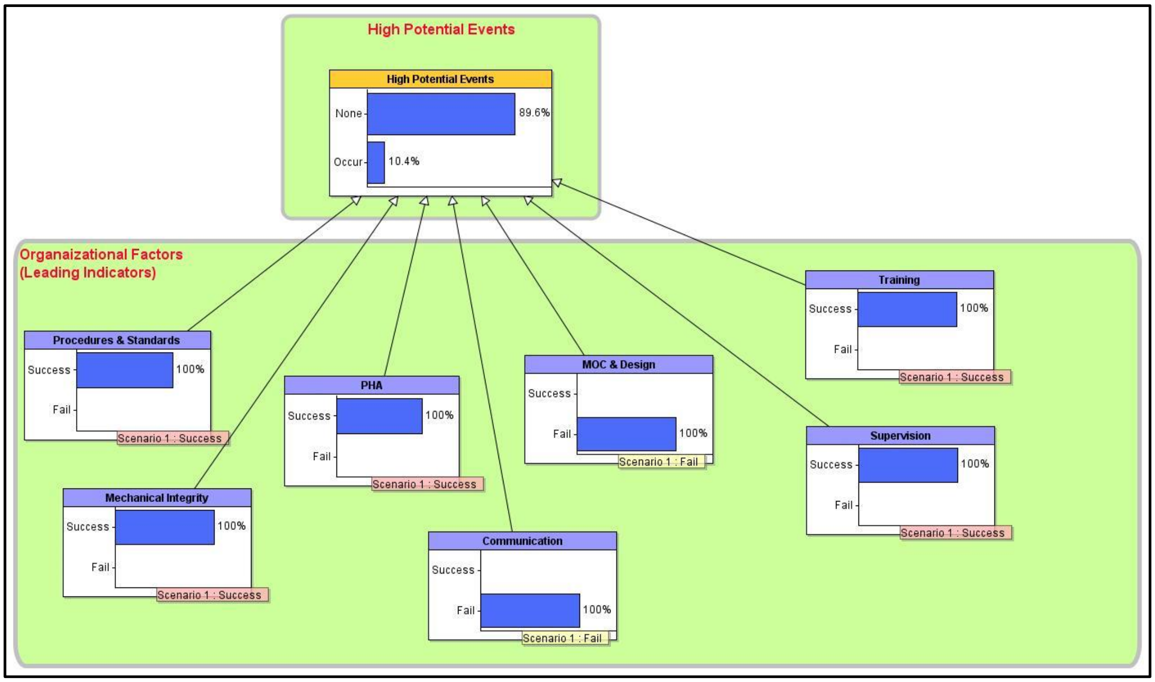

Figure 7. Failure of MOC/Design and Communication Organizational Factors

In addition, focusing on two effective organizational factors can be more efficient than focusing on three organizational factors. The probability of high potential events would greatly increase to 33.1% as result of co-failures of two effective organizational factors, mechanical integrity and PHA, as shown in Figure 8. In contrast, failures of three less effective organizational factors (communication, training, and MOC) would result in only 21.1% probability of having a high potential event, as shown in Figure 9. So, the effects of the mechanical integrity and PHA organization factors are much higher than the effect of all three of the previous mentioned organizational factors by more than 1.5 times.

