RISK BASED ASSET INTEGRITY INDICATORS

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by

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ABSTRACT

Currently, asset integrity is a major concern and presents challenges to the process industry that cannot be ignored. Assessing asset performance is also a difficult task, due to the involvement of versatile tangible, as well as intangible, assets' performance measuring parameters. Monitoring and assessing asset performance through indicators is gaining popularity in several sectors. However, the lack of a comprehensive set of appropriate indicators' development strategy, quantification technique, and measurement cohesion limit the use of an indicator system. To overcome these problems, a hierarchical framework is developed for identifying indicators and monitoring the performance of the asset. The hierarchical structure attempts to characterize the asset and relate it to a company's strategic goal. The hierarchical structure is based on the three major areas of asset integrity, and provides an opportunity to follow bottom-up perspective for identifying multilevel level indicators. This approach uses a risk metric to classify asset integrity, and risk provides a common ground to integrate leading and lagging indicators. The hierarchical structure is followed because the specific indicator results will have no values unless they are linked to the ultimate goal for ensuring asset integrity by measuring asset performance. Similarly, this framework and indicator will have no values unless a mathematical model is used to quantify the risk information. The analytical hierarchy process is used to determine the weight or prioritization of each level indicator and the aggregation of the indicators' outcomes are done depending on the associated risk. This will eventually aid in assessing asset risk based performance. To validate the developed model and to quantify the condition of assets of a process plant a benchmark study is

conducted. The estimated index value will determine the condition of the asset based on the performance risk index scale. As a result, the indicator system can provide a comprehensive view on a process plant equipment status and also can lead to the particular consideration of trends requiring attention.

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List of Abbreviations and Symbols

AI	Asset Integrity
MI	Mechanical Integrity
OI	Operational Integrity
PI	Personnel Integrity
EI	Element Indicator
AcI	Activity Indicator
KI	Key Indicator
SI	Specific Indicator
AII	Asset Integrity Indicator
KPI	Key Performance Indicator
HSE	Health and Safety Executive
HSL	Health and Safety laboratory
DNV	Det Norske Veritas
OGP	Oil and Gas Producer
CCPS	Center for Chemical Process Safety
OECD	The Organization for Economic Co-operation and Development
LPG	Liquefied Petroleum Gas
IAEA	International Atomic Energy Agency
AHP	Analytical Hierarchy Process
MOC	Management of Change
SSC	Systems, Structure and Components

WO	Work Order
PTW	Permit to Work
LOTO	Lock outs Tag outs
WANO	World Association of Nuclear Operators
SENUF	Safety of Eastern European Type Nuclear Facilities
SPI	Safety Performance Indicator
DOE	Department of Energy
EEA	European Environment Agency
ARIS	Asset Risk Index Scale
BLEVE	Boiling Liquid Expanding Vapor Explosion

w_i	Weight of Indicator
λ	Eigenvalue
λ_{max}	Maximum Eigenvalue
R_{LDi}	Risk factor for leading indicator
R_{LGi}	Risk factor for lagging indicator
n	Indication of inconsistency of expert judgement

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Chapter 1

1 Introduction

1.1 Background

In the process industry, asset integrity is presently a major concern. A large number of accidents/incidents took place in process industries in the past where the failures of equipment were found to be fundamental contributory issues. Failure of the equipment occurred due to lack of identification and subsequent rectification of deteriorating asset conditions. As components in a process plant operate, degradation is obvious and continues until finally resulting in a complete breakdown. Failure to detect the asset conditions that indicate a high likelihood for loss of containment can also result in disaster. With these regards, it is inferable that every incident starts in conjunction with the faulty assets operating in a process facility. The assets either lack adequate maintenance or improper operation originates the failure scenarios. The inadequate attention to the assets' health resulted in the following cases:

Case one: On April 8, 2004, at the Giant Industries' Ciniza oil refinery, Jamestown, New Mexico, United States, mechanics were mistaken regarding the position of the valve wrench indicator while reinstalling a pump after repair. The consequence was a sudden release of flammable liquid. Subsequently after about 30 to 45 seconds of the initial release of hazardous Alkylate, fire and the first of the several explosions occurred. The incident injured six employees and caused the evacuation of non-essential employees. Refinery equipment and support structures were damaged and the production was not resumed until the end of 2004. The review of the repair work prior to this incident revealed a history of repeated pump failures and showed the Giant's approach of following break-down maintenance instead of identifying the root causes of frequent failure. At the same time, the LOTO procedure and the valve position indicator were also neglected during maintenance, which resulted in this undesired event (CSB, 2005).

Case two: On the morning of November 19, 1984, a pipe used to transport light hydrocarbons from a refinery to a storage terminal in Mexico City, Mexico, ruptured and an accident occurred. Corrosion had gradually weakened a certain portion of the pipeline. The light hydrocarbons quickly found an ignition source, triggering a series of fires and explosions, resulting in approximately 500 fatalities and destroying the LPG terminal. The gradual degradation of the pipeline, which was either undetected or unaddressed, resulted in the failure of the equipment. This accident represents the largest series of major BLEVEs, and high fatality occurred because the housing was too close to the plant area. In this case also, due to the lack of attention towards maintaining asset integrity through routine inspection, and subsequent protection measure resulted in a catastrophic incident (Mannan, 2005).

Case three: On May 10, 2008, the largest LPG producer of Indonesia, Balongan LPG Plant, had a major accident and had to shut down the plant for eighteen days for repair purposes. The accident occurred because of critical failure in a fluid catalytic cracking unit, which is a high pressure system. Consequences of this failure were significant, as the plant supplies around 30% of LPG to national market. The company was in the excess of twelve million US dollar production loss. The Health and Safety Executive, UK, indicated the inability to predict or inability to anticipate in-service damage as one of the dominant root causes of failure in pressure systems. Thus, this un-anticipated in service damage of LPG process plant critical equipment can be considered as a failure of the asset integrity (Clough, 2009).

Case four: On March 23, 2005, a fire and explosion occurred at BP's Texas City Refinery in Texas City, Texas, killing 15 workers and injuring more than 180 personnel. The Chemical Safety Board (CSB) identified several aspects of importance in this event related to poor asset integrity. The incident occurred in an isomerisation unit in start-up mode, with a number of important level instruments defective and some operations' experience gaps. This eventually led to overfilling of a distillation column, and liquid overflowed into a relief system that was directed to an atmospheric vent in the unit. The vent system also filled with liquid, and eventually gasoline overflowed from the vent into the atmosphere of the process area. The failure to take effective emergency action resulted in a loss of containment incident. The vented gasoline certainly found an ignition source and a vapor cloud explosion occurred. The investigation reports of both Mogford (2005) and Baker (2007) panel pointed out asset integrity related several other underlying issues as the cause of the accident.

Case five: Beyond the process industries, on May 25, 1979, a DC-10 crashed on takeoff at the Chicago's O'Hare Airport when the pylon holding the left engine to the wing failed. The resulting crash killed 273 people including 2 on the ground. The damage to the pylon was a result of incorrect maintenance procedures during the replacement of some internal bearings eight weeks before the crash. Ignoring the standard procedure of removing the engine prior to the removal of the engine pylon, both the engine and pylon were removed at one time and a forklift was used to hold it in place. A failure of the forklift's hydraulic system left the engine unsupported and damaged the pylon. The damage went unnoticed for several flights, getting worse with each flight. Finally, during the incident, the pylon failed and tore the left engine away from the wing (CCPS-RPPS, 2007).

These are only a few brief examples of occurred incidents in different areas directly related to lack or failure of asset integrity issues/concerns. Beyond these, there are also several accident scenarios in the hydrocarbon industries that are listed in ''The 100 Largest Losses 1972 – 2009'' and compiled by Clough (2009). The undesired incidents in the process facility are some portentous signs for near future serious mishaps. The investigation of accidents/incidents in process industries revealed that in most of the cases the root causes of the incident were related to the negligence of asset integrity assurance or poor asset integrity systems. These incidents are occurring routinely one after another, and the desired integrity of asset has yet to be achieved. Much more attention is required to maintain the integrity level of the process plant.

Besides the accident scenario, the annual unwanted downtime in North American industry causes production loss of more or less 5% of total production, which is equivalent to staggering US$ 20+ billion annually. The numbers show the impact of downtime on overall performance and become a threatening issue for the survival of an industry. Much of this can be attributed to the failure of the industry to maintain the integrity of the assets or lack of recognition for necessary asset integrity. On the other hand, poor performance of asset integrity runs counter to the basic objective of industry being able to operate reliably while avoiding unwanted scenarios.

Over the last several decades, substantial improvements in the industry have been observed in the area of lost time injury frequency (LITF) and total recordable incident rates (TRIR), as shown in the Figure 1-1 (OGP, 2010). But, satisfaction with good occupational health and safety performance does not ensure the occurrences of serious mishaps in the future. The recent undesired incidents in the oil and gas sectors are some portentous signs for near future severe accidents. The anatomy of Texas City (2005) incident reveals that overlooking to asset health condition, i.e. the lack of mechanical, operational, and personnel integrity, were primarily responsible for the occurrence of the incident. This enforces the requirement of asset integrity, which had been neglected over the years. Again, requirement of asset integrity, in a process facility become more dominant with the increasing life of assets. With the ageing condition of equipment in a process plant, degradation progresses at a faster rate than expected. This causes frequent failure scenarios, and plant downtime also increases as a consequence of other incidents.

Engineering structures, equipment, safety systems and components play a vital role in the process industry in fulfilling business requirements. Any threat to these components will also threaten the performance of overall asset integrity. At the same time, most of the process industry deals with hazardous materials, and loss of containment of these could be catastrophic. So, the requirement of asset integrity is two-fold: one is for keeping the equipment in operating condition and another is keeping the hazardous material inside the containment. This could be achieved by ensuring asset integrity. Engineering integrity is an integrated system in which every component affects other component in overall system. So process industries should be aware that failure to maintain the integrity of any asset could have potential effects on humans, environment, and even on the financial aspect of the industry.

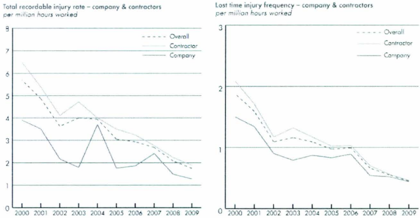

Figure 1-1: (a) Total recordable incident rate (b) Lost time injury frequency (OGP, 2010)

Asset integrity refers to the strategies and activities intended for maintaining plant assets or equipment to ensure that they remain available, safe, and reliable in order to operate continuously. It includes characteristics such as design, operations, maintenance, and inspection property to maximize return from operating assets. The importance of effective asset integrity increases as the industry assets continue to age. This issue has been realized by the Offshore Division, HSE (2007), for the offshore installations of UK continental shelf. Realizing the requirement of improving the integrity of installations to overcome the risk of major accidents, they have initiated the KP3-Asset integrity program. In addition, when there is effective asset integrity, industries will have safer process plants with less accident, fewer leaks, and less damage to the environment. Eventually, this will enhance the reputation of the organization. By implementing an effective asset integrity maintaining strategy, industries will significantly reduce serious damage to human lives and to the environment. As well, industries will even have improved business performance.

To assure integrity of assets, most of the organizations involved consultancy companies and addressed some particular safety critical components to determine the overall plant characteristics. Sometimes organizations carried out only the inspection and assess the overall asset performance, ignoring the maintenance activity, human factor, and organizational issues. On the other hand, to determine the performance of the plant organizations usually rely on the occupational health and safety performance. So, eventually these attempts turned out to be inadequate for maintaining and monitoring asset integrity and required a comprehensive approach. For ensuring asset integrity, a holistic approach is to be developed and followed that will consider every aspect of asset related issues. All threatening aspects of asset integrity should be neutralized proactively for the target of an incident free facility.

Monitoring the performance of asset integrity is one of the most important and challenging issues in the asset integrity management program. Integrity monitoring should be fact-based, rather than opinion based, and may include the following strategies pointed out by OGP (2008):

i. Key performance indicators (KPI), or simply performance indicators

ii. Barrier performance standard verification

iii. Audit findings

iv. Incident and accident investigations

v. Benchmarking and lessons learned from external events

In this research, for the purpose of monitoring, reviewing and evaluating, the asset integrity indicator system is adopted. Catastrophic or major incidents due to loss of asset integrity in process plant are relatively rare but not completely avoidable. That is why it is important to monitor asset performance and record even minor incidents which will eventually ensure the integrity in process facilities. But, for a process facility the indicators for monitoring asset integrity could be of quite large numbers as to cover every aspect. Furthermore, the information through the indicators could also be in varying characteristics and importance levels. As a result, it would not be possible, neither practical, to use all these parameters as indicators for asset performance monitoring or assessing. Therefore, in this research asset integrity indicator system will adopt a risk-based approach. The selection of floor level indicators will be based on the characteristics of risk associated with the events related to assets. The risk-based indicator system can simplify the complex array of information related to asset integrity. The consideration of risk characteristics will also allow the appropriate quantification of the indicators outcomes and numerical figures can be obtained for further aggregation.

1.2 Asset

An asset in respect to process industry is considered as an engineered piece of equipment that is essential for the overall function of a process industry and critical to every industry's performance. According to Sutton (2010), assets are all equipment, piping, instrumentation, electrical systems, and other physical items in a process unit. In a single word an asset is a physical facility that is required for process operation and has distinct value to the organization. BSI PAS 55-1 (2008) defined asset as "Plant, machinery, property, buildings, vehicles and other items that have a distinct value to the organization". So, for the process industries, which run three hundred sixty five days a year, seven days a week, and twenty four hours a day, the need to upkeep the assets condition is of prime importance. Thus, management of assets' is the highest priority for the performance and growth of the industry. A physical asset can be considered as a critical factor in achieving business goals. To maintain the comprehensiveness of the asset integrity approach, this thesis will consider the aspect of tangible as well as intangible assets.

1.3 Asset Integrity

CCPS-RBPS (2007) express that the primary objective of the asset integrity element is to help ensure reliable performance of equipment designed to contain, prevent, or mitigate the consequences of a release of hazardous materials or energy. Searching through the literature and different regulatory organizations' guidelines resulted in identifying five major types of asset integrity, defined as follows:

HSE (2007) defined "*asset integrity* as the ability of an asset to perform its required function effectively and efficiently whilst protecting health, safety and the environment."

On the other hand CCPS- RBPS (2007) also defined *asset integrity* in the same manner: "The asset integrity element is the systematic implementation of activities, such as inspections and tests necessary to ensure that important equipment will be suitable for its intended application throughout its life."

Again, OGP (2008) described that "*asset integrity* is related to the prevention of major incidents. It is an outcome of good design, construction and operating practices. It is achieved when facilities are structurally and mechanically sound and perform the process and produce the products for which they were designed."

The CCPS (2010) guideline for process safety metrics defined *asset integrity* as "work activities that help ensure that equipment is properly designed is installed in accordance with specifications, and remains fit for purpose over its life cycle."

Finally, Pirie (2007) of DNV defined *asset integrity* as a "continuous process of knowledge and experience applied throughout the lifecycle to manage the risk of failures and events in design, construction, and during operation of facilities to ensure optimal production without compromising safety, health and environmental requirements."

From the above definitions, it can be summarized that an asset in a processing facility achieves integrity when it operates as designed, which means it is being operated safely following standard procedure with competent personnel and complying with all necessary maintenance, inspections and tests; to be able to operate for its designed life means replacements, renovation, up-gradation, and repairs i.e. maintenance, must be done in a timely, planned manner, conforming design codes and engineering standards. For all assets' associated risks to remain as low as reasonably practicable, means all safeguarding and emergency systems associated with the asset must be in excellent shape and able to handle any risk escalation situation or subsequent damage from incidents.

This characterization of asset integrity will ultimately assist in determining the extent of asset performance measurement through risk based indicators.

1.4 Factors Affecting the Integrity of Asset

Technical issues have the greatest impact on the integrity of assets. Other than technical issues, which are highlighted here as a mechanical integrity, operational, organizational, and personnel related issues also have substantial impact on the asset integrity concern. The following are the major mechanical issues that have the utmost impact on the integrity of asset operating in a process facility:

i. External and internal corrosion and erosion of systems, structures and components which is also responsible for reduction of components' useful life.
ii. Fatigue condition of welded joints in systems, structures and components.
iii. Corrosion under insulation is a threatening issue that causes juvenile failure of components.
iv. Inappropriate specification, application, use, and maintenance of insulation and coating materials, as well as cathodic protection, contribute to corrosion.
v. Vibration level, overpressure, over temperature, overloading situation beyond design limit, and instrumentation that monitor critical operational parameters.
vi. Backlog of maintenance resulting from excessive deferrals, lack of technical resources to conduct the maintenance, maintenance staffing, and lack of prioritizing technique for determining safety and environmentally critical equipment.

vii. Equipment design and selection, personnel competencies, and inspection strategy and maintenance planning and schedules.

viii. Ageing of operating assets. As ageing facilities approach their designed life, management also reduces maintenance costs as production levels decline, which in turn contributes to an increased risk of major accidents.

ix. Selection of spare parts and consumables for maintenance and operation.

x. Meteorological phenomenon can also affect the availability of assets.

Besides these, the issues related to operational and personnel activities that have most impact on the performance of asset integrity are:

i. Incomprehensiveness of operating instructions and often continued operation beyond the safe design operating limits.

ii. Management of change issues are not executed following guidelines and not communicated properly.

iii. Immature safety culture and lack of management commitment and support for ensuring safety performance.

iv. Poor integration between maintenance and operations' management systems.

v. Risk management strategy and lack of root cause analysis to determine the issues that led to an incident or failure.

vi. Human factors including deliberate damage and competency of plant personnel.

vii. Poor communication system.

viii. Lack of adequate technical and interpersonal trainings.

1.5 Why Need Performance Measurement?

The famous industrial revolutionary Peter Drucker said, "It is not possible to manage what you cannot control and you cannot control what you cannot measure." Rouhiainen (1990) also realizes the importance of measurement irrespective of objectives and suggests that "Measurement is an absolute prerequisite for control, whether this is the control of production quality, accidents, or any other component of an industrial system." Again Amaratunga et el. (2002) defined measurement as something that provides "the basis for an organization to assess how well it is progressing towards its predetermined objectives, helps to identify areas of strengths and weaknesses, and decides on future initiatives, with the goals of improving organizational performance." Performance measures refers to an indicator scheme used by management to measure, report, and improve performance and are classed as either a key result indicator, a performance indicator, or a key performance indicator (Parmenter, 2007). The measurement of performance is important because of the following issues:

i. Identification of the current performance gap with the desired performance.

ii. For managing strategies, executing initiatives, and evaluating performance.

iii. Indication of progress towards closing the gap between desired and outcome.

iv. For effective and efficient control of the equipment reliability for its purpose.

v. To ensure current performance is broadly communicated and thoroughly understood by different levels of management.

vi. Performance improvement through the involvement of multi level management.

vii. To enable a proactive management environment along with reactive management.

Fortunately, catastrophic accidents occur on a relatively infrequent basis. However, when they do occur, they usually involve a lot of investigation and root cause analysis activity. The investigation reveals a number of for the accident scenario, which helps other stakeholders to learn from those situations. Other than wait for an accident to occur and investigate to identify the causes of failure, the assets' real time performance should be monitored. Otherwise, every process facility will be in need a of very robust and unnecessary accident protection system. The performance monitoring should be based on the risk based indicator system. Risk is inherent in all aspects of the asset maintenance and operation. Hence, the control of risk is central to asset integrity. This risk based monitoring of asset performance will cover both the active and reactive monitoring aspect. The rule thumb from Pareto charts states that 20% of equipment represents 80% of the risk, so the idea is to focus on that 20% of equipment (API, 2000). To ensure the asset integrity, this 20% of equipment should be given more importance and can be categorized as most critical or highly risk significant components. Thus, risk-based performance monitoring will allow problems to be identified and corrective action to be taken before a serious incident occurs.

1.6 Performance Measure

Performance measures constitute the 'Check element' of the famous Deming's Plan-Do-Check-Act (PDCA) cycle. The Check element involves monitoring different activities and strategies, as well as determining the performance gap between current and expected outcomes. Over the years, different types of performance measuring tools have been used depending on the area of measurement and the objectives of measurement. There are four major types of performance measures for an organization, including: input to the system measure, process activity measure, and output or outcome measures. Among these, OECD (2008) guidelines deal with the activity and outcome measures using indicators, for performance measurement. Parmenter (1997) mentioned that there are three types of performance measures, and these are: key result indicators, performance indicators, and key performance indicators. KRIs reveals how you have done in a perspective, PIs direct towards what to do, and the KPIs indicate what to do to increase performance dramatically. Parmenter uses an onion analogy to describe the relationship of these three measures, as shown in Figure 1-2. The outside skin describes the overall condition of the onion, the amount of sun, water, and nutrients it has received, as well as how it has been handled from harvest to supermarket shelf. However, as layers are peeled off the onion, more information is found. The layers represent the various performance indicators, and the core represents the key performance. KPIs represent a set of measures focusing on the aspects of organizational performance that are the most critical for the current and future success of the organization.

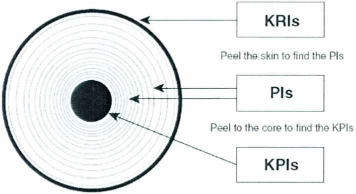

Figure1-2: Three types of performance measure (D. Parmenter, 1997)

Overall equipment effectiveness (OEE)

The OEE concept is usually utilized to measure the effectiveness of a manufacturing process, but it can also be utilized in non-manufacturing operations. Nakajima (1988) defined OEE as "a bottom-up hierarchy approach where an integrated workforce strives to achieve overall equipment effectiveness by eliminating the six big losses." Godfrey (2002) explores the benefit of using OEE to inform decision making throughout the lifecycle of an asset along with the power of OEE measure to improve the operational performance." The overall performance for a single component or for an entire facility can be measured depending on the cumulative impact of the three OEE factors. OEE is a measure of total equipment performance i.e. the degree to which the asset is doing what it is supposed to do base on OEE dimensions: actual availability, performance efficiency, and quality of product or output. Thus, OEE is considered a key factor in measuring both productivity and effectiveness, and the hierarchy of metrics focuses on how effectively a manufacturing operation is utilized. OEE measurement is also commonly used as a KPI in conjunction with lean manufacturing efforts to provide an indicator of success (Stamatis, 2010). Yet it is not a statistically valid tool and not intended for use as a corporate or plant level measure. OEE performance percentage assumes that all equipment-related losses are equally important and is a rough estimation of selected equipment effectiveness.

1.7 Asset Integrity Indicator

The term '*indicator*' traces back to the Latin verb 'indicare', meaning to disclose or point out, to announce or make publicly known, or to estimate or put a price on (Hammond, 2005). In accordance with the definition of Building Terms from Standards Australia (BTSA) (SAA HB50, 1994), *asset integrity indicator* can be defined as "a qualitative or quantitative measure of the quality of the asset's performance, efficiency, productivity of an activity which enables a comparison to be made for management process of performance against a standard target." Again, in glossary of key terms in evaluation and results-based management, OECD (2010) defined an indicator solely as a "quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect the changes connected to an intervention, or to help assess the performance of a development actor." This specific meaning is used to clarify concepts and diminish terminological confusion (OECD/DAC, 2010). EEA (2005) also defined an indicator as a quantitative measure that can be used "to illustrate and communicate complex phenomena simply, including trends and progress over time." HSE, KP3 report

(2007) stated that indicators measure performance and provide feedback on what is happening so that the user can shape the appropriate actions to respond to changing circumstances. Indicators have a variety of options in measurement, and an organization has to choose activities that are related to their goal. Therefore the identified indicators should be established and formulated to fulfill the overall goal. According to British Standard (2005), indicators allow an organization to perform the following activities:

i. Measure the status
ii. Evaluate the performance
iii. Compare performance
iv. Identify strengths and weaknesses
v. Set objectives
vi. Plan strategies and actions
vii. Share the results in order to inform and motivate people and
viii. Control progress and changes over time.

1.7.1 Purpose of asset integrity indicators

Indicators became essential, as well as effective, tools for tracking asset integrity performance in process industries. Indicators that correspond to asset integrity have several advantages that encourage their use for asset performance measurement. Target oriented appropriate indicators also act as a source of asset management information. CCPS-RBPS (2007) guidelines also enforce the requirement of metrics that could be used to monitor asset integrity. The following benefits of indicators are a few reasons they should be used for performance measurement:

i. Play a crucial role in making asset management information system operational.
ii. Reduce time for locating the fault in assets and locating the latent weakness of operating assets.
iii. Identify the early signals of deteriorating asset performance that could underpin the asset integrity.
iv. Provide warning of approaching trouble before a serious incident occurs.
v. Allow an ease in investigation and root-cause analysis through warning system so that corrective action can be taken before any unwanted incident occurs.
vi. Provide guideline to management for rational decision making in maintenance prioritization and to achieve top-level policy makers' attention.
vii. Compare and tune of target performance with the actual performance.
viii. Identify strong and weak areas of performance and knowledge transfer from similar strong and weak areas.
ix. Act as powerful motivational tools that provide an ease in decision making.

Asset integrity indicators should provide the earliest possible warning of declining performance that could be increasing the operational risk. It is therefore essential to use a broad set of indicators to cover process plant general performance in the region of maintenance, operation, and manpower related activities.

1.7.2 Types of Asset Integrity Indicators

Surprisingly, over the years, process industries around the world were satisfied with measurement provided through lagging indicators. More specifically, they were relying on occupational safety indicators, such as the fatal accident rate (FAR), lost time injury frequency (LTIF), and total recordable incident rate (TRIR). Managements are imposing more emphasis only on improving the foresaid lagging category in order to prove their system are operating efficiently, while neglecting the plant's physical asset condition. Mogford's (2005) investigation report on Texas City explosion pointed out that the site has numerous measures for tracking operational, commercial, environmental, and safety performance. But, these indicators, mostly of lagging type, not prioritized and did not clearly focus on the leading indicators as well. Mogford concluded that "by definition, catastrophic and major process incidents are rare events, and performance measures need to be preferably focused on leading indicators, or at least lagging indicators of relevant, more frequent smaller incidents." The same issue was also identified in the Noradic Nuclear Safety Research project report (Laakso et al., 1994), which stated that throughout the operation of nuclear power plant only a few major safety significant direct events can occur. So, with the limited quantity of direct event information, managements have little to determine future essentials. This enforces the requirement of easily measurable indirect plant performance parameters that will also provide an advanced warning of decaying performance. In this way, the direct impact can also be avoided as well. Baker (2007) stated the importance of use of lagging and leading indicators as reactive and active monitoring of performance, respectively, where "reactive monitoring allows an organization to identify and correct deficiencies in response to specific incidents or trends and active monitoring evaluates the present state of a facility through the routine and systematic inspection and testing of work systems, premises, plant, and equipment."

In the updated guideline, HSE, UK (2006) introduced the concept of 'dual assurance' with both leading and lagging indicator utilization for ultimate risk control. If both types of indicator sets are employed in a structured and systematic way then it will ensure the effectiveness of critical risk control system. BSI PAS 55 (2008) described the requirement of proactive, reactive, leading, lagging, quantitative and qualitative measure for physical asset. IAEA (2000) also pointed out that monitoring performance with combination of leading and lagging indicator sets provides the best performance measurement system. Considering all of the above issues, asset integrity indicators are also categorized into the following two major groups:

i. Leading or proactive indicator
ii. Lagging or reactive indicator

The combined application of indicators for monitoring asset performance will provide a comprehensive view of asset condition. Based on the performance of leading indicators, the outcome can be predicted and, with the lagging indicators result areas for improvement in the leading inputs can be determined. In the long run, lagging performance will be improved on the basis of good performances of leading indicators.

1.7.3 Characteristics of Asset Integrity Indicators

The selection of effective indicators can be done after a complete and thoughtful revision and collaboration of key processes, equipment, organization culture, and activities involved in process facilities that possess greater risks. The successfulness of asset integrity indicator system depends on the proper selection of indicators and their precise uses. If the indicators are not selected correctly and used improperly then this could be misleading rather than assisting in performance measurement. The selection of indicators should be based on certain characteristic that will assist in identifying the proper indicators. To determine the appropriateness of potential indicators, McNeeney (2005) provides a detailed set of criteria known as the 'SMART' test. The acronym stands for the five characteristics: specific, measurable, attainable, realistic, and timely. Identified indicators have to comply with these five characteristics for maintaining quality and effectiveness in performance measurement. IAEA (2000) also identified an ideal set of characteristics for selecting operational safety indicators for maintaining the quality of indicator information. Indicator characteristics varied with their context of application. In case of asset integrity where too many issues are involved, effective characteristic selection is a major concern. To identify generic sets of indicators for monitoring asset integrity, suggested characteristics of IAEA (2000) and DOE (2002) criteria were analyzed thoroughly to figure out required potential characteristics of asset integrity indicators. Analyzing these potential traits, the following characteristics are preferred for selecting asset integrity indicators that will go with the risk based concept too:

i. Relevance and direct relationship with the assessment category.
ii. Unambiguous and understandable at each level.
iii. Reliable, meaningful, and easily integrated to asset related activities.
iv. Capable of expressing in quantitative terms and able to provide information timely.
v. Capable of representing the risk significant issues involved in the operation.

The selection of indicators for assessing the asset integrity is a vital issue that determines the effectiveness of the risk based asset integrity indicator strategy.

1.8 Objectives of Research

Maintaining equipment fitness for purpose and ensuring safety systems functionality when necessary is of paramount importance to process industries (CCPS, 2007). In a typical day, maintenance will spend 40% of its time investigating the root causes of a problem (Gonzalez, 2005). This significant amount of time can be reduced by introducing indicators for monitoring assets continuously. Considering the above issue along with the strategy and purposes of ensuring asset integrity, the objectives of this research work are to:

i. Develop a generic hierarchical framework to relate the top level strategy of ensuring asset integrity with the events occurring on the site floor.
ii. Identify comprehensive sets of risk based leading and lagging indicators in the mechanical, operational, and personnel areas of asset integrity following developed hierarchical framework and using the standard guideline.
iii. Develop sets of questionnaires: one for standardization of the hierarchical framework indicators weight and another for collection of basic level risk information.
iv. Develop an aggregation technique to provide the same basis for both types of indicators' risk estimation and to determine the top level risk index.

v. Validate developed model by collecting, aggregating, and integrating information and determine leading and lagging risk index to monitor asset integrity performance.

1.9 Novelty of this Research

The major focus of this research is the development of a risk-based indicators system to assess the asset integrity in process industries. This research is unique in asset integrity area since it utilizes the risk definition by selecting indicators, collecting risk information, and aggregating risk levels based on the highest associated risk of the indicator. This approach considers both the leading and lagging aspects of indicators that are quantifiable in terms of risk and can be easily mapped with the standard risk index scale to determine the asset's condition. This study also proposed a comprehensive set of multi-level indicators that are easy to establish in particular process facility. Depending on the availability of current features and future requirements, the indicators can also be excluded or included, respectively in the identified indicator sets. This developed approach is a comprehensive, systematic, and integrated risk based asset integrity indicator system where the physical asset integrity in the section of mechanical and operational activity can be built on the personnel integrity of every employee.

1.10 Thesis Outline

The thesis is comprised of six chapters. Each chapter of the thesis illustrates the distinct aspect of asset integrity indicators to achieve stated objectives.

Chapter 1 addresses the background, elucidating the asset, asset integrity, and asset integrity indicator concepts and, objectives. It also discusses novelty of the proposed research.

Chapter 2 presents a brief review of performance measurement frameworks. Also, it presents a review of guidelines and literature pertaining to the current research work, followed by limitations of these approaches. This chapter also includes goals and described the scope of current research work.

Chapter 3 provides a detailed description of the risk based asset integrity indicator methodology. It includes the delimitation and development strategy of multilevel hierarchical indicator framework approach for asset integrity. Furthermore, in accordance with the framework structure, indicators at each level along with leading and lagging indicators at specific level were identified. It also discusses the indicator data aggregation, as well as data collection policy and standardization of multilevel indicator weights.

Chapter 4 presents a benchmark study that determines the feasibility and applicability of developed indicator systems in different process plants. It also describes the means for questionnaire development for data collection followed by data analysis, evaluation, and result discussion.

Chapter 5 represents an additional work that is very much related with the asset integrity assurance issue. It formulates a risk based spare parts inventory management methodology that will fulfill the spare parts requirement during maintenance.

Chapter 6 concludes the research work by summarizing the potentiality of the approach, followed by overall discussion and recommendations on future research scope in this area.

Chapter Two

2 Literature Overview

2.1 Introduction

Asset integrity can be considered a measurement of the performance of assets that operate in a process facility. At the same time, it can be said that asset integrity is achieved when the measured performance matches the stakeholder's vision or meets legislative requirement. So the measurement of performance implies two important issues, which are assessing the performance and accomplishment of a target. Measuring the performance using indicators is very popular in nuclear industries and is also gaining popularity in process industries. Performance measurement has long been used by management to monitor and ensure organizational capabilities and to identify whether current performance met the objectives as planned or not.

Several regulatory organizations, researchers, and specialists have provided guidelines for developing performance indicators, and quite a large number of researches on the development of performance measurement framework have been proposed in the past decade. The following are a few of these approaches, which have been discussed and followed over the years for the purpose of measuring performance.

2.2 Performance Measurement Approach

The performance measurement approach enables the ability to plan, measure, and control performances that can bring substantial benefits to any organization. Performance measurement is an ongoing process, and can provide several types of information, including information about inputs, activities, outputs, outcomes, and impacts. According to the American heritage dictionary (1991), "Performance measurement is the selection and use of quantitative measures of capacities, processes, and outcomes to develop information about critical aspects of activities, including their effect." The following are widely used performance measurement techniques selected for brief discussion.