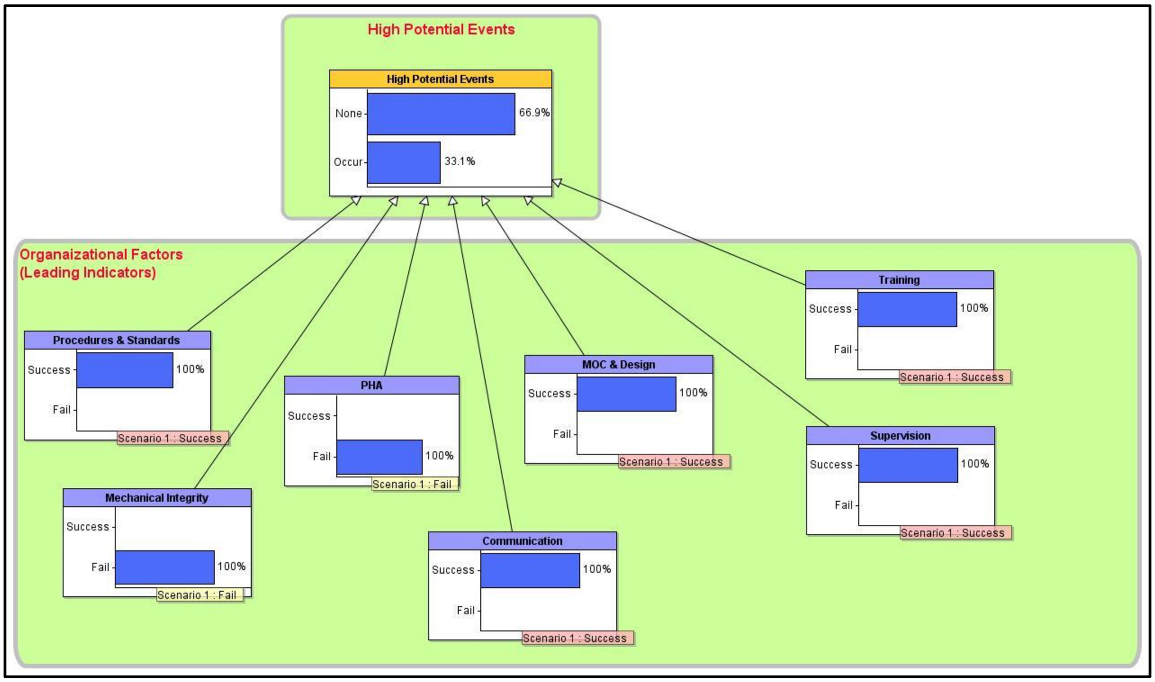

Figure 8. Effects of Failures of Mechanical Integrity and PHA Elements

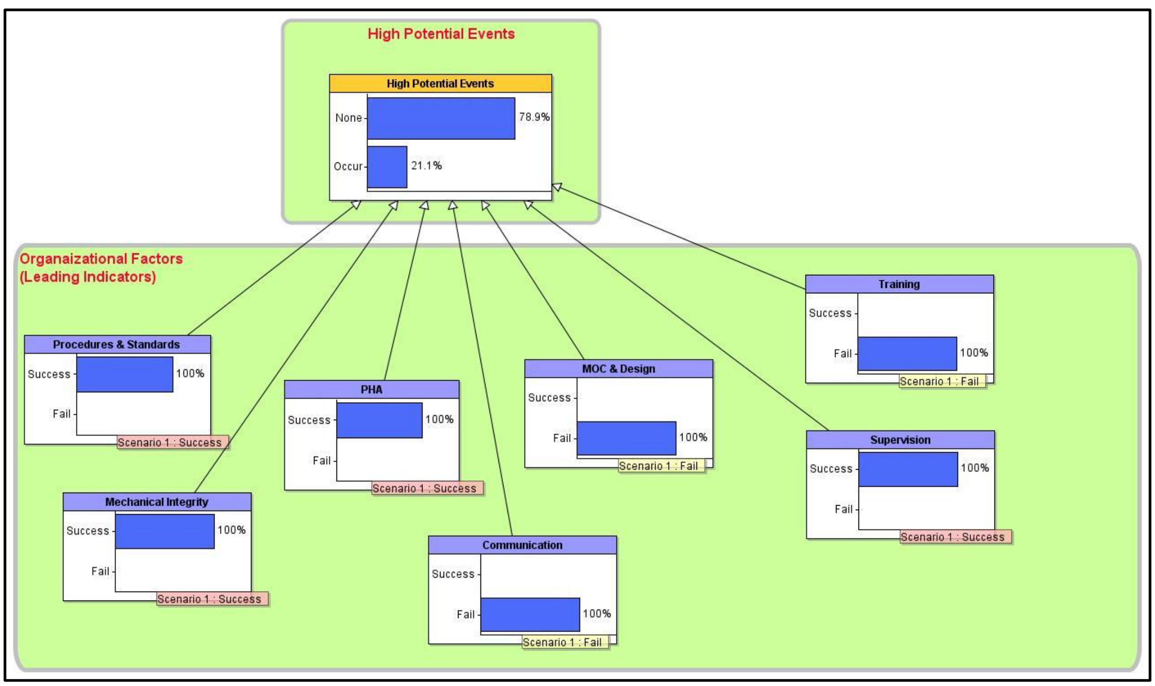

Figure 9. Failure of Three Less-Effective Organization Factors

4.6 Quantitative Assessment of Highly Effective Causal Factors

The Bayesian network technique discussed in the previous section provides a good comparison analysis in general. However, there are two main concerns with the previous assessment. First, the reported high potential events may include some incidents that are not related to process safety and need to be verified. Secondly, the previous analysis did not consider the interactions and dependent relationship between the different organizational factors.

In order to check the reliability of the causal factors data, a more detailed analysis would be required. All the listed incident investigation reports within the International Association of Oil & Gas Producers (OGP) data were reviewed to check the accuracy of associated results. The descriptions of some of the listed events were found to be related to transportation incidents and near-misses, which should not be classified as process safety events. Also, there are some process safety events found incomplete and without assigned causal factors (OGP, 2014c).

Based on the intensive review of 2013 OGP data, there were 95 process safety events were investigated. The causal factors were not assigned for 28 process safety events out of the 95 events. The remaining 67 process safety events were analyzed, and one or more causal factors were assigned for each event. Table 4 below shows the most common seven causal factors for the high potential process safety events according to 2013 OGP data report (OGP, 2014c).

Table 4. Most Common Root Causes of Process Safety Events

Causal Factor	High Potential Process Safety Events	
	Number	%
Mechanical Integrity	30	46.9
Procedure/Standards	29	45.3
PHA/Risk Assessment	28	43.8
MOC/Design	22	34.4
Competence/Training	15	23.4
Communication	13	20.3
Supervision	12	18.8

Main comparisons were performed between the original data and the revised data to check and verify the accuracy of the previous results and conclusions. In general, the new revised data verified the sequence of the most common causal factors that lead to high potential events found in previous analysis. As found in previous results, the most effective causal factors were found to be mechanical integrity, procedures/standards, process hazard analysis, design/management of change, training/competence, communications, and supervisions. The rate of the high potential process safety events caused by the mechanical integrity was found to be 46.9% which is almost the same in both data analysis. Procedures/standards organizational factor was the causal factors for 45.3% of the high potential process safety events, which is approximately 10% higher than the previous analysis in the original data. Process hazard analysis and managements of changes causal factors were the root causes for 43.8% and 34.4% of the process safety events, compared to their causal factor rates of 28% and 23% in the original data analysis. Training/competence, communication, and supervision causal factors caused 23.4%, 20.3%, and 18.8%, respectively, of the high potential process safety events. These three causal factors were almost the same as calculated in the original data analysis. Figure 10 below shows a general comparison between the high potential safety events of the original analysis and high potential process safety events of the revised analysis that are caused by the most effective organizational factors in year 2013.

Figure 10. Comparison between Original and Revised Data Analysis

The analysis of root causes of the high potential process safety events are more complicated because there are a lot of intersections between the contributed causal factors, where most of the high potential process safety events are caused by more than one causal factor. So, further analysis would be required to study the single independent effect of each causal factor and the intersections between each two causal factors.

The common high potential process safety events that caused by failure of both mechanical integrity and procedures/standards were found to be nine process safety events. Twelve high potential process safety events were caused by deficiencies in both mechanical integrity and process hazard analysis causal factors. The failure in both procedures/standards and process hazard analysis organizational factors were the root causes of fourteen high potential process safety events.

A cost-effective analysis would be required to measure most effective organizational factors and their best combinations. The combination of the mechanical integrity and procedures/standards organizational factors resulted in 50 out of 64 high potential process safety events, which represented 78.1% of the total process safety events. Also, about 71.9% of high potential process safety events resulted from the combination of the mechanical integrity and process hazard analysis causal factors. The process hazard analysis and procedures/standards causal factors caused 68.8% of the high potential process safety events. About 64.1% of the total high potential process events resulted from the failure in the design/management of change and mechanical integrity organizational factors. Table 5 below shows the most effective combinations of two organizational factors on the high potential process safety events.

Table 5. Effects of Combining Two Organizational Factors

Combining Two Causal Factors		**High Potential Process Safety Events**	
1st Factor	**2nd Factor**	Number	%
Mechanical Integrity	Procedure/Standards	50	78.1%
Mechanical Integrity	PHA/Risk Assessment	46	71.9%
Procedures/Standards	PHA/Risk Assessment	44	68.8%
Procedure/Standards	MOC/Design	44	68.8%
PHA/Risk Assessment	MOC/Design	43	67.2%
Mechanical Integrity	MOC/Design	41	64.1%

The combination of two organizational factors caused significant variable effects on the high potential process safety events as seen in Table 5. The best dual combination was obtained when the mechanical integrity and procedures/standards causal factors were used, which resulted in 78.1% of the high potential process safety events. This analysis could be used to control and reduce the high potential process safety incidents by maintaining the effectiveness of related causal factors. In other words, retaining the effectiveness of the mechanical integrity and procedures/standards organizational factors will prevent or reduce the consequences of around 78.1% of process safety events.

There were significantly different effects between the various combinations of causal factors. The combination of the mechanical integrity with procedures/standards causal factors was higher than the combination of the mechanical integrity with management of change/design causal factors by about 14%. Also, the effects of dual combinations of causal factors were significantly higher than the effects of single causal factors. The single mechanical integrity causal factor caused 46.9% of high potential process safety events, which is very low compared with the dual combination of two causal factors, e.g., the mechanical integrity causal factor was less than the combination of the mechanical integrity with procedures/standards organizational factors by about 31%.

The tri-combinations of causal factors were studied and evaluated using a cost-effective analysis. The combination of mechanical integrity, procedures/standards, and process hazard analysis was found to be the causes of 58 out of 64 high potential process safety events, which represents 90.6% of the total high potential process safety events. The combination of the mechanical integrity, procedures/standards, and design/management of change organizational factors resulted in 89.1% of the total high potential process safety events. About 84.4% of the high potential process safety events were caused by the combination of procedures/standards, process hazard analysis, and management of change/design organizational factors. In addition, the combination of mechanical integrity, process hazard analysis, and design/management of change organizational factors resulted in 84.4% of the high potential process safety events. Table 6 below shows the effects of tri-combinations of different organizational factors on occurrences of high potential process safety events.

Table 6. Effects of Tri-Combinations of Organizational Factors on Process Safety

Combining Three Causal Factors			High Potential Process Safety Events	
1st Factor	2nd Factor	3rd Factor	Number	%
Mechanical Integrity	Procedure/ Standards	PHA/Risk Assessment	58	90.6%
Mechanical Integrity	Procedure/ Standards	MOC/Design	57	89.1%
Procedure/ Standards	PHA/Risk Assessment	MOC/Design	54	84.4%
Mechanical Integrity	PHA/Risk Assessment	MOC/Design	54	84.4%

The best effective tri-combination of causal factors consisted of the mechanical integrity, procedures/standards, and process hazard analysis, which caused about 90.6% of the high potential process safety events. Table 6 clearly shows that there are small variances (less than 6%) between the different tri-combinations of main causal factors. On the other hand, there were noticeable differences between the dual combinations and tri-combinations of organizational factors that reached more than 12% in most cases, if the combination of the mechanical integrity with procedures/standards was excluded.

A tetra-combination of the most effective organizational factors was examined and found to result in 100% of the high potential process safety events. This highly efficient combination consisted of (1) mechanical integrity, (2) procedures/standards, (3) process hazard analysis, and (4) design/management of change organizational factors. The different numbers of organizational factor combinations had variance effects on the process safety events. Figure 11 shows the rate of high potential process safety events that resulted from various single, dual, tri-, and tetra- combinations of the most effective organizational factors.

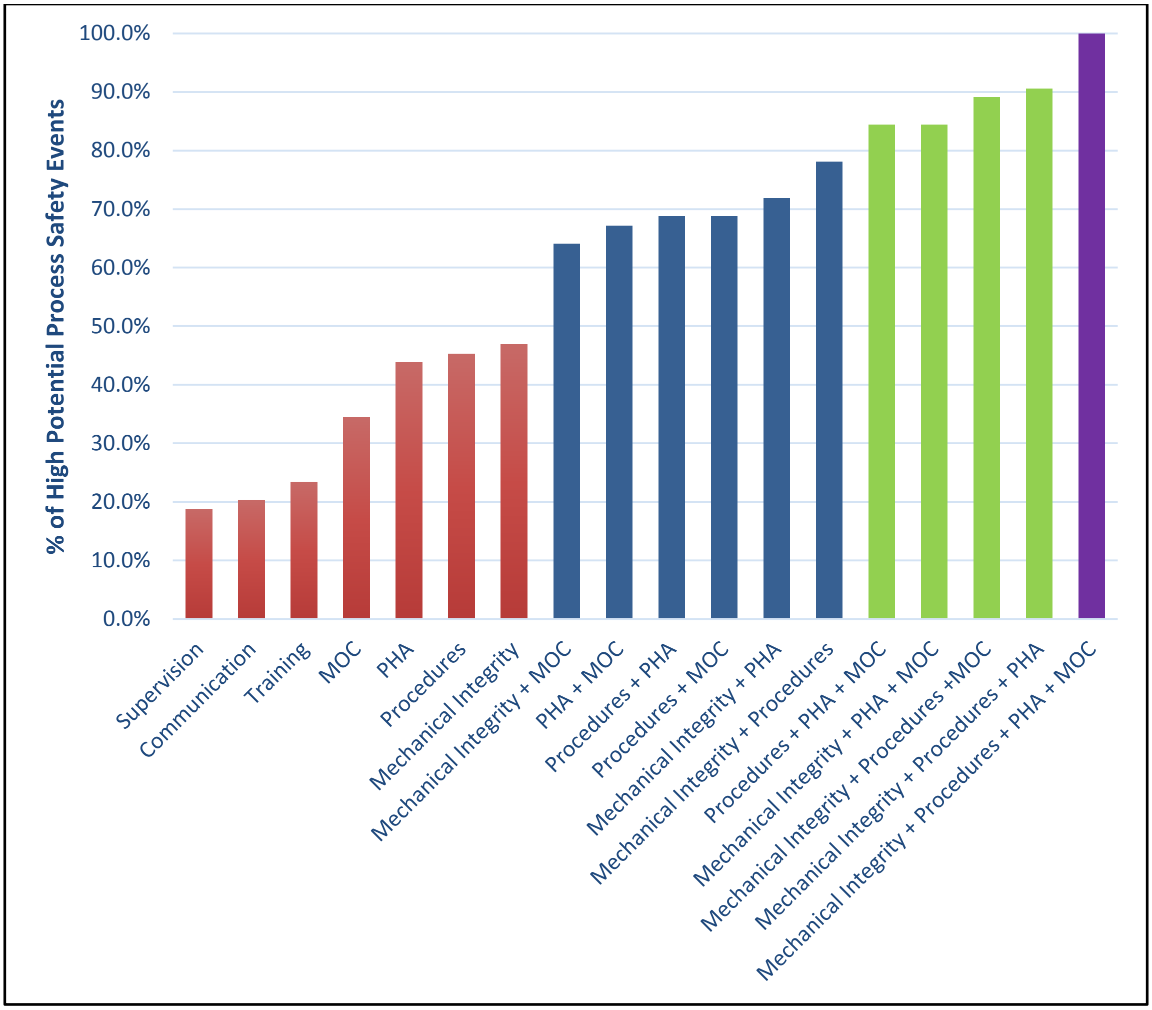

Figure 11. Several Combinations of Most Effective Organizational Factors

4.7 Metrics to Measure Process Safety Indicators

As evidenced in the last section, specific organizational factors highly influence the process safety incidents. A variety of metrics should be developed to measure theses organizational factors, and specifically qualitative and quantitative measures. In this section, comprehensive metrics will be developed for the most significant leading indicators that include the following organizational factors:

- Mechanical Integrity
- Standards/Procedures
- Process Hazard Analysis/Risk Assessment
- Management of Change/Design

4.7.1 Mechanical Integrity

Mechanical integrity greatly influences process safety performance. Failure of mechanical integrity was the root cause of many major process safety incidents. Most hazardous material leaks are due to failure of pipes/valves integrity or failure of proper inspection programs, both failures categorized under mechanical integrity program. The analysis of 2013 OGP data report revealed that failure of mechanical integrity was a causal factor of about 47% of highly potential process safety incidents.

Deficiencies in the mechanical integrity system can lead to major process safety disasters. In the BP Texas City Refinery explosion, the failure of level indication and alarm was one of the root causes that led to the overfilling of the splitter tower and blowdown drum. A flammable material was released into the atmosphere and formed a vapor cloud of the flammable material. The cloud was ignited and the subsequent vapor cloud explosion killed 15 people and injured approximately 180 people. The deficiency in mechanical integrity of the modified temporary bypass released approximately 30 tons of cyclo-hexane in Flixborough, England, in 1974. A vapor cloud was formed and ignited, which resulted in a massive vapor cloud explosion with 28 fatalities, 36 injuries, damaging the entire facility (Crowl & Louvar, 2011).

Mechanical integrity significantly connects with several subsectors within industrial facilities, including management, design, construction, engineering, operation, and maintenance. Also, mechanical integrity correlates to all structures and equipment within the industrial facility such as tanks, pumps, compressors, piping, heat exchangers, reactors, control valves, gas detectors, instrumentations, and firewater equipment (Sanders, 2011).

The scope of any mechanical integrity program should maintain industrial facility assets during the complete life cycle and include design, installation, commissioning, operation, production, and mothballing. Equipment design is the first, baseline step in maintaining an effective and efficient mechanical integrity program that protects people, assets, and the environment. The design should comply with safety level standards that reflect best practices and technologies. The equipment design must be administered by qualified and certified engineers with experience in designing similar industrial systems.

Mechanical integrity during equipment design includes but is not limited to selection of the right material, capacity, support strength, operating pressure, and temperature.

Mechanical integrity is also very important during the construction, installation, and normal operation of the industrial facility. Most equipment will not work as intended if not installed correctly, and of course installation entails a wide array of critical component, including sensitive instrumentation, detectors, controls, indicators, and flange connections. All equipment should be maintained during the normal operation of the industrial facility using scheduled preventive maintenance, high quality repairs, and regular inspection/testing. Equipment installation and maintenance should be performed by a qualified crew, and an approved procedure should be followed.

Several metrics can be utilized to measure the process safety leading indicators of mechanical integrity. To simplify metrics development, mechanical integrity can be categorized into two main classifications: design/installation and ongoing mechanical integrity. These main classifications are further classified into smaller divisions below:

1) Design/Installation Mechanical Integrity
    a. Design
        i. Designer qualification: rate/number of design implemented by uncertified designer
        ii. Design quality: rate/number of audit/inspection items related to design issues

iii. Material: equipment detected with incorrect design material

b. Installation

i. Installer qualification: rate/number of equipment was installed by uncertified crew

ii. Installation procedure: rate/number of installation procedures that was not clear or not followed

iii. Material: equipment installed with incorrect material

2) Ongoing Mechanical Integrity

a. Inspection

i. Qualified Inspectors: rate/number of uncertified inspectors

ii. Training: rate/number of overdue training

iii. Findings: rate/number of high priority findings

b. Preventive Maintenance

i. List: number of critical equipment not within the preventive maintenance list

ii. Overdue: rate/number of overdue equipment

iii. Qualification: rate/number of uncertified maintenance personnel

c. Maintenance/Repair

i. Repair quality: number of repaired equipment failed within 60 days of major maintenance or repair

ii. Equipment quality: rate/number of urgent or unplanned repairs

iii. Maintenance procedures: rate/number of maintenance procedures that was not clear or not followed

iv. Qualification: rate/number of uncertified maintenance personnel

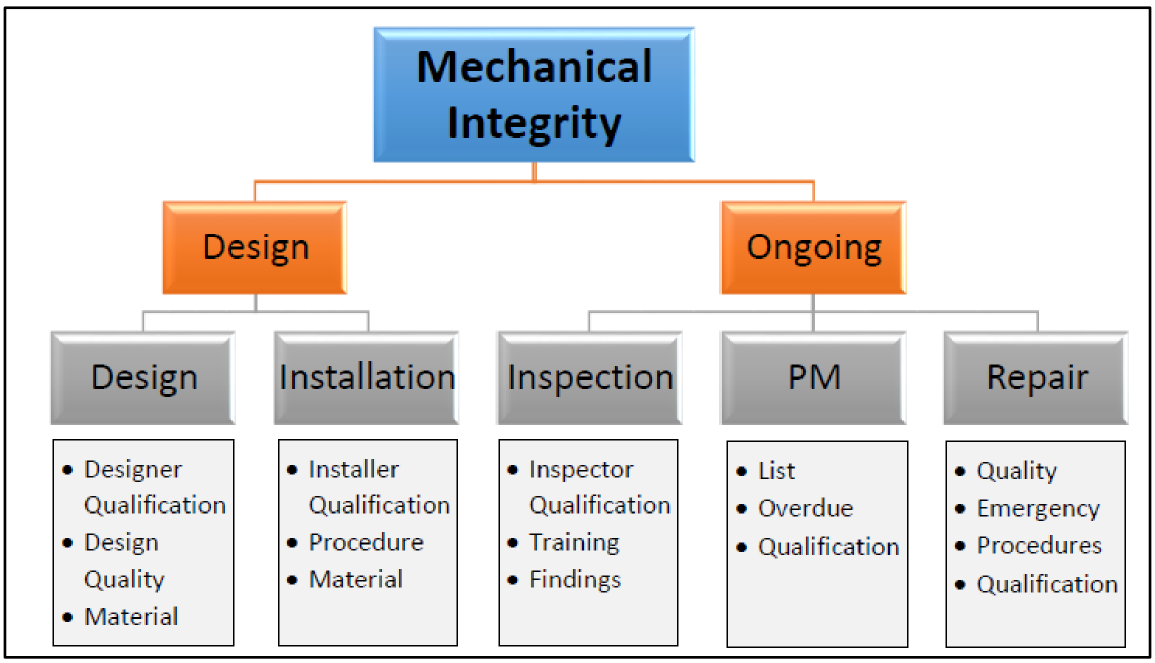

Figure 12. Developing Process Safety Metrics for Mechanical Integrity

The classification of mechanical integrity can be used to evaluate mechanical integrity effectiveness as shown in Figure 12. Also, this classification can be used to identify the exact deficiencies within the mechanical integrity program and possible ways for improvement (CCPS, 2007).