2.2.1 Kaplan and Norton's Balanced Scorecard Approach

The balanced scorecard approach was introduced by Kaplan et al. (1992) to overcome the shortcomings of traditional approaches of a company's performance measurement that considered only financial results. Balanced scorecard translates an organization's mission and strategy into a comprehensive set of performance measures that provide the framework for a strategic measurement and management system. This is a strategic performance management tool that takes into account the fact that companies need to manage intangible assets and not only physical assets. Along with the traditional financial approach, indicators should address three more perspectives, which are customer, internal business process, and learning and growth. So, this measurement system is more balanced since it uses a mixture of financial and non-financial measures. One frequently used balanced score card type is a key performance indicator scorecard with a framework describing value-creating strategies that link intangible and tangible assets. The balanced scorecard is based on measures of efficiency, quality, and effectiveness at each level of the performance framework. Key performance indicators can also be organized into scorecards using a matrix after being aligned with the established strategy of the organization. KPI scorecards are most applicable and helpful when a strategic program already exists at a higher level in an organization with clear idea of what to accomplish. In this way, the diverse indicator enables individuals and teams to define what they must do to contribute to higher level goals. Thus, the balanced scorecard is used to measure the performance of an organization in a more holistic way with numbers of different perspectives (Kaplan et al., 2001a & 2001b).

2.2.2 Wireman's Hierarchical Approach

According to Wireman (2005), performance indicators are just that, an indicator of performance. Also pointed out certain characteristics of performance indicators; these are the ability to highlight opportunities for improvement, to identify weak areas, and point to solutions for solving problems etc. To fulfill the requirement performance indicator, Wireman proposed a system of multi-level performance indicators systems. The pyramid structure in Figure 2-1 shows hierarchical approach for multi-level performance indicators' development and illustrates the relationship among these different levels of indicators. The top layer of the indicators' system is corporate strategic level, which is a measure of vision followed by the financial performance indicator, efficiency and effectiveness indicators, tactical level indicators, and the actual functional performance of indicators. Also mentioned is the correct way to develop performance indicators, which is to work from the top or corporate level and then develop indicators at each subsequent level to allow the indicators to be connected with each level. It is important to develop indicators following the top-down approach; otherwise they may be conflicting rather than supportive. Again, the indicators should link to performance at either higher or lower levels on the indicator pyramid; otherwise, it will be worthless to use indicators.

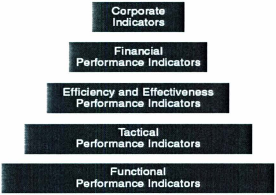

Figure 2-1: The hierarchical top down 'performance indicators system' (T. Wireman, 2005)

2.3 Regulatory Organization's Guidelines for Indicator Development

A set of performance indicators has been developed by World Association of Nuclear Operators (WANO) (2006) for the use in nuclear power plants that will also allow the user to exchange information and assess the performance of their plants objectively. There are a total of ten top level quantitative performance indicators in this set for monitoring plant safety, reliability, efficiency, and personal safety (Chakraborty et al., 2003). This is a widely used set of performance indicators in nuclear power stations worldwide for monitoring safety and economic performance. All of these performance indicators are of lagging type. Performance indicators are mainly used as a management tool so each user can monitor its own performance and progress, set challenging goals for improvement, and consistently compare performance with that of other plants or the industry. The indicators give a quantitative indication of nuclear plant safety and reliability, plant efficiency, and personnel safety. WANO's experience has shown that using performance indicators can contribute to significant improvements in plant performance.

International Atomic Energy Agency (IAEA) (2000) developed a framework considering the concept of nuclear power plant safety performance. To develop a complete set of operational performance indicators, a hierarchical structure was developed, in which the top level is operational safety performance and the immediate next level is operational safety attribute and finally from these the operational safety performance indicators were developed. The specific indicators were developed to measure performance and locate the degrading areas of performance, so that the appropriate authority can come with necessary corrective action. Here, the key attributes that were chosen correspond to the operational strategy and associated risk. This goal setting approach enhances the effectiveness of monitoring the operational performance. This approach was applied to different nuclear power stations throughout the world and considered as an excellent approach for monitoring operational safety performance.

Safety of Eastern European Type Nuclear Facilities (SENUF) has developed a framework and accordingly selected some appropriate quantitative indicators for monitoring the effectiveness of maintenance performance (SENUF, 2006). They also use the comprehensive framework, which is an attribute strategy of the IAEA (2000) for developing maintenance performance indicators. At the same time, they use some specific performance indicators developed by the WANO and the IAEA that are useful for the evaluation of maintenance performance. Finally, they have also provided a guideline for implementing this maintenance performance monitoring technique to specific nuclear power plants.

A Step-by-step guide to "developing process safety performance indicators" (HSE, 2006) has been produced jointly by HSE and the Chemical Industries Association (CIA), based on gathered information and ideas from several industries. According to this guideline, the main reason for measuring the performance is to make sure that risks are adequately in control in the process facility. To do so, the two organizations have proposed a method of setting indicators. The main difference of this guideline with other approaches is the introduction of the dual assurance concept. Dual assurance is the measurement of the risk control system performance through leading and lagging indicators in a systematic and structured way. The intention is to provide an early warning of dangerous deterioration of a critical system through leading indicators. Finally the guideline has outlined a six-stage process towards implementing process safety performance indicators in an organization. It has also included a set of leading and lagging process safety performance indicators for overall installation performance monitoring.

OECD (2008) guidelines on developing safety performance indicators mentioned that an observable measure that provides insights into the concept of safety is difficult to measure directly. They have divided the safety performance indicators into two major categories. The first set is outcome indicators that tell whether the system achieved a desired result or not, and the other set is activities indicators that allow an organization with a means of checking, on a regular and systematic basis, whether they are implementing their priority actions in the way they were intended or not. The guideline is intended for implementing a safety performance indicator program for any enterprise that handles significant quantities of hazardous substances. It sets out a seven-step process with the aim to locate and fix potential problems through indicators before an accident occurs.

Considering the measurement of existing and future performance as an essential element of any improvement program, CCPS has developed a guideline for measuring process safety performance (CCPS, 2007). To continuously improve the performance, they provide a guideline for developing leading and lagging metrics and encourage in implementing effective indicators for monitoring performance. They have also recommended using three types of metrics; these are: lagging, leading, and near miss metrics in process safety management systems. In this guideline, they have presented these three metrics as a measurement tool at different levels of the developed "safety pyramid." Finally, CCPS have also demonstrated industry-wide lagging, leading, and other metrics examples.

Health & Safety Laboratory (HSL) of HSE, UK (2006) carried out a scoping study to develop an industry wide common performance indicator model. The major findings of the study concluded that the nuclear industries are the pioneers in performance indicator development, but the other sectors are also active. The other sectors, like offshore, aviation, transportation, military and chemical industries, are working in this field, as well. Among these who are currently using the performance indicators, most of the cases of performance indicators developed in the absence of any fundamental foundation or model. This simply means that they are developing and using indicators without any target or without the intension of fulfilling any target requirement. If indicators are developed without following a structured approach then the outcome of the indicator will not provide a holistic view of overall process facility conditions. Another important issue is the development and application of leading indicators in performance measurement. Presently, most of the process industries rely only on the lagging indicators and, more specifically, on the performance of occupational health and safety. Finally, HSL have recommended the development of generic principles for developing SPIs and for perusal of different scoring mechanisms for indicators, as well.

2.4 Asset Integrity Development Guideline

Several regulatory organizations have provided guidelines on maintaining asset integrity. These guidelines are mostly concerned with the oil and gas operational activity and the ageing installations in offshore area. These guidelines focus on the asset integrity management strategy to decrease major incident risks. Oil & Gas Producers (OGP) and Health & Safety Executive (HSE), UK, have a major contribution in developing guidelines for managing asset integrity in the respective areas of concern.

2.4.1 OGP Guideline on Asset Integrity

International Association of Oil & Gas Producers (OGP) provided a guideline to facilitate the organizations in reducing major incident risk by focusing on asset integrity management. This guideline is also applicable for existing assets at every stage of the lifecycle for managing asset. However, the collected safety performance information shows improvements in occupational safety that does not necessarily ensure reduction of major accident risk. For the purpose of collecting information and evaluating the risks of major incidents, OGP (2008) points out the need for KPI. To monitor and review the asset integrity performance, OGP also has given several examples of KPIs based on HSE, UK, guideline, which are of leading and lagging category. These indicators mostly cover the operation, maintenance, and staff performance region. At the same time, OGP has given a guideline on how to use these KPIs to evaluate the asset integrity performance against the stated goal. This guideline basically summarizes the ways to control major incident risk throughout the operation period of oil and gas exploration and production activity.

2.4.2 HSE on Asset Integrity

In 2004 the Offshore Division of the HSE, UK, started Key Program 3 (KP3)-Asset Integrity (HSE, 2007). The objective was to ensure that offshore duty-holders adequately maintained safety-critical elements (SCEs) of their installations. SCEs are the parts of an installation and its plant that exist to prevent, control, or mitigate major accident hazards, the failure of which could cause or contribute substantially to a major accident. HSE have considered "Asset Integrity" as the third pillar in the Step Change in Safety temple model strategy along with recognized hazard and reduces risk and personal ownership for safety issues. Asset integrity refers to the risk of failure of a structure, plant, equipment or systems that could cause or contribute to a major accident. It also assists in developing an Asset Integrity toolkit containing comprehensive guidance with reference to good industry practice documents for effective safety-critical plant and equipment maintenance management. For initial consideration HSE have developed three potential key performance indicators, which are: KPI1, loss of containment i.e. reportable hydrocarbon releases; KPI2, verification of significant compliance issues; and KPI3, production losses associated with deficiency in maintaining safety. Finally, for monitoring the cross industry asset integrity only the KPI3 were replaced with safety-critical maintenance backlog after having a detailed study and observation.

2.5 Integrity Indicator Development Approach

There is a scarce amount of literature that directly deals with development of indicators. Sharp et al. (2008) has developed KPIs for offshore structural systems, relating to aspects which are important for both safety and asset integrity. Barrier analysis is used for identifying the safety critical elements, and performance indicators were developed to illustrate the barrier with the quantifiable measure. Thus, hazards to structural integrity were used as a basis for developing performance indicators. Besides these, most of the research work has been concentrated in the field of maintenance performance measurement. Ahren et al. (2004) have identified the performance indicators used by the Swedish National Rail Administration through a case study. Along with the identification, the study also analyzed the impact of these indicators on the organization goal and strategy by establishing a link and effect model. Again Parida et al. (2007) has proposed a multi-criteria hierarchical maintenance performance measurement framework for the purpose of maintenance performance measurement. The indicators are developed considering the corporate or strategic levels as a first hierarchical level followed by the tactical or managerial level and finally the functional or operational level. The levels of hierarchical structures could be more than three depending on the structure of the organization. Khan et al. (2009) has developed a risk-based approach to measure the process safety performance using sets of leading and lagging indicators. This is a unique work in the field of process safety for monitoring performance using indicator results. The model uses the probability of an event occurrences and the consequences of that event to figure out associated risk and aggregated values using analytical hierarchy process framework to determine the process safety indexes in the form of leading and lagging index. The applicability of the developed model was also demonstrated by a case study on a liquefied natural gas facility. The developed model with identified indicators showed its potentiality by improving the process safety performance.

2.6 Asset condition index

Using asset condition index, to evaluate the asset's status is a very popular measurement tool. Asset condition index is a standard means of determining an asset's current and future physical condition. This index allows the comparison of conditions between different assets and helps in rational decision making for prioritizing maintenance and other related issues. Here, a predefined measurement scale and weight allocation technique is used for each category of asset. hydroAMP (2006) defined a condition index as the outcome of a condition assessment and used a condition index ratings system for equipment in assessing asset condition. Appropriate condition indicators were used and their qualitative scores were based on inspections, tests, and measurements that were performed during the condition evaluation along with the operation and maintenance history of equipment. Weighting factors were applied to the condition indicator scores, which were then combined into a condition index, with a normalized scale of 1-10. For developing a comprehensive asset condition index NFR-PROSMAT (2000, 1999) moves beyond the traditional approach of considering technical aspects only. Along with the technical parameter, they have considered financial as well as statistical parameters in developing an asset condition index. This index was used to observe the asset degradation pattern and also to compare the current condition with the original state of asset.

2.7 Discussion and Remark

Most of the above mentioned guidelines and literature are intended for developing process safety performance indicators. On the other hand, the rest of the literature deals with the maintenance performance measurement using indicators in case of different specific areas. The development and application of indicators for monitoring performance are elaborately studied in the nuclear power plant field. Right now, the stakeholders are moving from a deterministic approach to a probabilistic approach for monitoring performance. Their approach highlighted the operational safety performance indicator development. But, in the other industries, like process industries, indicator systems are still in the early stages. There are a few literatures and guidelines that deal with the asset integrity indicator's development. In developing or providing guidelines for asset integrity indicators, the researchers have also followed the same available procedure of developing process safety indicator guideline. In fact, it is logical to follow the guideline of process safety indicators, as the asset integrity is one of the nine elements in the risk based process safety pillar of managing risk (CCPS-RBPS, 2007). Again, maintenance of equipment and its performance measuring is an important issue in assuring asset integrity.

So, the frameworks of monitoring maintenance using indicators will also assist in determining the set of indicators for asset integrity. Only OGP (2008) has provided a brief guideline on developing asset integrity indicators, which corresponds to the HSE guideline. On the other hand, the model developed by Khan et al. (2009) is a very comprehensive and structured approach that also follows the HSE guideline in developing both types of indicators for measuring process safety. Another important issue is that most of the literature and guidelines do not deal with the quantification and aggregation technique by which the floor level indication can be converted into a top level performance index. The outcome of individual indicators may not reveal the overall exact health condition of the asset operating in a facility. So, the impact of deviation on the overall performance may not be clear or the decision should not always be taken on the basis of individual indicator outcome. Asset performance measurement requires a quantified value that can represent the current condition and is capable to predicting future condition based on this value.

In most process facilities, measurement using different parameter, condition assessment and evaluation already exists. But, the measurement of only a few certain parameters are not sufficient to ensure asset integrity. Here, a comprehensive set of indicators is needed for monitoring performance that will cover the overall area of assets and related issues that can affect plant integrity. At the same time, the co-ordination and logical evaluation of the outputs of these indicators against targeted goals is also essential. Today's process industries are measuring performance only for the sake of measuring, without having a mission or vision. Even the organization has goals, failing to link the indicator's measurement with the overall strategy results in a worthless attempt. The missing point here is the alignment between the performed activities through indicators with the existing policies. So, this type of measurement of performance will be misguiding rather than supportive for continuous improvement. Based on the identified drawbacks of described approaches and literature, a risk based asset integrity indicator system is proposed with the aim of achieving the stated objectives.

Chapter 3

3 Research Methodology

3.1 Introduction

In today's competitive process industry environment, asset integrity is a important concern. So, the stakeholders are in need of a strategy that will monitor the integrity level of operating assets. Monitoring the asset integrity performance will eventually help in increasing the level of reliability and availability, as well as the life span of facility. In this research project, a risk-based asset integrity indicator approach is proposed for monitoring and ensuring the asset integrity. This approach is developed to fulfill the stated objectives and purposes. Indicator system is aimed to measure and evaluate the current level of asset integrity based on associated risk information. The indicator system is the combination of both leading and lagging indicators, and this will ensure the comprehensiveness of an approach in assessing assets. The proposed model has the capability to integrate and aggregate qualitative and quantitative risk information following a similar approach.

3.2 Risk Based Asset Integrity Indicators Methodology

Asset integrity is a critical issue in process industries. Selecting meaningful and effective tools for measuring performance and ensuring asset integrity is becoming increasingly important due to the involvement of a large number of factors. In this research the "*risk-based asset integrity indicators*" approach is proposed to determine the level of asset integrity. Following the risk-based strategy, the process plant will be assessed with respect to the likelihood and severity of incidents indicated by the indicators. The developed process will follow a structured and logical procedure for the identification of credible incident sequences and the assessment of their corresponding likelihood. The indicators of leading and lagging category will be used as a means to monitor the performance of assets. Both types of indicators will be developed following a structured approach that will ensure the asset integrity strategy and objectives. The methodology for estimating asset integrity level is shown in Figure 3-1, which depicts the different sequential steps.

3.2.1 Delimitation of Asset Integrity

Asset integrity is a very complex issue in process industry perspective with many facets. According to the definition of the asset life cycle, asset integrity starts from the design activity and ends with the decommissioning phase (UKOOA/HSE, 2006). Asset integrity is a common goal to all involved in the design, manufacturing, installation, operation, inspection, maintenance, modification, and decommissioning. All these activities have an impact on the integrity of an infrastructure and equipment in a process facility at all stages of the lifecycle. For the time being, it is of interest to maintain and improve the asset integrity of an operating process facility. This decision squeezes the activities involved in maintaining asset integrity with the activities related to the upper part of the dotted line, as shown in the Figure 3-2.

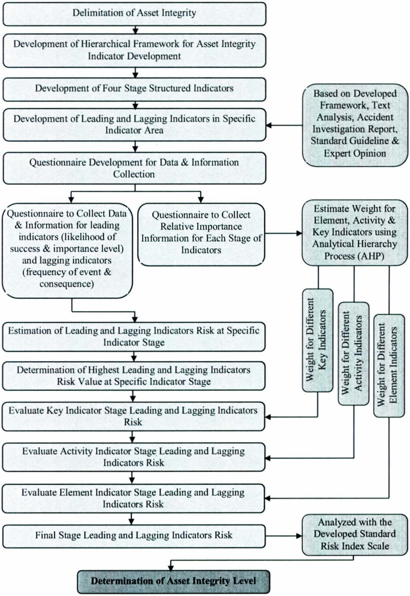

Figure 3-1: Methodology for estimating risk based asset integrity level

Irrespective of the type, process plants are usually designed and constructed to operate for around 20 to 25 years. Considering the designed life, the upper part activities of assets' lifecycle in Figure 3-2 has great significance in achieving asset integrity. Maintaining asset integrity during the operational period will help in achieving the target design life and even could extend it further. The activities in the upper part of Figure 3-2 can be broadly grouped into operational integrity and mechanical integrity. All operation related activities are considered as operational integrity and inspection, maintenance, and modification activities are considered in the mechanical integrity group. In an operating process facility, these activities are an integral part of everyday operation involving operators, maintenance employees, inspectors, contractors, engineers, and other personnel involved in designing, specifying, and installing, as well as in decision making. So, the personnel involved to carry out different activities of the above mentioned two integrity element have great influence in maintaining the integrity of asset. For this reason, the third element in the integrity structure is considered as the personnel integrity. Lehtinen et al. (1998) pointed out that accident prevention is the ultimate goal for any process installation and can be achieved through the use of reliable structures, components, systems, and procedures in a plant operated by competent personnel. Personnel involved in different activities should be competent enough to execute defined tasks with confidence. However, these three elements primarily involve inspection, preventive maintenance, predictive maintenance, corrective maintenance, operating procedure and activities, and quality assurance processes, including procedures and training that underpin the asset integrity.

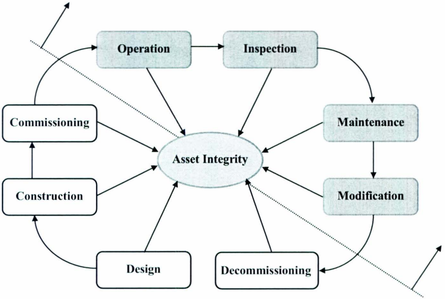

Figure 3-2: Elements that have an impact on the integrity of an asset over its life cycle (after UKOOA/HSE, 2006)

3.2.1.1 Asset Integrity Element Interrelation

Figure 3-3 depicts the relation between asset integrity with its selected major elements, as well as the interrelation between the elements themselves. All of these three elements of asset integrity are interrelated and the performance of one element has great influence on the other element. Operational activity explores the scopes for mechanical integrity, and both of these elements very much depends on the persons who are continuously dealing with these elements' activities. This enforces the requirement of personnel integrity to define the asset integrity comprehensively. So, for ensuring asset integrity, very good interaction between mechanical, operational, and personnel integrity is mandatory. Emphasis should also be placed on the individual element for performance improvement. If these three elements are monitored and managed effectively and comprehensibly, asset integrity can be obtained. Each of these elements has great significance on asset performance, which will be explored in a later stage.

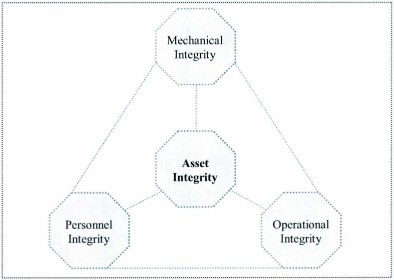

Figure 3-3: Relation between asset integrity with its contributory element

3.2.1.2 Major Element Contribution to Asset Integrity

Asset integrity in process industry is a cardinal strategic issue that is firmly rooted in maintenance and operational activities along with manpower competency. As asset integrity mainly arises from technical issues like maintenance, inspection, modification, and engineering assessment, which are grouped in the mechanical integrity category. These activities are directly related with the target of maintaining good asset physical health condition. If the physical assets are in good condition then there is less chance of an undesired event. That is why mechanical integrity is considered the prominent contributor of asset integrity. The other two elements, operational, and personnel integrity, also have potential influence on asset integrity. The influence and contribution of these three elements to asset integrity is shown in Figure 3-4, which is developed in accordance with the target of this research work. The area covered by the each element in the pyramid diagram represents its contribution of that element to overall asset integrity performance.

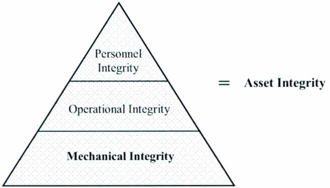

Figure 3-4: Major element contribution to Asset Integrity performance

3.2.2 Hierarchical Framework Development for Asset Integrity

The risk-based asset integrity indicator system uses a hierarchical framework to develop different level indicators for monitoring and measuring overall asset integrity. The proposed hierarchical framework has been developed from the IAEA (2000) concept for the monitoring of nuclear power plant operational safety performance. This approach followed a four stage top-down indicator scheme, as shown in Figure 3-5, that links the top level strategic goal with the floor level events. In a bottom-up approach, there is a very good chance of losing focus on the details of individual processes or activities. The proposed top-down indicator scheme can take care of this issue since the number of indicators will continue to increase with the progression towards downwards stages. So, there will be the maximum number of indicators at the root level and less chance of missing important activities. Substantial effort is also given in developing the hierarchical framework to make sure that the functionality and involvement of different level of management can be accommodated. Each level of management personnel in a process plant can be assigned to a particular stage of indicator supervision. Asset integrity cannot be measured directly; only the floor level specific indicators are directly measurable. So, for measurement of asset integrity performance, this multilevel indicator system is developed and brings down up to specific indicator level. This hierarchical structure is followed because the specific indicators result will have no value unless it is linked to the ultimate goal for ensuring asset integrity through performance measuring. Thus the hierarchical structure eventually turns out to be an asset integrity monitoring system.

In the proposed asset integrity hierarchy, indicators are used at several levels. The hierarchical structure started with the element indicators, followed by activity, key and specific indicators. Since the characteristics of these levels differ, the functions of indicators also differ from level to level. The individual indicators represent the actual condition of the asset to assure the reliability of the plant at any given time. The indicator system can provide a comprehensive view of the process plant equipment status and also can lead to particular consideration of trends requiring attention. This is done by using the leading and lagging indicators jointly that support the asset performance measurement.

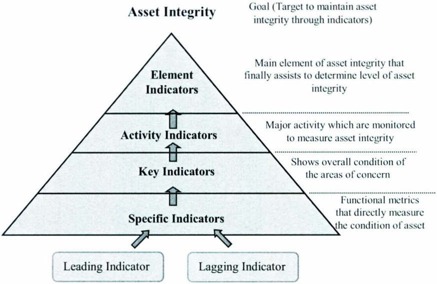

Figure 3-5: Hierarchical indicator pyramid for monitoring integrity level of asset (after IAEA, 2000)

Asset integrity can be described as a state of operation in which the risks are at an acceptable level. The management of a process plant should be able to arrange adequate control measure of the operating assets and make plans to overcome the risk. At the same time, they have to be prepared for all foreseeable risk situations that can be encountered and may cause threats to the integrity of the plant's assets. The risk should be below the limits set by the regulators and concurrently as low as reasonably acceptable, by taking care of the assets. This can be accomplished by the risk based asset integrity indicators system. The ultimate objective of developing asset integrity indicators is to create intervention strategies to avoid future incidents.

3.2.2.1 Description of Different Stages of Indicators

Since strategic goal, achievement of asset integrity or first three stages of indicators in the hierarchy structure cannot be measured directly, so the proposed indicator structure is stretched further via activity and key indicator until it reaches a level of easily quantifiable or directly measurable specific indicators. The purpose of the four stage framework is to ensure alignment between the top level policy and the event occurring on-site. The top level policy is the assurance of asset integrity and the events at site are the activities involved in plant operation. This will also allow developing indicators to follow the top-down strategy and allow indicators information to flow following a bottom-up scheme. The arrow direction in Figure 3-5 represents the risk information flow direction towards an asset integrity goal. Clear understanding of each stage of hierarchy is important to identify the correct indicators those will drive to asset integrity goal. The structured approach uses the following terminology to maintain logical relationships between indicators.

Element Indicator: As previously described, element indicators are the main contributory elements of an asset integrity goal. In respect to asset integrity, the mechanical, operational, and personnel issues related to activities has greatest influence on the equipment performance. These elements are the starting point of developing other types of indicators in the respective stages of the hierarchy. The satisfactory performance of these three elements is an underlying factor and prerequisite for ensuring asset integrity throughout the operational period.

Activity Indicator: Since the element indicators are also not directly measurable, these major elements are expanded to activity indicators. Activity indicators arise from the events that are usually performed or practiced to maintain the fitness for service of plant equipment. The activities, practices, and culture followed in mechanical, operational, and personnel sectors, respectively, are grouped into different category and named as activity indicators. These indicators are used to visualize the performance of major activities.

Key Indicator: This is one of the widely cited terminologies in several sectors, specifically where measurement is performed using indicators. Most of the regulatory organization guidelines place more emphasis on this and are known as key performance indicators or KPI. In the context to asset integrity, key indicators are to support the activity indicators by representing overall asset condition. These are convenient parameters that also maintain relationship between root level indications with activity indicators.

Specific Indicator: These types of indicators are very important, irrespective of the perspective of performance measures. The outcomes of specific indicators are the only quantifiable measure of asset performance. This measurement supports and facilitates achieving the asset integrity goal. The specific indicators should be chosen comprehensively, following the described characteristics that will ensure meaningful, reliable, and accurate information. In this research, the specific indicators are also divided into two important categories, which are: leading and lagging indicators.

3.2.3 Reason for Hierarchical Framework

Hierarchical framework is a structure of entries having several levels arranged in a pyramid like formation. In this structure, the height of a stage represents that level's significance and the width of a stage represents the quantity of the indicator at that stage relative to the entire framework. The hierarchical structure has the following features that could be used to achieve the stated objectives:

i. Hierarchical framework provides a way to connect the strategic management goal with the current plant specific condition.

ii. A multi stage in the hierarchy provides the flexibility in prioritization of action and measurable bottom level specific indicators can be used to generate meaningful measure for the upper level performance (NSPI, 2009).

iii. Framework provides correct information at a glance regarding the asset performance to higher level management for strategic and rational decision making.

iv. Sometimes the indication of a single indicator does not ensure the viability or actual impact or can be misleading. In those cases, hierarchical framework based upper level indicators could provide comprehensive and improved assessment of the event.

v. Hierarchical structure facilitates easy mapping and assessment of asset performance by allowing weighting or prioritization of different indicators in a particular stage.

vi. The hierarchical framework approach allows different levels and areas of management to focus on the particular stages of indicators that are relevant to them and to locate where they have to put more emphasis to mitigate the effect of deleterious factors.

vii. Framework also has the capability to modify/incorporate/eliminate different level indicators in the course of time when necessary.

viii. The pyramid structure can be diagrammed either in the shape of triangle or in tree format for convenient indicator representation.

3.2.4 Indicator Framework Overview

Measurement of asset performance is an essential precursor to all attempts to improve. Indicators have become a widely used measuring tool in many different fields and play an important role in highlighting problems, identifying trends, and contributing to the process of priority setting, policy formulating, evaluating and monitoring of progress (Schirnding, 2002). The depicted hierarchical structure in Figure 3-5 provides a functional platform to develop multilevel indicators. Later, the multi level indicators will be illustrated by a tree diagram as illustrated in Figure 3-6 for better orientation of indicators and representation of integrity goal.

3.2.5 Risk Based Approach for Asset Integrity Indicator

Asset integrity is off the mark physical condition of asset that eventually ensured the reliability of the equipment operating in a process facility. Reliable equipment, coupled with dependable human performance, is critical in managing risk. In addition, both are necessary conditions for reliable operation of process plants that will minimize risk.

Collins et al. (2003) in the HSL investigation report mentioned that, among the sample of 718 losses of containment related chemical accidents over an 11 year period, about 81% of these came as a consequence of inadequate risk management strategies. So, to reduce the number of incidents, risk profiles of assets should be given priority while planning for monitoring asset performance. In this research, to measure and evaluate asset integrity the risk based indicators approach is used. The objective is to identify areas of most risk and put relatively more emphasis on those for optimum outcome. Risk is typically described as the quantified form of the probability of an event occurrence and its potential consequences in terms of economic, health, and environmental costs (CCPS, 2000). The risk based indicator system is a risk information tool, which can generally be used to monitor asset performance and to alert the user if asset performances exceed certain levels or followed undesired trends. Indicators can also be used for assessing the efficiency, effectiveness, dependability, and completeness of asset health. To do so, the specific indicators have been extended and categorized into two distinct groups. These are leading and lagging indicators, which will be focusing on the parts of activities where incidents are most likely to occur. This root level indicator will provide risk information and the asset performance can be assessed subsequently. So, from the risk based concept of indicator, asset will achieve integrity if they are operated and maintained such that the likelihood and consequence of an event that delivers risk to people, environment, and the facility remains within an acceptable limit.

3.2.5.1 Risk Based Leading Indicator

Risk based leading indicators are intended to identify two primary *pro-active* risk factors: the likelihood of success and the corresponding importance of that success for an event. From this information, posterior risk associated with the policies, procedures, activities, and practices can be predicted. These indicators are usually expected to provide in process information on activities that are employed to improve asset integrity performance. Leading indicators are most useful as a precursor to asset integrity degradation for early management response so that adverse result can be avoided. They also enable one to take pre-emptive actions to improve changes of achieving strategic asset integrity goals. The major benefit of using leading indicators is it can assist in figuring out the root cause of an unexpected trend easily. With the advanced feedback of asset performance, necessary immediate action can be taken before an undesired incident occurs or deficiency can show up that can decrease performance level. Thus, leading indicators basically reflect present or future performance rather than past performance. These indicators are hard to identify and difficult to quantify. One way to approach this issue is to identify and develop leading indicators that can measure the performance of functional areas within the process facility, such as operation, maintenance, inspection, management of change, training, and engineering support (Holmberg et al., 1994). The characteristics of these functional areas will be taken into consideration and studied systematically to find out the suitable predictive risk based leading indicators.

3.2.5.2 Risk Based Lagging Indicator

In contrast, risk based lagging indicators are intended to identify also two primary *reactive* risk factors: the likelihood of failure and the corresponding consequences of that event. They are conventional quantitative type indicators and usually reported throughout the process industries to drive plant performance and for benchmarking against similar plants. These indicators help to assess whether asset-related activities are achieving their desired performance or not. Risk based lagging indicators often measure changes in asset performance over time, by identifying and reporting incidents and subsequent impacts on health, environment, reputation, and property. But, unlike leading indicators, they do not tell the root causes for the incidents or how the reoccurrence can be prevented. In this case, corrective action can only be taken after the adverse events and the effect of corrective measure taken may not become apparent until the next measuring cycle.

The leading indicators can be considered measures of inputs to asset integrity systems, which are associated with the causes of an activity and lagging indicators, are measure of outputs, which are associated with the results of that. The concept of using only lagging indicators will not give any information how the outcome is achieved or any early warning on the way to achieving the strategic goal. On the contrary, using leading indicators only will enable the ability to focus on short-term performance measurement and will not be capable of visualizing the long term outcome measurement. So for optimum asset integrity performance measurement, asset integrity indicator systems should contain a combination of leading and lagging indicators.

3.2.6 Performance Index Development

Risk based leading and lagging indicators play the critical role of monitoring the operating asset condition, so these indicators can also be considered as "performance indicators." For a comprehensive performance measurement system, the number of indicators in the three major areas of asset integrity will usually be increased. Mengolini et al. (2008) mentioned that several indicators are required for performance measurement because focusing on a single feature can often be misleading rather than supportive. When too many indicators from several areas are considered then two important issues arise. One of them is the presence of dissimilar units of indicators from different areas, which will be taken care of by the proposed risk based approach and helps to create a unit-less measure. Another issue has to compile the entire indicators outcome into an overall measure of asset performance. In this situation performance indexing is a very useful tool that is capable of combining all the indicators' information into a single value. A risk index scale will be developed for indicator performance mapping that will illustrate the assets' conditions. This will eventually also assist in comparing the composite outcome of indicators to a corresponding asset performance target.