4.7.2 Standards/Procedures

The operation procedures and standards have great effects on process safety performance. Base on OGP data analysis, deficiencies in procedures and standards were the second highest causal factor of process safety incidents after the mechanical integrity. Approximately 45% of high potential process safety events were caused by failure in procedures/standards organizational factor. Failure to follow the appropriate procedures during startup or shutdown of critical processes may result in serious process safety incidents.

The main classification of procedures/standards organizational factor with recommended metrics are as follows:

1) Operating Procedures (classification is shown in Figure 13)
   a. Written Procedures
      i. Availability: rate/number of operation procedures not available
      ii. Normal shutdown: rate/number of normal shutdown procedures not available
      iii. Emergency shutdown: rate/number of emergency shutdown procedures not available
      iv. Quality: rate/number of operation procedures not clearly defined
      v. Review: rate/number of procedures reviewed annually

vi. Overdue procedures: rate/number of operation procedures with overdue review dates

vii. PHA: rate/number of procedures that lack hazard analysis

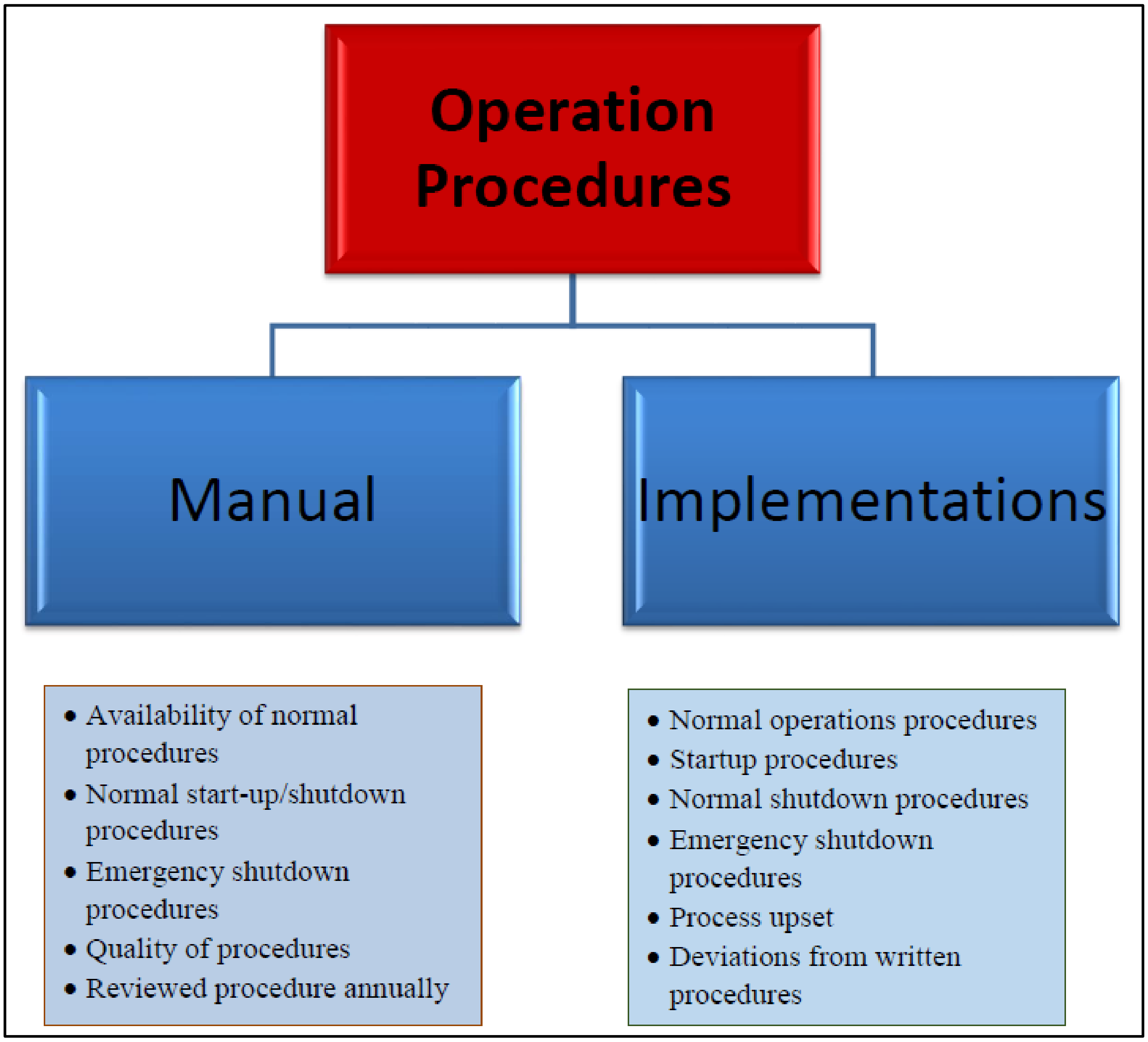

Figure 13. Recommended Safety Metrics for Operation Procedures

b. Implementation

i. Normal operation: rate/number of operating procedures not followed during normal operation

ii. Startup: rate/number of operating procedures not followed during startup
iii. Shutdown: rate/number of operating procedures not followed during normal shutdown
iv. Emergency shutdown: rate/number of operating procedures not followed during emergency shutdown
v. Process upset: number of processes upset due to not following procedures
vi. Deviation: rate/number of deviations from the written procedures

2) Standards
   a. Written
      i. Access: rate/number of difficult to access standards
      ii. Clarity: rate/number of standards that are not clear
      iii. Coverage: rate/number of processes not under the scope of current standards
      iv. Review: rate/number of standard reviews annually
   b. Implementations
      i. Clarity: rate/number of standards that are not easy to be implemented
      ii. Quality: rate/number of deficiencies found in standards

iii. Waivers: rate/number of waivers of standards

iv. Deviations: rate/number of deviation from standard requirements

4.7.3 Process Hazard Analysis/Risk Assessment

The process hazard analysis (PHA) and risk assessment organizational factor significantly contribute to process safety performance. It is the main tool to identify and analyze the hazards within the industrial facility in a specific area or in general. Process hazard analysis and risk assessment organizational factor was the causal factor of approximately 43% of high potential process safety incidents. The detailed classification of process hazard analysis and risk assessment organizational factor with recommended metrics are shown in Figure 14 and are as follows:

1) Process Hazard Analysis (PHA)

    a. Process Guidelines

        i. Policies: rate/number of unclear polices related to PHA

        ii. Overdue PHA: rate/number of PHAs overdue for new design and for revalidation

        iii. Training: rate/number of trained employees on PHA

        iv. Documentation: rate/number of PHA report that was unavailable or inaccessible

        v. Design: rate/number of PHA conducted after 50% detailed design stage

b. Meeting and Report

   i. Leader: rate/number of certified PHA leaders

   ii. Team members: rate/number of trained team members

   iii. PHA report: rate/number of major audit findings not identified during PHA

   iv. Quality: rate/number of recommendations per process unit

c. Recommendations and Action Items

   i. Overdue: rate/number of overdue action items

   ii. Repeated: rate/number of repeated action items

   iii. Types: rate/number of administrative action items compared to control and design action items

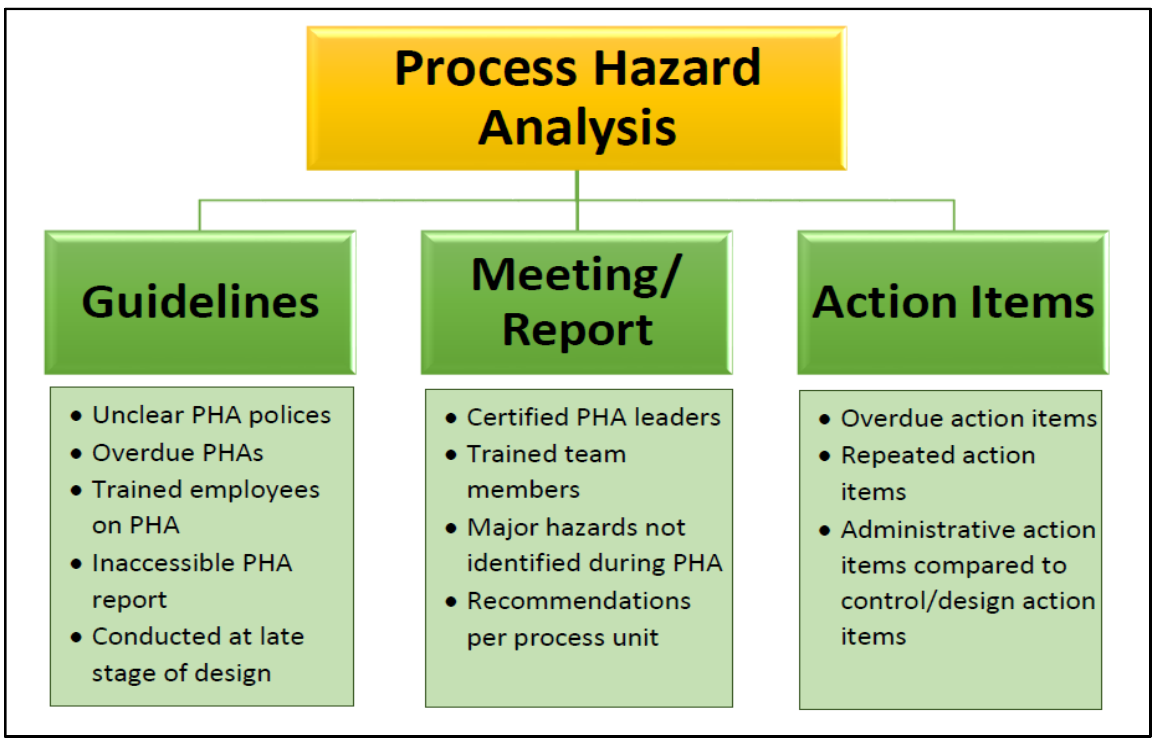

Figure 14. Recommended Safety Metrics for PHA

2) Risk Assessment

    a. Analysis

        i. Data: rate/number of mistakes in collected data used in risk analysis

        ii. Qualification: rate/number of risk assessments conducted by inexperienced or uncertified group

    b. Report

        i. Clarity: rate/number of unclear recommendations/findings in risk assessment reports

        ii. Quality: rate/number of reviews or audits that indicate a mistake within risk assessment reports

The previous recommended metrics can be revised and modified to fit specific industrial facility needs (CCPS, 2007).

4.7.4 Management of Change/Design

Management of change (MOC) is a major element that has contributed to several process safety incidents. Changes in processes, procedures, equipment, and any other hardware or software changes within the industrial facility may result in new hazards not properly identified or analyzed. BP Texas City Refinery and Flixborough explosions are examples of two major process safety incidents that were caused by deficiencies in the management of change (MOC) organizational factor. Placing occupied trailers next to the isomerization unit that handled flammable materials indicated a failure of management of change during BP Texas City Refinery explosion. Installation of undersized temporary bypass spool revealed major deficiencies in the management of change in the Flixborough explosion (Crowl & Louvar, 2011).

Process safety enhancements of any industrial facility should be implemented in the design stage, where most of risks and hazards can be eliminated or controlled. Inherently safer designs and engineering controls can improve process safety systems (Crowl & Louvar, 2011). Multiple hazard analysis techniques shall be conducted during the different design stages to identify and analyze the associated hazards within the system and to achieve a safer design.

The main classification of management of change (MOC) and design organizational factor with recommended metrics are as follows:

1) Management of Change (MOC)
    a. Program
        i. Definition: unclear words or statements in MOC definitions
        ii. Scope: rate/number of general confusion generated by determination of whether specific changes fall under the scope of MOC
        iii. Polices: unavailability of clear and detailed polices/procedures
        iv. Documentation: rate/number of MOC report unavailable or inaccessible

b. Implementations
   i. Hazard analysis: rate/number of MOCs implemented without PHA
   ii. After the fact: rate/number of MOCs conducted after the change or at the final design stage
   iii. Quality: rate/number of MOCs completed immediately before start-up
   iv. Recommendations: rate/number of MOCs recommendation or action items not implemented or implemented after start-up
   v. Violation: rate/number of critical changes done without MOC

2) Design
   a. Hazard Analysis (discussed in section 4.6.3)
   b. Mechanical Integrity (discussed in section 4.6.1)

5. DISCUSSIONS AND RESULTS

In this section, a systematic procedure to develop process safety leading indicators will be discussed in detail. This discussion will include emphasis on the organizational factors' importance, selection of appropriate metrics, process safety leadership, and revalidation of leading indicators measurements. Also, this section will include discussion about the importance of maintaining process safety performance at all times, especially during depressed periods. The current problems in process safety data systems will be clarified, and a comparison between normalized metrics and absolute metrics will be discussed.