3.2.7 Risk Based Indicator Development

Selecting appropriate indicators for measuring asset performance is very critical. Indicators are of diverse nature, having different units and a wide array of information that is also quite tough to integrate. This is why most of the available literature does not deal with the performance indexing system. The risk-based approach provides an opportunity to locate the target region in developing indicators. The risk concept allows fixing one target, which is the identification of risk significant events and will be done via indicators. At the same time risk also provides an easy way to integrate the indicator outcome to an index. Risks involved in different activities are of paramount importance in managing asset integrity. A successful asset integrity system requires consideration of risk for developing multilevel indicators. So, the indicators will be selected considering all the risk enhancing scenarios since the target is to avoid any kind of incidents that could lead to an accident.

For developing a comprehensive set of indicators, the asset integrity guidelines provided by HSE (2007), RBPS (2007), and OGP (2008) are considered and followed at each stage. The identification of an initial set of indicators was based on literature review. The Texas City explosion investigation report provided by Mogford (2005) and Baker (2007) panel were thoroughly studied to identify a comprehensive set of indicators. These investigation reports have highlighted several asset integrity related issues that were overlooked. Besides these, the detailed accident investigation report by Collins et al. (2003), titled "Loss of Containment Incident Analysis" was also considered. This report investigated 718 accident scenarios and grouped them into different categories to identify the causes of the accidents. In developing indicators the specified causes relating to physical equipment, operational activity, and human factors are also taken into consideration. Along with these the IAEA (2000) and SENUF (2006) reports were also analyzed for a potential set of multilevel asset integrity indicators development. More emphasis is given to identify the floor level specific indicators. In the specific levels the selected leading and lagging indicators will cover all the aspects of plant, process, and people. This will be done by identifying the potential degradation mechanism and threats to the integrity of the equipments.

3.2.7.1 Mechanical Integrity Indicator Development

Mechanical integrity (MI) is an integral part of the asset integrity system that supports the protection of the plant, process, employee, environment, and surrounding community. MI in respect to process facility is a major concern and failure to adequately maintain equipment can have catastrophic results. Mechanical integrity has gained popularity with the introduction of Occupational Safety and Health Administration (OSHA) regulations on Process Safety Management of Highly Hazardous Chemicals. The OSHA regulation 29 CFR 1910, section 119(j) requires a mechanical integrity system where all inspection and testing of equipment are performed using written procedures and by competent personnel (OSHA, 1992). In addition, the Environmental Protection Agency (EPA, 40 CFR Part 68, USA) in "Risk Management Program" and American Petroleum Institute (API, RP 750:1990) in "Management of Process Hazards" also pointed out the requirement of *mechanical integrity* assurance (Mannan, 2005).

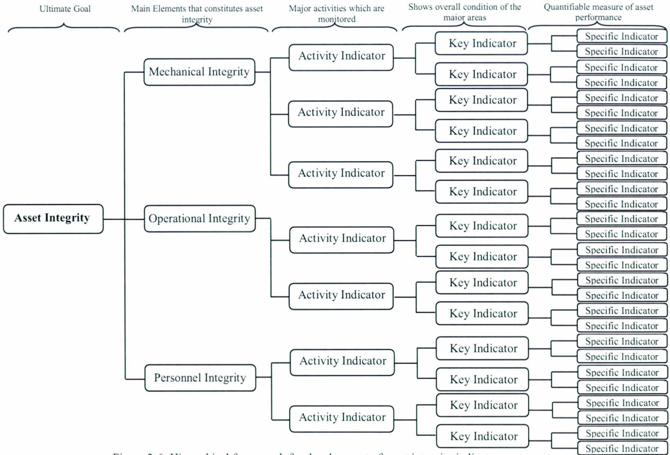

Figure 3-6: Hierarchical framework for development of asset integrity indicators

The Chemical Manufacturers' Association, USA, defines mechanical integrity as "the establishment and implementation of written procedures to maintain the ongoing integrity of the process equipment." Mechanical integrity is the state of a process or equipment that indicates that it is capable of complete operations within the designed limit. It can be ensured through a documented program of procedures, policies, inspections, and tests and through preventive and corrective maintenance based upon good engineering practice, applicable codes, standards, specifications, and manufacturers' recommendations. The objective is to ensure equipment does not fail in a way that causes an unwanted scenario. Sutton (1997) states, MI beyond the fact the title contain the word "mechanical." *Mechanical Integrity* covers much more than mechanical engineering issues. Mechanical integrity is also not just the maintenance of equipment, although maintenance is a major part of an MI. Other good engineering practices, such as inspection, process safety, reliability discipline, and quality assurance etc., are also included. MI is the systematic implementation of all activities necessary to ensure that important equipment will be suitable for its intended application throughout the life span of an asset. It also increases the plant availability by reducing equipment failure and minimizing the unplanned maintenance time.

Mechanical Integrity indicators are employed to monitor and assess the activities performance in all engineering and other practices carried out to ensure the quality of the service of operating equipment. Using the root level risk information, MI activities can be monitored at three distinct stages. The following tree diagram in Figure 3-7 represents the identified activity, as well as the key indicators in those respective areas. The mechanical integrity will be monitored using four major activity indicators, which are: inspection, maintenance, inspection & maintenance management and engineering assessment.

Inspection: Inspection is one of the integral parts of the mechanical integrity program. Inspection is the systematic way to verify of compliance with standards or to assess the current condition of equipment. This is usually performed with the assistance of special inspection instruments or tools along with visual observation. Most of the process industry utilizes the inspection data to determine the overall asset condition. The success of inspection activity depends on inspection strategies, types/methods, tools, intervals, and the coverage. These parameters vary with respect to the type of components to be inspected and with the applicable legislation requirement. So inspection should be monitored via key indicators tailored to specific indicators. Inspection activities are assessed through three key indicators; these are: inspection strategy, inspection effectiveness and compliance with statutory requirement. These key indicators are expanded to specific level and several leading and lagging indicators are proposed in these areas, as shown in Figure 3-8. These indicators will collect the basic information to determine the inspection performance.

Maintenance: Maintenance is intended to minimize asset downtime whilst maximizing inherent safety, reliability, availability, and integrity levels of the equipment. Maintenance is a complex practice that involves different types of maintenance perspectives and several other related aspects. It usually involves measurements, tests, repairs, replacements, adjustment, and testing after maintenance activities to restore or retain equipment to its original operating condition. Conventionally, maintenance has been considered as a secondary process (Löfsten, 1999) or sometimes treated as a necessary evil. This strategy will be changed if equipment is not monitored properly and maintained routinely before breakdown. To identify the performance of maintenance activity, five relevant key indicators are employed. These are: PM performance, CM performance, reliability perspective of SSC, availability of equipment, and compliance with rules and regulation. These five key indicators further expanded up to several applicable specific leading and lagging indicators levels as shown in Figure 3-9.

Inspection & Maintenance Management: The inspection and maintenance activity will have no value or will not be effective unless they are managed properly. The management requires the planning and scheduling along with logistic support arrangement. Failures to provide and implement proper maintenance procedures have been reported as a root cause of accidents in several occasions. This activity indicator should be employed for ensuring mechanical integrity. For monitoring inspection and maintenance management activity four convenient key indicators are proposed, which are: planning and scheduling, correspondence with operational activity, work flow monitoring, and procurement and inventory control. These key indicators performances are determined by certain specific leading and laggings indicators, which are shown in Figure 3-10.

Engineering Assessment: Assessment is a very important issue to determine the present performance and to decide the future essentials. All maintenance and inspection activities should be assessed from a technical as well as a financial, point of view. It's a prerequisite for any type of engineering activity. Again two key indicators are proposed to determine the assessment performance. These are: financial optimization and control and quality of work execution. And finally, a few developed root level specific leading and lagging indicators are shown in Figure 3-11.

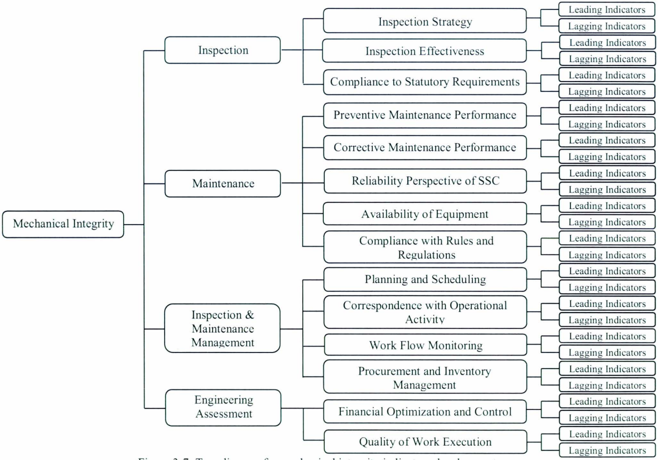

Figure 3-7: Tree diagram for mechanical integrity indicators development

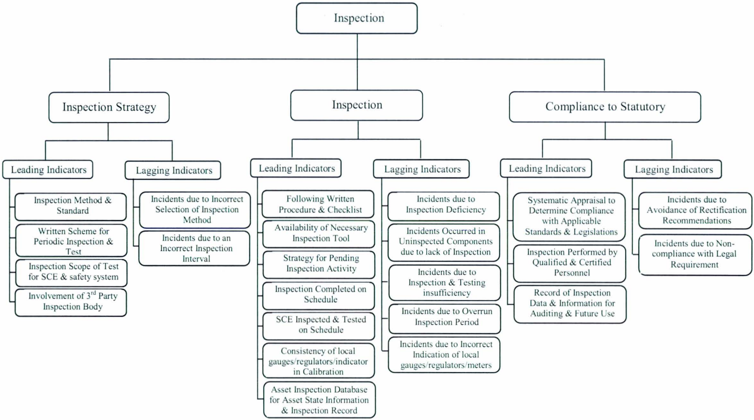

Figure 3-8: Leading and lagging indicators for inspection activity

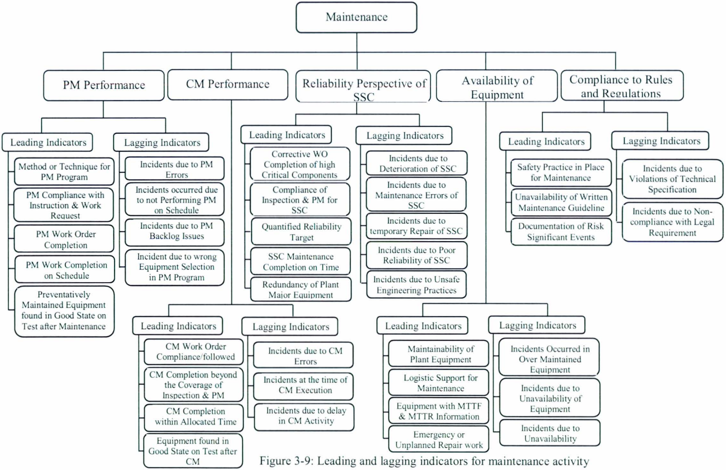

Figure 3-9: Leading and lagging indicators for maintenance activity

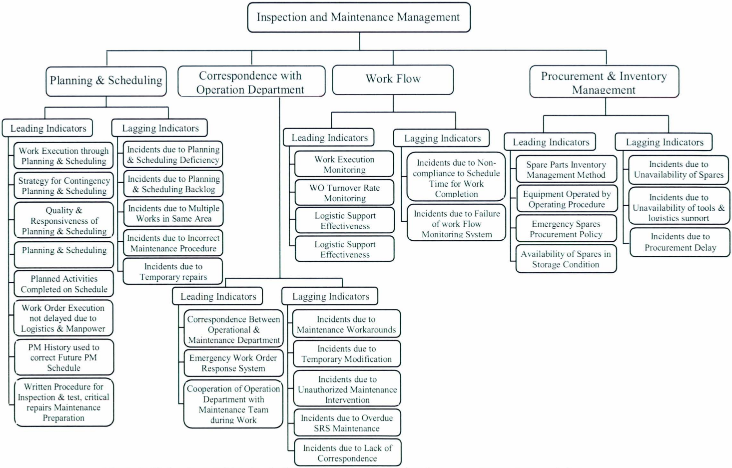

Figure 3-10: Leading and lagging indicators for inspection and maintenance management activity

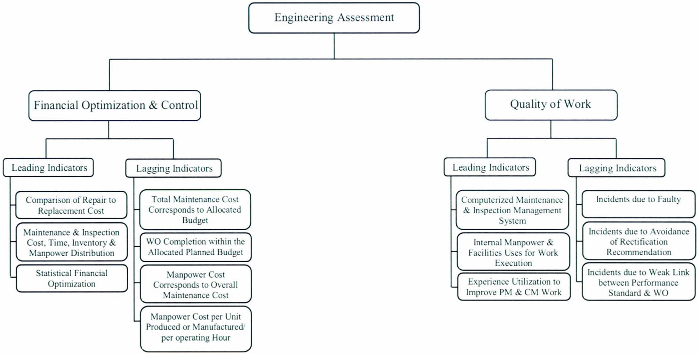

Figure 3-11: Leading and lagging indicators for engineering assessment activity

3.2.7.2 Operational Integrity Indicator Development

It is commonly believed that asset integrity can be achieved only by maintaining mechanical integrity. But, the success of asset integrity is also rooted in the performances of operational practices. The equipment in a process facility could be in excellent condition, but it will not assure integrity unless operated appropriately. The equipment should be operated as per standard updated operating guideline and within the designed limits. Safe and reliable operations are essential in today's process facility to maintain the integrity level. Strict control of operational discipline and competent operation in a process facility is essential to establish operational integrity. Sound equipment with sound operation will ensure the optimum level of asset integrity.

Operational Integrity: Pirie (2007) defined OI as "appropriate knowledge, experience, manning, competence and decision making data to operate the plant as intended throughout its lifecycle." Beyond appropriate operating procedure, OI performance also depends on the other issues, like safety system, plant configuration, and emergency management system and on some other non-technical management systems as well.

Operational Integrity Indicators are developed to monitor the different activities, operations, and processes in the operational areas. The performance of the operational integrity element depends on certain activities. These activities move beyond operational performances and also include technical initiatives and safety system management issues. Operational integrity elements have been divided into five major activities, as shown in Figure 3-12, which are practiced to maintain operational integrity. These are: operating performance, state of SSC, plant configuration and modification, engineering safety system, and emergency response arrangement.

Operating Performance: Plant operating performance has great influence in the operational integrity achievement. Incidents may occur if the operating procedures are inadequate, incorrect, or could be misinterpreted due to ambiguity in understanding. Efficient plant operation, particularly during the abnormal condition is really a tough task. Operational errors have been noticed several times as a root cause for accident occurrences even while the plant was in normal operating conditions. This type of incident can be avoided by following a written operating procedure for normal as well as in emergency situations. Operating limits for each operating mode and operating instructions should be clearly defined and updating should be done routinely. Operating procedures and instructions should be regularly reviewed for maintaining completeness and accuracy levels. The activity indicator performance will depend on the two key indicators: operating procedure and forced outage. Key indicators are further expanded to specific leading and lagging indicators level, as shown in Figure 3-13, for the necessity of quantifiable indicators.

State of SSC: State of systems, structures, and components also influence the operating performance. Corrosion and fatigue condition of equipment is an important aspect for any type of establishment. The importance of attention also increases with the increase age of SSC. With the increase of age the corrosion propagation rate also moves more rapidly. The reliable performance of SSC eventually provides confident in incident free operation. To ensure dependable performance, this activity indicator is planned to monitor through three key indicators. These are: corrective WO, corrosion and fatigue condition, and ageing conditions of SSC. The developed specific leading and lagging indicators in these key areas are shown in Figure 3-14.

Plant Configuration & Modification: Plant configuration is a design aspect that is beyond the scope of in-service asset integrity approach. Still, modifications arise with the design configuration and limiting operating conditions during inspection and maintenance period. The modifications in design and configurations plants also have impacts on the operational integrity performance. Plant configuration is to be analyzed first to identify potential areas of improvement. Several technical, financial, and safety issues have to be considered during modifications. Assessment of modification requirement and change in operating procedure are most important. Since operating performances have relation with these activities, they also need to be monitored. Three key indicators are employed to monitor the plant configuration and modification activity. These are: plant design, modification effectiveness, and modification assessment. Thoroughly studying the key areas of performance observation, several specific leading and lagging indicators are developed, as shown in Figure 3-15.

Engineering Safety System: Engineering safety systems and safety related systems and items should be given more priority in every respect. These systems are usually remains standby, so their operating performance should be ensured at the time of requirement. This could be done by performing routine inspection and arranging provision for immediate maintenance of safety system related breakdown issues. Safety systems help to avoid the rise of any undesired event. So, with the need of monitoring the performance of this important activity, two key indicators are proposed. These are: safety system performance and safety system related backlog. Under these two key indicators, appropriate developed specific leading and lagging indicators are shown in Figure 3-16.

Emergency Response Arrangements: This is a reactive arrangement system followed by an undesired incident. Major incidents in a process facility are rare, which is why the emergency arrangement system receives less attention. But, future occurrences cannot be neglected and arrangements should be made to lower the impact level if an unlikely accident occurred. And, continuous observation of this activity is essential to ensure the response system operability and to avoid the enhancement of occurred incident. In this area, two key indicators are set-up, followed by numbers of specific leading and lagging indicators, as shown in Figure 3-17, to collect routine information. The key indicators are emergency response system performance and emergency preparedness. These two will cover the entire process facility and includes training, educating and motivating employees and contractor staffs in emergency notification, response, preparedness and evacuation procedures.

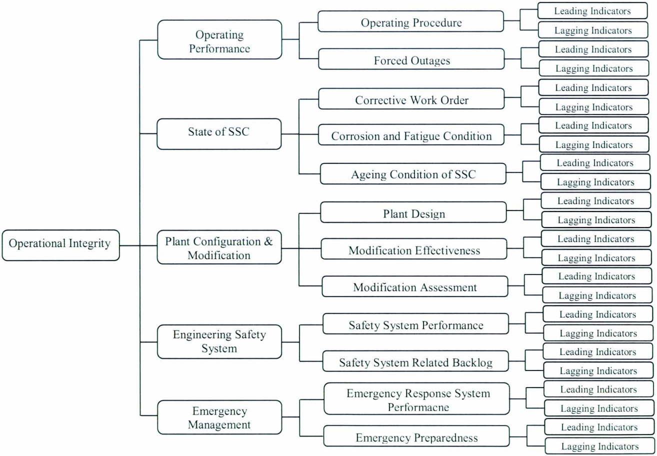

Figure 3-12: Tree diagram for operational integrity indicators development

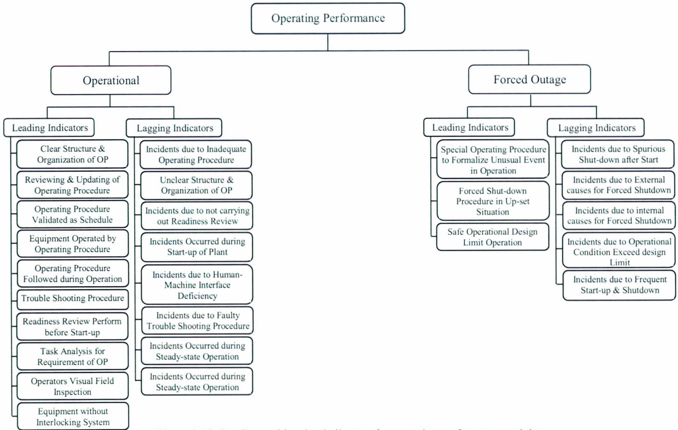

Figure 3-13: Leading and lagging indicators for operating performance activity

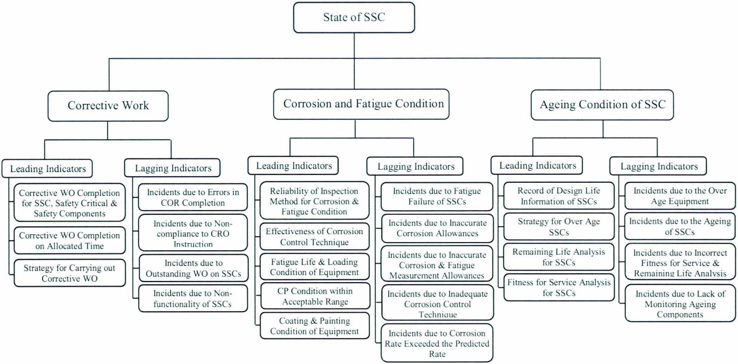

Figure 3-14: Leading and lagging indicators for state of structures, systems and components activity

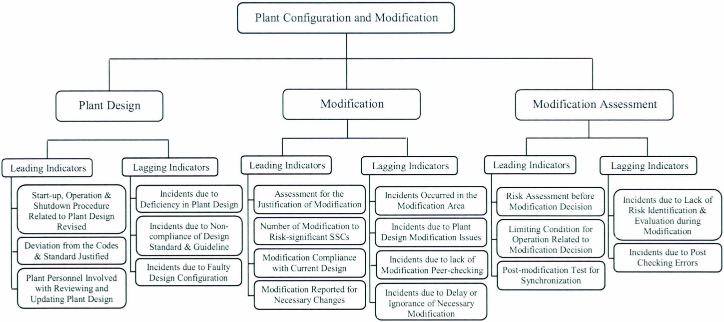

Figure 3-15: Leading and lagging indicators for plant configuration and modification activity

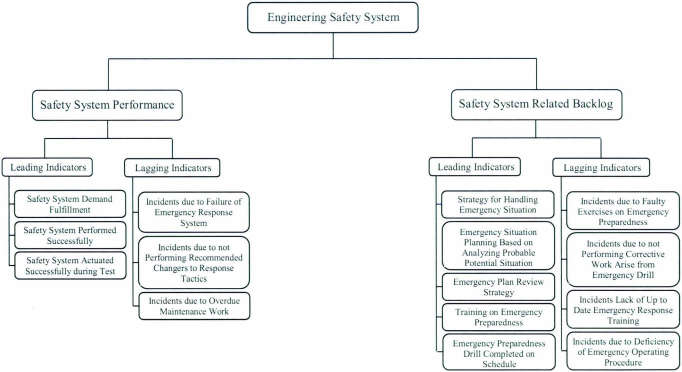

Figure 3-16: Leading and lagging indicators for engineering safety system activity

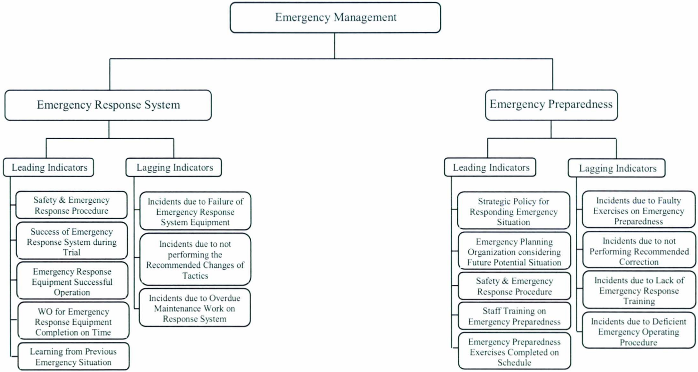

Figure 3-17: Leading and lagging indicators for emergency management activity

3.2.7.3 Personnel Integrity Indicator Development

The integrity of mechanical and operational elements can only be achieved if all involved activities are adequately handled by competent personnel. Without efficient, trained, and competent personnel asset integrity goals can never be attained. So, asset integrity in this respect means making sure all operating facilities are operated properly, inspected, and maintained adequately by efficient manpower. Human factors are important issues in process operation and research revealed that human errors contributes to unsafe practices and accidents more than two thirds of the time in industries (Wilson et al. , 2005). Human factor aspect has a dominant impact on the activities that are carried out for attaining mechanical and operational integrity sectors. For long term growth of a process facility and to ensure asset desired performance, competent personnel have to be developed. The development process involves training of personnel, and it should be an on-going process that contributes to keeping the professional skills up to date. Along with this, the commitment from the senior management is also required to make sure of consistence performance from plant personnel. Kletz (1993) mentioned that, "Organizations have no memory; only people have memories." Their experience with past incidents should be shared with others with lack of experience, so that the likelihood of making errors can be reduced. To maintain integrity, any process needs to take human factors into consideration that protect integrity.

Personnel Integrity can be defined as the condition when plant personnel showed adequate performance in all asset integrity related activities and their skill levels are developed continuously with the updated trainings scheme. It basically requires the assurance of optimal human performance so that no incident will occur due to human errors. The success of this element is also firmly rooted in the personnel's self behaviors towards achieving asset integrity and the organization culture.

Personnel Integrity Indicator: Personnel integrity indicators are a means of measuring human performance effectiveness in everyday's plant activities. Human performances are closely related with the physical plant asset activities along with a few subjective issues. Multistage indicators are developed here also to visualize the performance level. To monitor the plant-wide human performance, the personnel integrity element has to be observed using the proposed four activity indicators. These are: training, staff competence, permits to work, and communication, as depicted in Figure 3-18 in tree diagram format.

Training: Training is the best way to develop plant personnel to attain the personnel integrity goal. This is the acquisition of knowledge, skills, and abilities to meet the required performance level for particular activities. The roles and responsibilities of every personnel in a process facility should be specific and clearly defined. Then, the training need and scope should be identified accordingly. Relevant training should be provided to those personnel based on their involvement in specific task (OGP, 2008). Training requirements related to update operating procedures and safety culture is mandatory along with other technical, specialized, and interpersonal training. Mogford (2005) pointed out that in a Texas City refinery several management of change (MOC) were conducted and operating procedure were changed accordingly, but no indications were found that training had occurred. Training should not be limited to plant personnel only; contractors personnel should also be trained in some mandatory aspect. Training of a contractor's personnel issues were also recommended in the Piper Alpha investigation report (Mannan, 2005). Here, training activity will be monitored using two key indicators, which are: safety culture and technical and interpersonal training. These key indicators are further expanded for the requirement of quantifiable specific leading and lagging indicators. Both sets of indicators in respective areas are developed and presented in Figure 3-19.

Staff Competence: Plant personnel competence levels can be considered as one of the main barriers towards achievement of personnel integrity. Competence is the ability to precisely and reliably meet the performance requirement for a specific role. Key activities, tasks, and supervision in the critical areas required competent personnel so that incidents can be avoided. Competence plant personnel can make the difference between flawless performance and occurrence of major incidents. Operations and maintenance technicians working directly on a particular asset required competence i.e. skills, knowledge, and personal attributes in the relevant typical workplace areas (OGP, 2008). Considering the importance of staff competence, the investigation report of Piper Alpha recommended that the minimum qualification of offshore platform managers should be of graduate level (Mannan, 2005). To verify the staff competence, level two key indicators are employed, which are: staff performance and assessment of competence. In the same manner, these key indicators are monitored through several specific leading and lagging indicators that are shown in Figure 3-20.

Permit to Work: OGP (1993) defined a permit to work as "a formal written system used to control certain types of work which are identified as potentially hazardous" The PTW usually contains information on hazards involved in the maintenance operation, the appropriate personal protective equipment to be worn, and lock-out-tag-out (LOTO) information. The aim of PTW is to make sure that adequate planning and consideration is given to the risks of a particular task. At the same time, the PTW should be followed during work execution that may have potential adverse consequences. The Piper Alpha explosion investigation report pointed out that one of the prominent cause of the accident was a failure in one of the major management system that is a PTW system. The report also places considerable emphasis on the need for an effective PTW system (Mannan, 2005). Considering this, OGP (1993) has developed a guideline that describes different steps to be followed for issuing PTW. This important activity performance also needs to be monitored and to do so two key areas are identified; these are: effectiveness of PTW and compliance with PTW indicators. To observe the performance in these two key areas specific leading and lagging indicators are developed in their respective field and shown in Figure 3-21.

Communication: Communication is one of the most important issues in a process facility and can be considered as a key factor to asset integrity accomplishment. Effective communication is a prerequisite for implementing an asset integrity strategy and helps to create and maintain a safe workplace. Communication channels should be open, redundant, and capable of flowing from both vertical and horizontal direction. All managements, plant supervisors, managers, operators, and workers should be aware of their definite task and increased communication between them will reveal numbers of weakness in a process plant. In this way, the near misses and incidents occurrence can also be minimized. The activities under the communication should be monitored closely and any problem in a communication system should be given top priority and subsequently should be solved immediately. For observing the performance for this vital activity, three best suited key indicators are chosen. These are: reporting incidents, communication systems and management of change. Reporting all types of incidents irrespective of severity through proper communication system will have great influence on future occurrences. All type of MOC processes need to be communicated to every relevant and required place. Specific leading and lagging indicators are developed, as shown in Figure 3-22 under the key indicators for the need of quantifiable indicators.

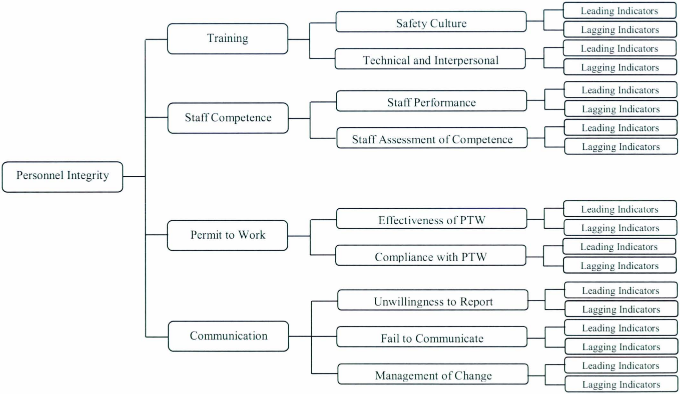

Figure 3-18: Tree diagram for personnel integrity indicators development

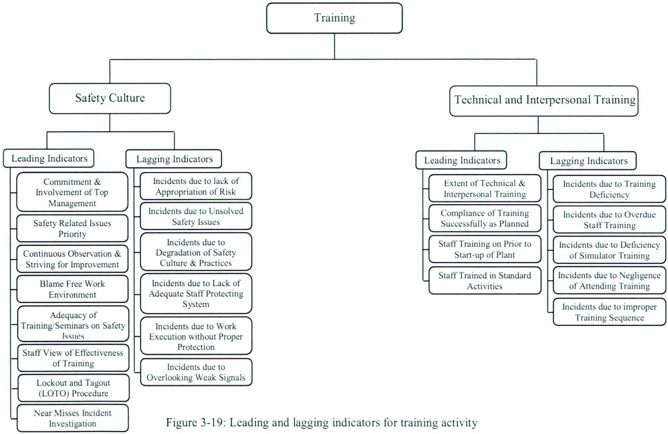

Figure 3-19: Leading and lagging indicators for training activity

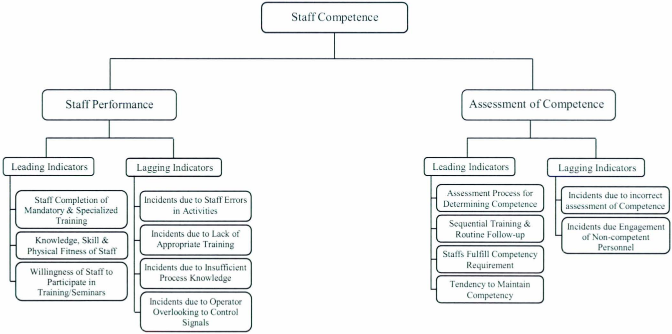

Figure 3-20: Leading and lagging indicators for staff competence activity

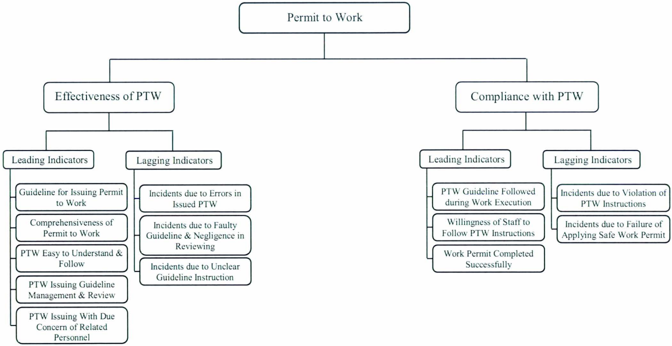

Figure 3-21: Leading and lagging indicators for permit to work activity

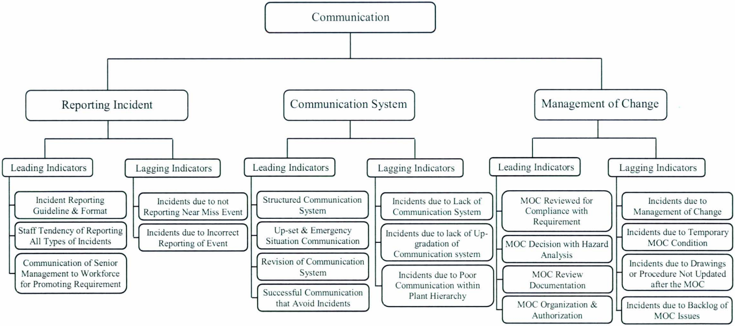

Figure 3-22: Leading and lagging indicators for communication activity

3.2.8 Aggregation Technique

The meaning and relation of specific indicators' risk information are more important rather than its measurement only. "A numerical value of any individual indicator may be of no significance if treated in an isolated manner, but may be enhanced when considered in the context of other indicator performances" (IAEA, 2000). So, the aggregation method has to be used to represent the overall performance of all operating assets. The asset integrity indicator system should be integrated in a systematic way to achieve the target for which they are developed. Aggregation is a special technique that combines and aligns the values of lower level indicators' outcomes in a common scale that assists in estimating the values for higher level indicators. Proposed indicator system based on hierarchical structure provides an easy way to systematically aggregate lower level information and to flow towards the upper level.