5.1 Develop Process Safety Leading Indicators

Process safety leading indicators for each industrial facility shall be developed using a systematic technique to select, measure, and review process safety leading indicators as shown in Figure 15. Selection of appropriate and cost-effective leading indicators is the first step in the development process. Based on 2013 OGP data report analysis, organizational factors were the highest contributors to high potential process safety events, as shown in Table 4. Mechanical integrity, operational procedures, process hazard analysis, and management of change organizational factors were the most effective causal factors, respectively. Combinations of different organizational factors resulted in more effective coverage of process safety events, as shown in Figure 11. Selecting the most effective indicators is a very important step to prevent process safety incidents.

The second step in developing process safety leading indicators is identifying detailed metrics to measure efficiently the selected leading indicators. These process safety leading metrics shall be measurable, effective, well understood, meaningful, and lead to correct conclusions (CCPS, 2010). Several process safety leading metrics shall be used to measure the performance of each single leading indicator as shown in section 4.7. Many industrial facilities faced a lot of difficulties in selecting the effective and comprehensive metrics (Kenan & Kadri, 2014).

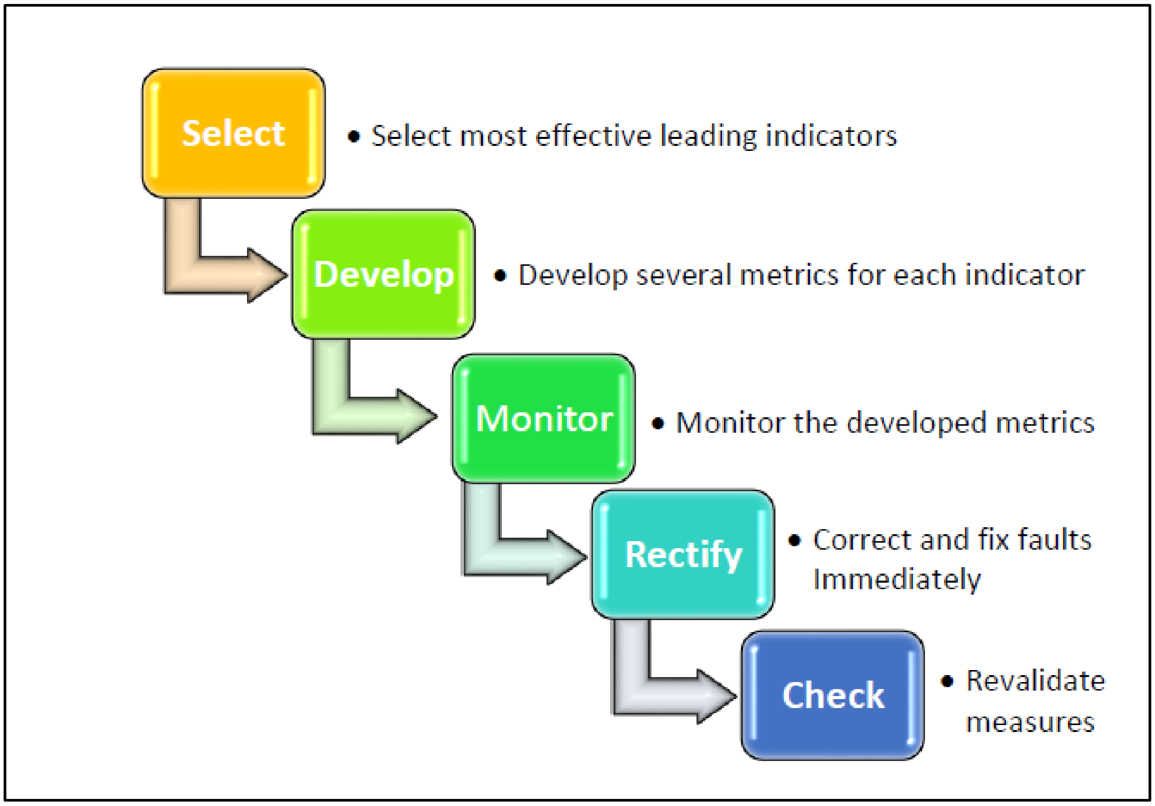

Figure 15. Developing Process Safety Leading Indicators

The third step is to conduct an accurate measurement of process safety leading metrics. There should be a well-organized process safety data collection system to gather the required data to measure all process safety metrics. These measured metrics shall be analyzed to determine the performance of each selected process safety leading indicator (organizational factor). The measures of process safety leading indicators and related metrics would require continuous monitoring to ensure that all potential hazards and faults within the process safety system are identified and corrected before an accident occurs. The process safety leading measures shall be reported to high management on a frequent basis and shall be communicated to employees within the industrial facility.

The fourth step in developing process safety leading indicators entails corrective actions. When process safety measures reveal a low performance of a specific leading indicator, an immediate action should be taken to fix the deficiencies and improve performance. Process safety leading metrics can be used to identify the faults within the affected leading indicator. A follow-up should be conducted to verify the completion of corrective actions and retain of process safety leading indicator.

Revalidation of the process safety leading indicator measurements is the fifth step in the development process. The process safety lagging indicators and near-misses shall be investigated and analyzed to identify faults and deficiencies within the process safety system that lead to these events. The process safety leading indicators measures shall be checked against near-misses and lagging indicators. A variation between the two measures would indicate inaccurate measurement of process safety leading indicators. The selected leading indicators should be modified to cover the causal factors of near-misses and lagging indicators, or assigned metrics shall be revised to correctly measure the subject leading indicators. Also, there may be deficiencies in the process safety data collection system that should be identified and rectified.

5.2 Process Safety Leadership

Management commitment and support are essential to maintain and implement successful processes of measuring safety leading indicators. Management commitment shall include providing all required staff and resources to implement effectively all steps of process safety leading indicators program (Kenan & Kadri, 2014). This will also indicate the importance of process safety leading indicators for the entire industrial facility, where employees will be definitely affected by management. Frequent management engagement in the process safety leading program is very important to overcome all difficulties that face the implementation program (CCPS, 2010).

Process safety management leadership is essential to develop, implement, and monitor a process safety leading indicators program. Because of the importance of process safety leadership, some industrial facilities began to place considerable efforts into developing process safety leadership programs. Dow chemical company has established a new leader review process to enhance the process safety leadership of new managers/leaders. As per this process, new leaders are required to conduct a thorough safety review within 90 days of taking a leader position. The assigned leader cannot approve any critical job or management of change (MOC) that involves reactive materials until he completes the assigned new leader process safety review. The review process should include all high potential process safety hazards and available reactive chemicals within the industrial facility (Efaw, 2012).