Aggregation of data from lower root level specific indicators to top level strategic goals will be performed in two steps. In the first step, the root level specific risk information will be aggregated. The root level leading and lagging indicators for monitoring asset performance are of different natures with different units such as number, ratio, percentage etc. So, it is quite difficult to transform all these outcome values of indicators into a common comparable rating scale. To overcome the diverse nature of indicator data, a risk based approach is followed. Risk provides a common ground of measuring units for both types of indicators (Khan et al., 2009). At the same time, risk measurement can be used without units for asset performance that makes the aggregation process easier. In the second step, the risk factors of individual indicators will be multiplied by the appropriate weighting factor at each level of indicators to get the final asset risk index. To identify the varying levels of importance for each stage of indicators', analytical hierarchy process (AHP) will be used. Pair-wise importance comparison of indicators from an expert's panel will be analyzed by AHP to assign different weights to same group of indicators. Finally, the weighted average technique will be used to calculate leading and lagging risk index at different levels of the hierarchy and to obtain the final risk index value. Thus, the developed aggregation technique will integrate risk information from lower level specific indicators to the top level of the hierarchical framework. This is done to quantify the risk index through the corresponded importance level of the each level indicator in the hierarchy to determine the overall asset integrity index.

3.2.9 Indicator Risk Determination

Risk is a random event that may possibly occur and, if it did occur, would have a negative impact on the goals of the organization (Vose, 2008). Indicators indicate the quantified value and the trend in risks by combining two primary factors. The product of these two primary factors: likelihood and consequences constitutes risk. Consequences in this respect will be considered as health and safety, production loss, environmental damage, repair cost, and reputation loss. Like other industries process industries, have the common practices of ignoring low probability events, even those, which could have potential consequences. This type of scenario is very much evident from the Esso Longford gas explosion in 1998; a low probability event like major gas leak causes the catastrophic accident (Hopkins, 2000). The risk based indicator approach will provide a picture of the overall risk other than looking into likelihood and consequences separately. The timely indication can change the risk profile of a process facility before risk events tends to manifest. Assets risk in a process facility should be measured on a timely basis by leading and lagging indicators. Asset indicators' risk value act as feedback and can be used for monitoring, controlling and determining future essentials to achieve strategic the goal and asset integrity. Monitoring will be done by indicating significant changes in risk level, control will be done by mapping underlying risk with the risk index, and management can make rational decision of future essentials based on individual asset indicator risk.

3.2.9.1 Leading Indicator Risk Determination

Step Change in Safety defined 'leading performance indicator' as "something that provides information that helps the user respond to changing circumstances and take actions to achieve desired outcomes or avoid unwanted outcomes. Their role is to help improve future performance by promoting action to correct potential weaknesses without waiting for demonstrated failures." The developed forward-looking specific leading indicators can be employed for monitoring two important parameters: percentage likelihood of success and the importance level of the success for an input activity. Here the term importance level is used, as no adverse incidents have occurred yet and mapped using the Appendix A consequence criteria. Using these two parameters, the risk associated with the individual action is estimated by Equation 3-1.

$$\begin{aligned}&\text{Risk factor for leading specific indicator } \left(R_{LDSI}\right)_i \\ &= \left(100 - \%\text{ age of success}\right) \times \text{importance of success}\end{aligned} \qquad (3\text{-}1)$$

Where i is the number of leading indicators in the specific indicator group.

All of the specific indicators are monitored through multiple leading indicators. There are different aggregation operators available to deal with the individual parameters and to get a combined result. Usually, the arithmetic average and weighted average are used to normalize the indicators' risk factors. Averaging the risk factor does not represent the actual condition of the plant. By averaging, high risk events are actually diluted and the outcome could misguide the management too. This simply means that the indicator with a high risk factor will be compensated by the other low risk factor indicators. But, in reality, it is not possible to lower the risk level of an event by the good performance of other events. Here, the proposed approach gives priority to worst-case scenario and considers the maximum risk value among all leading risk factors under each specific indicator. The maximum risk value will be considered as a risk factor for that particular leading specific indicator. This highest risk value using Equation 3-2 will be the risk factor for that particular key indicator and will be used for further aggregation.

$$\begin{aligned} &\text{Risk factor for leading key indicator } \left(\mathrm{R}_{\mathrm{LDKI}}\right)_j \\ &= \text{Highest risk score among 'i' leading specific risk factor } \left(\mathrm{R}_{\mathrm{LDSI}}\right)_i \end{aligned} \tag{3-2}$$

Where j is the number of key indicators in an activity indicator.

The leading key risk factor from Equation 3-2 will be multiplied by the respective weights of key indicators to get the risk factor for the leading activity indicator using Equation 3-3.

$$\begin{aligned} &\text{Risk factor for leading activity indicator } \left(\mathrm{R}_{\mathrm{LDAcI}}\right)_k \\ &= \sum_{j=1}^{j} \mathrm{w}_j \times \text{Risk factor of leading key indicator } \left(\mathrm{R}_{\mathrm{LDKI}}\right)_j \end{aligned} \tag{3-3}$$

Where k is the number of activity indicators in the element indicator.

The leading activity risk factor from Equation 3-3 will be multiplied by the respective weights of activity indicators to get the risk factor for the leading element indicator using Equation 3-4.

$$\begin{aligned}&\text{Risk factor for leading element indicator } \left(R_{LDEI}\right)_l \\ &= \sum_{k=1}^{k} w_k \times \text{Risk factor of leading activity indicator } \left(R_{LDAcI}\right)_k\end{aligned} \tag{3-4}$$

Where l is the number of element indicators in asset integrity.

Finally, the leading asset integrity risk factor is estimated by multiplying the risk factor for the leading element indicator with respective weights of element indicators using Equation 3-5.

$$\begin{aligned}&\text{Leading risk factor for asset integrity } \left(R_{LDAI}\right) \\ &= \sum_{l=1}^{l} w_l \times \text{Risk factor of leading element indicator } \left(R_{LDEI}\right)_l\end{aligned} \tag{3-5}$$

3.2.9.2 Lagging Indicator Risk Determination

Lagging indicators are traditional performance measurement tools and represent the result of unwanted incidents. The identified floor level specific lagging indicators can be employed to those specific areas for recording the occurred incidents. These lagging indicators will also monitor two basic risk parameters, such as the frequency or number of event occurrences for a particular time period and the severity of the occurred incident. Here, in case of lagging indicators, since the event has occurred already, the term severity is used and also mapped using the Appendix A consequence criteria. Using the collected two parameters' information risk related with the individual event is estimated by Equation 3-6.

$$\text{Risk factor for lagging specific indicator } (R_{LGSI})_m = \text{Number of occured events in unit time} \times \text{severity of that event} \quad (3\text{-}6)$$

Where m is the number of lagging indicator in the specific indicator group.

In this case also, several lagging indicators are developed to monitor the after effect of events under each specific indicator. So, the same strategy followed in case of leading indicators will be used here and highest risk factor using Equation 3-7 will be used for further aggregation.

$$\text{Risk factor for lagging key indicator } (R_{LGKI})_j = \text{Highest risk score among 'm' lagging specific risk factor } (R_{LGSI})_m \quad (3\text{-}7)$$

Where j is the number of key indicator in the activity indicator.

The lagging key risk factor from Equation 3-7 will be multiplied by the respective weights of key indicators to get the risk factor for the lagging activity indicator using Equation 3-8.

$$\text{Risk factor for lagging activity indicator } (R_{LGAcI})_k = \sum_{j=1}^{j} w_j \times \text{Risk factor of lagging key indicator } (R_{LGKI})_j \quad (3\text{-}8)$$

Where k is the number of activity indicators in the element indicator.

The lagging activity risk factor from Equation 3-8 will be multiplied by the respective weights of activity indicators to get the risk factor for the lagging element indicator using Equation 3-9.

$$\text{Risk factor for lagging element indicator } (R_{LGEI})_l = \sum_{k=1}^{k} w_k \times \text{Risk factor of lagging activity indicator } (R_{LGAcI})_k \quad (3\text{-}9)$$

Where l is the number of element indicators in asset integrity.

Finally, the lagging asset integrity risk factor is estimated by multiplying the risk factor for the lagging element indicator with respective weights of element indicators using Equation 3-10.

$$\text{Lagging risk factor for asset integrity } (R_{LGAI}) = \sum_{l=1}^{l} w_l \times \text{Risk factor of lagging element indicator } (R_{LGEI})_l \quad (3\text{-}10)$$

3.2.10 Analytical Hierarchy Process Technique

It was mentioned earlier that the aggregation of risk based asset integrity indicators will be done in two steps. The first step totally depends on the plant specific information that varies from interval to interval and will be collected in that specific time interval for assessment. But, the second step that is related to the weight allocation between different indicators in the asset integrity hierarchy is independent of the varying phenomenon. So, this weighting part can be standardized by taking expert opinion of indicators' relative importance. Once the indicators standard weight factors are determined, multiplying this with the specific indicators parameter aggregation target can easily be achieved. The analytic hierarchy process (AHP) technique will be used for analyzing the expert opinion and to determine the standard weight factors.

AHP developed by Thomas L. Saaty (1980) is one of the most popular and commonly used approaches for multi-criteria decision analysis. This is a standard statistical analysis technique to determine the relative weight i.e. importance of parameters. AHP is based on pair-wise comparisons between criteria or attributes provided by one or more experts in deriving weights for individual alternatives (Alonso et al. 2006). AHP is especially suited for assessing the qualitative information from experts. AHP also uses a weighted average approach, but it uses a method for assigning ratings so derived weights can be considered more reliable and consistent. Here, the objective is to determine the weight factors for the multilevel indicators and AHP is selected considering the following advantages:

i. Pair-wise comparisons solve the problem of handling the different types of scales and provide a very convenient form of data input from experts.
ii. It enables the synthesis of both subjective and objective evaluation measures and capable to detect inconsistent judgement in pair-wise comparison.
iii. Relative importance of each parameter is apparent and allows justifiable weight computing.
iv. AHP allows integrating multiple experts' judgements by taking the geometric average of the individual pair-wise comparisons (Zahir, 1999).

3.2.10.1 Multilevel Weight Calculation using AHP

Multilevel weight in the asset hierarchy means the weight determination of key, activity, and element indicators. The same procedure will be followed for all three levels of indicators weight determination. Since hierarchical structure is already developed, the multilevel weight calculation using the AHP methodology will be performed following these steps:

Step one: developing a pair-wise comparison matrix

Depending on the number of indicators in the particular level of hierarchy a comparison matrix will be developed. Pair-wise comparison allows determining the relative order or ranking of a set of indicators by assigning weight. In a pair-wise comparison of indicators, the contribution of an individual indicator to achieve the asset integrity goal will be considered. To overcome one of the drawbacks of AHP fixed scaling system in relative importance, an open scaling system is proposed. In pair-wise comparison, the experts are allowed to give any weighting value in the upper triangular of the matrix. If the given weight value is less than 1 that means that the compared indicator in less important than the other indicator. On other hand, more than 1 means the compared indicator is more important than the other indicator. If both the indicators are equally important then 1 will be given as weight value. The diagonal elements of the matrix are always 1 and for the lower triangular matrix the reciprocal values of the upper triangular matrix will be used. Now if C_1, C_2 ...C_n is the set of indicators then the quantified judgements on pairs of indicators C_i, C_j can be represented by an n-by-n matrix

$$A = (a_{ij}), \quad (i, j = 1, 2, \ldots\ldots, n)$$

and matrix A has the form

$$A = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2n} \\ . & . & \cdots & . \\ . & . & \cdots & . \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1 \end{bmatrix} \qquad (3\text{-}11)$$

Step two: Geometric averaging of experts' judgement

For standardization of multi-level indicators' weights, pair-wise comparison of indicators will be done by several experts. Several methods are available for averaging the expert judgment. Among those a key aggregation mechanism is the geometric mean that gives a good approximation of correct value. A geometric mean, unlike an arithmetic mean, tends to dampen the effect of outlying weight values, which might bias the mean if an arithmetic mean were calculated. The mathematical representation of the geometric mean is shown in Equation 3-12, by taking the n^{th} root of the product of compared indicator relative weight from n experts.

$$\text{Geometric mean of indicator weight } (\text{GM}) = \left(\prod_{k=1}^{n} x_k\right)^{1/n} \qquad (3\text{-}12)$$

Where x is the relative weight of indicator provided by a particular expert and n is the number of experts in the panel.

Step three: Mathematical basis of AHP

The relations between the weights, w_j, and judgements, a_{ij}, can be given by

$$a_{ij} = \left(\frac{w_i}{w_j}\right), \qquad (\text{for i, j} = 1,2,\ldots\ldots,n)$$

and matrix A in (11) can be written as

$$A = \begin{bmatrix} 1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & 1 & \cdots & w_2/w_n \\ . & . & \cdots & . \\ . & . & \cdots & . \\ w_n/w_1 & w_n/w_2 & \cdots & 1 \end{bmatrix} \qquad (3\text{-}13)$$

This paired matrix should be normalized to obtain the eigenvalues, which should correspond to eigenvectors. There are several methods for calculating the eigenvectors and again the geometric mean will be used. Weight at each level will be calculated using Equation 3-14.

$$\overline{w}_i = \left[\prod_{j=1}^{n}\left(\frac{w_i}{w_j}\right)\right]^{1/n} \qquad (3\text{-}14)$$

This weight will be totaled and the sum will be used to normalize the eigenvector elements and standardized weight can be determined from Equation 3-15.

$$w_i = \frac{\overline{w}_i}{\sum_{i=1}^{n}\overline{w}_i} \qquad (3\text{-}15)$$

These standardized weights are normalized to a sum of 1, i.e. $\sum_{i=1}^{n} w_i = 1.0$.

3.2.10.2 Consistency Index and Consistency Ratio

Since the AHP analysis is based on the subjective judgment, the consistency test has to be performed before using the calculated weight value. This scenario arises when the comparison matrix dimension has more than two elements. Consistency index and consistency ratio are used to verify the reliability of pair-wise comparison and to check whether there is inconsistency in subjective judgments. The AHP technique for determining weight remains incomplete unless consistency indexes are computed and checked with the random consistency values.

In the ideal case, the eigenvector w of A with eigenvalues 'n' is represented as

$$Aw = nw \tag{3-16}$$

And the matrix A can be written as

$$A = \begin{bmatrix} 1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & 1 & \cdots & w_2/w_n \\ \vdots & \vdots & \cdots & \vdots \\ w_n/w_1 & w_n/w_2 & \cdots & 1 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} \tag{3-17}$$

Human judgements are not completely perfect and the condition $a_{ik} = a_{ij} \cdot a_{jk}$ in the reciprocal matrix and Equation 3-16 does not hold and is replaced by

$$Aw = \lambda w \tag{3-18}$$

Where 'λ' is an eigenvalue, and in this case the eigenvector value 'w' should satisfy the Equation 3-19.

$$Aw = \lambda_{max} w, \quad \text{Where } \lambda_{max} \geq n \tag{3-19}$$

Here, λ_{max} is the maximized eigenvector of a pair-wise comparison matrix and can be calculated using the Equation 3-20.

$$\lambda_{max} = \sum_{j=1}^{n} {w_1}/{wj} \cdot w_1 + \sum_{j=1}^{n} {w_2}/{wj} \cdot w_2 + \ldots\ldots\ldots\ldots \sum_{j=1}^{n} {w_n}/{wj} \cdot w_n \qquad (3\text{-}20)$$

The difference between λ_{max} and 'n' is an indication of inconsistency of expert judgement and the logicality of the weighting can be evaluated through the consistency index that is estimated by the Equation 3-21.

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (3\text{-}21)$$

The final step is to estimate the consistency ratio that is the ratio of the CI to the random consistency index (RCI) for the same order matrix. This is done to compare the level of consistency relative to the consistency of large samples of purely random judgement .The following Table 3-1 gives the values for RCI derived from simulation. The CR is given the Equation 3-22.

$$CR = \frac{CI}{RCI} \qquad (3\text{-}22)$$

Saaty (1980) suggested that a consistency ratio of 0.10 or less is acceptable. If the CR is more than 0.10 then the experts' judgements are unreliable, and CR 0.00 means judgements are perfectly consistent.

Table 3-1: Random consistency index (Saaty, 1980)

Dimension of Comparison Matrix (n-by-n)	Random Consistency Index	Dimension of Comparison Matrix (n-by-n)	Random Consistency Index
1	0.00	9	1.45
2	0.00	10	1.49
3	0.58	11	1.51
4	0.90	12	1.48
5	1.12	13	1.56
6	1.24	14	1.57
7	1.32	15	1.59
8	1.41		

3.2.11 Leading and Lagging Risk Index Scale

Risk index (RI) is a composite representation of an estimated asset risk condition that is manipulated in some manner to give a crisp value. Risk index is formed by aggregating several indicators' risk scores and multiplied with the varying levels of importance at each level of indicators. The weighted average expresses the current overall leading and lagging risk condition of assets by generating a single index value. These index values have to be interpreted by a risk scale for categorization and for quick illustration of performance. To do so, a four tier standard risk index scale is developed following the API (2008) risk index system as shown in Table 3-2. A proposed index scale is developed considering the specific indicator risk mapping strategy for maintaining consistency. So, any leading or lagging risk index score in between 0 to 100 can be easily mapped on the index scale category. At the same time, any other level of individual indicators' risk in the indicator hierarchy risk can also be mapped with this scale. The risk scale tier categories are developed by assigning thresholds limit for each tier. The limit for the first tier is chosen from 0 to 19, indicated as green that represents the low risk. The second tier indicated as yellow represents medium risk with the risk index limit from 19 to 44. The third tier indicated as orange represents high risk with the risk index limit from 45 to 74. The final tier represents the extreme risk indicated as red with the risk index limit of 75 to 100. The interpretation of each tier is easy and allows the management to make a quick decision in determining the future essentials. The thresholds limit also allows the management to trace easily the changes in the risk profile of asset.