The new Dow chemical leader review is required to include all reactive chemicals that exist within the industrial facility. Moreover, the new leader review is recommended to include all high-potential process safety hazards associated with industrial facility processes. Knowledgeable and experienced instructors shall train the new leaders about the hazards associated with the existing reactive chemicals. The new leader review process includes study of worst case scenarios, reviews of the fire and explosion index, a review of the HAZOP status, and conduct field verifications (Efaw, 2012).

5.3 Maintaining Process Safety Performance during Depressed Times

The process safety leading indicators would require continuous monitoring to ensure that all developed potential hazards and weaknesses in process safety systems are identified immediately to take corrective actions before an incident occurs. Any delay in identifying and eliminating these potential hazards may result in high potential process safety incidents. Thus it is essential to maintain high levels of process safety performance during all industrial facility activities, such as normal operations, start-ups, and major plant shutdowns. Continuous monitoring of process safety leading indicators measures would require effort and time. Most leading indicators can be measured and monitored using regular inspections, safety observations, and audits (HSE, 2006).

Some petrochemical industrial facilities may fail to maintain high levels of process safety performance, especially during depressed periods, as during these periods, focus is often on operational and maintenance activities employed in limited timeframes while ignoring process safety measures. Mechanical integrity and management of change processes may be overlooked during a major plant shutdown in which several activities and tasks shall be completed in short period. The Flixborough explosion revealed a failure in mechanical integrity and management of change when a decision was taken to install an available substandard bypass pipe to continue plant operation (Crowl & Louvar, 2011). The process safety measures were ignored during the depressed period, and correct actions were not taken to order the correct pipe or wait to fix the reactor.

5.4 Independent Process Safety Data System

Process safety indicators measures are collected and analyzed from several filed and process data within the industrial facility. Most of the safety data collection systems in the petrochemical industry were designed to handle the personnel safety indicators, such as injuries, fatalities, and first aid cases. These systems were not designed to handle process safety indicators (Kenan & Kadri, 2014). After the development of process indicators, these safety data collection systems were modified to include the process safety events. As a result, the process safety data were mixed with personnel safety data, an occurrence that could result in losing track of process safety events. It cannot be determined whether the fatalities resulted from personnel incidents (falls, electrocutions) or from process incidents (fires, explosions). Also, the listed fires cannot be identified as a consequence of process safety incidents or not. Fires associated with process equipment and chemicals would be classified as process safety incidents, but trash fires (inside the building) and house fires (within the industrial facility camp) should not be classified as a process safety event.

Developing effective process safety indicators would require constructing an independent process safety data collection system. This system should be automated and able to analyze the different metrics input and data to show variable measures of the selected leading and lagging indicators in a timely manner. This system should be linked to investigation analysis of process safety incidents and near-misses, where the most common root causes should be analyzed and monitored closely.

5.5 Absolute and Normalized Process Safety Metrics

The process safety leading indicators and metrics can be expressed mainly in two forms: absolute metrics and normalized metrics. Absolute metrics would represent the measures as a direct count of events such as number of conducted process hazard analysis, number of reviewed operation procedures, and number of conducted management of change. Normalized metrics would represent the measures as a rate or ratio such as rate of open HAZAP items, rate of trained employees, and rate of overdue preventive maintenance items (CCPS, 2010).

Normalized metrics are ratio expressions that are used frequently to make an effective comparison of process safety performance between different industrial organizations and companies. There are several denominators that can be used to calculate the normalized metrics, such as total work hours, chemical production capacity, and energy consumption. These metrics can be easily understood by non-technical parties such as management, stakeholders, and communities. Process safety lagging indicators are normally represented using consistent normalized metrics to measure the rate of process safety incidents (Wang, Mentzer et al., 2013).

Absolute metrics are simple and direct representations of the number of reported events or activities. These metrics are not designed to be used in the comparison between different industrial organizations. Both absolute and normalized metrics do not provide information about the quality of process safety events or activities (CCPS, 2010).

The main objective of process safety leading indicators is to improve process safety performance. Absolute metrics should be used in representing the critical process safety data because the normalized metrics can draw attention from vital information by focusing on the rate expression (CCPS, 2010). It is important to know the actual number of failures in the process safety system to work on and fix them. Another concern is that the numbers in absolute or normalized metrics would not provide details about criticality of the event or activity. Failure in the mechanical integrity of the main fuel line to hazardous equipment and failure in the mechanical integrity of water line should not justify equal attention. However, both failures have the same value representation in the absolute and normalized metrics. Thus, it is recommended to include details about each recorded event or activity. Also, the weighting factor can be used to represent the criticality of the event or activity.

6. SUMMARY

Process safety leading indicators are essential to monitor and improve process safety performance before a potential event occurs. The leading indicators are well-connected to near-misses and lagging indicators to form a system that able to measure the performance and identify the deficiencies within the process safety system. Lagging indicators function more as reactive monitoring, while leading indicators function as proactive monitoring. Organizational factors have significant effects on the process safety systems in petrochemical industrial facilities.

Process safety leading indicators should be developed using a systematic approach. Type and quantity of selected leading indicators are very important to have a cost-effective process in which a limited number of indicators provide effective insights of process safety systems. The petrochemical industrial organizations should focus on most effective leading indicators. The analysis of OGP data reveals that the most effective causal factors are mechanical integrity, operation procedures/standards, process hazard analysis, and design/management of change, respectively. Comprehensive safety metrics should be developed for each selected leading indicator. An accurate measurement should be conducted for these developed metrics, and immediate action should be taken to fix any deficiency with the process safety system. Lagging indicators and near-misses data should be used to check leading indicators measures.

7. FUTURE WORK

The current available safety database is lacking of process safety leading indicators measures. Also, petrochemical industrial companies are still in the experimental stages of measuring the leading indicators. A significant amount of process safety leading indicators data are expected to be available for the public within the next few years, as the petrochemical industrial companies focus on measuring the process safety performance. Within the next few years, there should be several process safety surveys that can form a good source for a safety database.

Future work will include revalidation of the developed systematic technique using direct process safety indicators data. There may be an actual implementation of developed process safety leading indicators process in a petrochemical industrial organization to check its effectiveness. The future work should also include an estimation of the ratio between the leading indicators, lagging indicators, and near-misses that form the process safety pyramid. The relation between safety culture and process safety leading indicators should be studied, and influences of each element shall be estimated in a quantitative approach.

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