Table 3-2: Asset risk index characterization scale and color code

Asset Risk Index Scale			
Ranking of Risk	**Risk Index Range**	**Risk Class**	**Color Code**
1	75≤Risk Index≤100	Extreme	**Red**
2	45≤Risk Index<75	High	**Orange**
3	20≤Risk Index<45	Medium	**Yellow**
4	0≤Risk Index<20	Low	**Green**

3.2.12 Data Collection

Data collection is essential for validating the proposed asset integrity indicator model. Data will be collected for both of the sections of the developed approach. To determine multilevel indicators' weight in the asset integrity hierarchy, relative importances of indicators' information will be collected. This information will be collected from several experts to standardize the respective weight of indicators. Collecting and analyzing information from several experts' and academician will assist in damping the subjectivity of weight determination. On the other hand, since the developed indicators are not yet employed in any process industry, to check the feasibility of these indicators risk information has to also be collected. This information is also necessary to determine the functionality of a proposed model and to perform the benchmark study. The successfulness of plant specific data collection will ensure the viability and appropriateness of the identified specific indicators. There are several ways to collect the data from various sources, such as interviews, inquiries/survey, discussion, and questionnaires. Among these, considering the nature of the required information/data in this approach, the questionnaire system is selected. "A questionnaire system is easier to administrate and to treat" for achieving desired outcome (IAEA, 2000). So, two sets of questionnaires were developed and are presented in Appendix B based on guidelines provided by IAEA, OECD, and OGP. The first questionnaire is used to collect leading and lagging risk information of assets and will be described in detail in the benchmark study. The second set is particularly developed to collect feedback from experts on different level indicators pair-wise comparison value. The questionnaires were communicated to the respective respondents via emails. In both of the questionnaires' simple examples are demonstrated how to give input easily. This makes the questionnaire set more trustworthy and is expected to have desired feedback from evaluators.

3.2.13 Multilevel Indicator Weight Assessment

The feedback from experts (list of expert in Appendix C) for pair-wise comparison was analyzed thoroughly using the described AHP technique. Estimated standardized weights for three level indicators are presented in Table 3-3. Both academic and process plant personnel were selected in the expert panel to get feedback on the pair-wise comparison quaternaries. The calculated consistency ratio as shown in Table 3-3 does not represent any outliner value that goes beyond the acceptable range. So, the judgements provided by the experts are consistent and reliable for further use in aggregation.

Table 3-3: Standardized weights for multilevel indicator in asset indicator hierarchy

Indicators	Relative Importance (Weights)	Consistency Index (CI) (%)	Consistency Ratio (CR) (%)
Level 1: Key Indicator			
Area: Mechanical Integrity			
Inspection Strategy	0.38	1.20	2.08
Inspection Effectiveness	0.36		
Compliance with Statutory Requirement	0.26		
Preventive Maintenance Performance	0.25	1.42	1.27
Corrective Maintenance Performance	0.16		
Reliability Perspective of SSC	0.24		
Availability of Equipment	0.17		
Compliance with Rules & Regulation	0.19		
Planning & Scheduling	0.30	0.10	0.11
Correspondence with Operational Activity	0.25		
Work Flow Monitoring	0.26		
Procurement & Inventory Management	0.19		
Financial Optimization & Control	0.47	N/A	N/A
Quality of Work Execution	0.53		
Area: Operational Integrity			
Operating Procedure	0.62		
Forced Outages	0.38		
Corrective Work Order Issued	0.34	0.08	0.14
Corrosion & Fatigue Condition	0.37		
Ageing Condition of SSC	0.29		
Plant Design	0.42	0.50	0.87
Modification Effectiveness	0.28		
Modification Risk Assessment	0.29		

Safety System Performance	0.51	N/A	N/A
Safety System Related Backlog	0.49		
Emergency Response System Performance	0.54	N/A	N/A
Emergency Preparedness	0.46		
Area: Personnel Integrity			
Safety Culture	0.54	N/A	N/A
Technical & Interpersonal Training	0.46		
Staff Performance	0.50	N/A	N/A
Assessment of Competence	0.50		
Effectiveness of PTW	0.48	N/A	N/A
Compliance with PTW	0.52		
Reporting Incident	0.35	0.27	0.47
Communication System	0.29		
Management of Change	0.36		
Level 2: Activity Indicator			
Area: Mechanical Integrity			
Inspection	0.31	0.83	0.93
Maintenance	0.24		
Inspection & Maintenance Management	0.23		
Engineering Assessment	0.22		
Area: Operational Integrity			
Operating Performance	0.20	0.54	0.48
State of SSC	0.21		
Plant Configuration & Modification	0.17		
Engineering Safety System	0.22		
Emergency Response Arrangement	0.20		
Area: Personnel Integrity			
Training	0.30	0.40	0.44
Staff Competence	0.24		
Permit to Work (PTW)	0.23		
Communication	0.23		
Level 3: Element Indicator			
Mechanical Integrity	0.40	0.71	1.27
Operational Integrity	0.34		
Personnel Integrity	0.26		

3.2.14 Implementation of Indicators

Maintaining asset integrity is a continuous process throughout the lifespan of the assets in a process facility. This enforces the requirement of implementing the asset integrity indicators in different areas of the process plant. To support the management decision making on integrity related issues, asset integrity indicators should be implemented effectively. Because the function of asset integrity indicators is not limited to measuring asset performance only, it also can be used as a means to manage the asset for maintaining integrity level. It may be questioned with the large number of specific indicators and the practicability of the implementation of these indicators in real life situation. According to the Oxford dictionary, 'integrity' is defined as 'the state of being whole and undivided.' To maintain asset completeness, a single or limited indicator system is not capable to express all the relevant aspects of asset health, environment, and safety issues in designated areas (Vinnem et al., 2006). Again the outcome of any individual indicator may have no significance if treated independently but may become relevant when considered in the context of other indicators' performances (IAEA, 2000). These issues justified the requirement and development of a large number of indicators and requirement of implementation, as well. Most of the indicator related activities are usually followed and practiced throughout the process industries. This has been proved with the information collection strategy of the benchmark study. Even the indicators' areas of concerns or activities are not practiced or followed performance of asset can be estimated. And, to ensure future comprehensive asset performance measurement and subsequent good asset performance requirement, the non practiced indicators can be established. The technique and steps for establishing the asset integrity indicators` system in any process plant is given Figure 3-23. The flow diagram represents the stepwise process for implementing, measuring, and marinating asset risk performance. Concern related to the implementation of this indicator system comprehensively is to locate the exact indicators areas. The hierarchical structure will provide an easy way to locate the areas and to establish specific indicator systems for monitoring the performance of an asset. Sometimes the functionality of leading indicators may be puzzled with lagging indicators' activity. Care should be taken while locating the leading and lagging indicators activities in all of the major areas of assets. The proposed approach is a systematic orientation of risk information collection and storing systems that are analyzed after certain time interval. If the risk performance is within the acceptable limit based on the process plant risk acceptance strategy then measures should be taken to maintain this performance and even should strive for better performance. If not then the most risk vulnerable or contributing areas should be identified and measure have to be taken to improve future performances. Since the performance of each indicator can be mapped with the developed risk index, the major risk significant areas that are contributing to poor asset performance can be figured out. These areas can also be ranked according to the associated risk value and prioritize subsequently that provide an ease to rationale decision making in asset performance improvement task. This means areas should be given more concern that could have greatest influence on the better asset performance. This will also ensure optimum resource utilization, and better asset performance can also be achieved consequently.

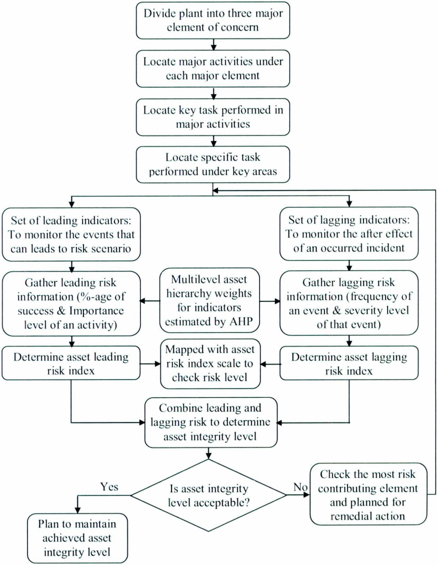

Figure 3-23: Implementation of indicator system for achieving asset integrity (after HSE, 2006)

Chapter 4

4 Benchmark Study

4.1 Introduction

The developed specific leading and lagging indicators under the hierarchical indicator structure are aimed to monitor the risk condition of assets. The risk condition will determine the tangible asset functionality and intangible parameter performance to the desire service level. To do so, first of all the indicators should be established in the specific areas of process facility. The process for implementing the indicators' system for monitoring asset performance has been described in the last chapter. The developed indicators are not yet established to any process facility. Even when the indicators are established, it requires considerable time to observe the activities in different areas and to deliver appropriate data. So, to check the applicability and functionality of developed indicators in different process industries, a benchmark study approach is conducted. The aims of the benchmark study are to validate the developed indicator system, as well as to compare the asset risk performance among different industries. Such comparison can be termed as benchmarking and promoted as a means to better identify opportunities for improvement also (CCPS, 2010). Again, for comparing the asset performance, risk indicated by leading and lagging indicators is considered comparison parameter for the benchmark study.

4.2 Questionnaire Development for Specific Indicators

To carry out the benchmark study the first step is to collect data from process facilities that are associated with various process events. Benchmarking is most used to measure the performance of tangible as well as intangible assets using a specific indicator. In this case, since the specific indicators are not yet established, the study will be performed in a different manner. For the collection of data, the developed specific leading and lagging indicators were transformed into questionnaire format. In developing the questionnaires, effort was made to investigate all aspects of tangible and intangible asset. The proposed methodology adopted a risk-based approach, so the questionnaires should be developed in such a way that the risk information can be achieved. Based on the specific leading indicators, a questionnaire was developed that seeks basic leading risk information from the respondent. The required two factors for leading indicators risk are the percentage of success of an event or activity and the importance level of that success. On the other hand, the specific lagging indicators were used to develop a lagging questionnaire that also seeks two basic lagging risks information. These are the number of incidents occurred for a particular time period and the severity of that event for lagging indicators case. The developed questionnaire for both leading and lagging case are shown in Appendix B. These questionnaires were conveyed to different process plant personnel and the feedback on specific floor level plant information was collected. The lists of the respondents from the process plant are presented in the Appendix D. Importance level in case of leading indicators and severity level in case of lagging indicators are associated with the factors. Equipment failure or lack of required mandatory activities leads to the above mentioned issues and results in either production loss or breach of an environmental standard or injury/death of employee or extra repair cost or could be any combination of these consequences. The detail description of the consequences considered for mapping the importance or severity level in risk estimation is presented in Appendix A.

4.3 Result Analysis

The benchmark study questionnaires were communicated to five process industries with the aim to collect specific risk information. The collected input data from those process plants were analyzed and aggregated following the described aggregation procedure. The leading and lagging risk index values are finally determined by using the multilevel standardized indicator weight from Table 3-3 and results are presented in Table 4-1.

Table 4-1: Asset integrity leading and lagging risk index for participants' process plant

Name of Participant Process Facility	Leading Risk Value	Lagging Risk Value
Dubai Electricity & Water Authority	23	16
Lafarge Surma Cement Ltd	24	15
INTECSEA Canada	20	9
Lloyd's Register Kazakhstan LLP	56	34
QatarGas	19	23

The overall result shows that leading indicators' risk values are always higher than lagging indicators' risk values except in the case of QatarGas. Most of process plants usually practice the lagging indicators and the leading indicators are not established properly. So, it is obvious that the risk represented with the leading indicators will be higher. In case of QatarGas, the outcome of leading indicators are different from others because they are used to use the leading and lagging indicators activities' since process safety performance indicators are practiced over there (Khan et al., 2010). In the benchmark study, the QatarGas leading asset risk index was found as the best in its class among the participants. When risk values of QatarGas are mapped with the risk index, the leading indicator values are on the low risk region and the lagging are in the medium risk region. Mechanical integrity element has the highest risk contribution to both cases of leading and lagging indicator asset integrity index, followed by operational and personnel integrity element.

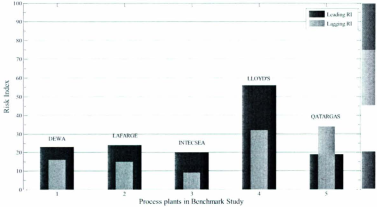

Figure 4-1: Overall asset risk index for process plants in benchmark study

On the other hand, the leading risk performances of Dubai Electricity & Water Authority, Lafarge Surma Cement Ltd, and INTECSEA Canada are on the medium risk category and the lagging indicator performances are on the low risk region. Since the leading performance of these process plants are in the moderate region, the lagging performances are also under adequate control. This also proved the requirement and the functionality of leading indicators for a lagging outcome. This means if the inputs to the system are adequate then the outcome will also be as desired within a tolerable limit. These performances of assets for a particular period are reasonably fair for the time being. To maintain this performance level and to even further lower the risk values, efforts should be given to the outliner indicator areas. The risk contribution for DEWA and Lafarge also show the same order of contribution as QatarGas. The only exception is in case of lagging performance of Lafarge where the risk contribution of personnel element is more than the operational element. For INTECSEA Canada, in leading indicators case personnel integrity has the greatest risk contribution followed by mechanical and operation elements. And, for lagging indicators the mechanical element has the highest contribution followed by personnel and operational element contribution. Among the studied process plant performances, the performance of Lloyd's Register Kazakhstan LLP showed higher risk values in both of the leading and lagging categories. The leading indicators fall in a high risk category and the laggings fall in a medium risk category. This is the result of the poor leading i.e. input to the system performance that also resulted in a higher risk outcome in case of lagging indicators. The risk levels of their assets are higher due to the poor performance of the safety system, planning, and scheduling, as well as plant design and inspection as indicated by the leading indicators. In case of lagging indicators, the poor performance of inspection as well as maintenance, are primarily responsible for higher asset risk index value. So, the assets of Lloyd's Register

Kazakhstan LLP are in the most vulnerable condition among the studied process plant asset performances. Here, in case of leading indicators, the operational element has the highest risk contribution followed by mechanical and personnel elements. For lagging indicator case, the personnel element has the greatest contribution followed by mechanical and operational elements. Again, in this case the lagging asset risk index INTECSEA Canada's performance was found as the best in class among the participants. The variations in the asset performance of different process plants are obvious due to the difference in strategy, functionality, and attitude towards asset integrity. The variations in asset risk index outcome are depicted in Figure 4-1. In most of the cases of the benchmark study, it is observed that the mechanical element has the greatest impact on the asset performance irrespective of leading and lagging indicator risk scheme. So, the benchmark study result also goes with the declared hypothesis that the mechanical integrity has the highest impact on the asset integrity. The identified best in class leading and lagging asset risk index can be considered as a benchmark asset integrity performance for the time being.

4.4 Sensitivity Analysis

Sensitivity analysis intends to illustrate how much model output values are affected by variations in the inputs data/aggregation technique to the model. The mathematical model of this study involves many input variables and uses a weighting system for transferring the input data to the upper level. Since weighting technique to allocate relative importance is controversial due to its subjective nature, and the uses of indicators that involve aggregation of numerous input values may smooth out higher risk values. So, asset integrity measurement systems involving many input variables and weighting technique require sensitivity analysis for model output quality assurance. The sensitivity analysis study is organized to observe the impact of indicators' weights on the overall risk index and to check the varying input data sensitivity to the model output risk index.

4.4.1 Impact of Indicators Weight on Overall Risk Index Value

In this step, the effect of individual indicators' weight and aggregation operator on the overall risk index will be analyzed. Both the AHP technique for indicators' weight determination and the aggregation operators has significant influence for achieving higher level risk index values. Weighting is a subjective issue and to neutralize the subjectivity relative importance questionnaires were conducted to thirteen expert personnel, as described earlier. Although the brainstorming outcome of pair wise comparison neutralizes the subjectivity, it may be argued that these are still subjective judgements. So, the variation of indicators weights were also checked to observed the variability of outcome. To observe the variation in the outcome, the following scenarios presented in Table 4-2 with varying weight were analyzed. Sensitivity analysis was performed based on the scenarios that reflect different observations on the relative importance of the parameters in different level. Sensitivity analysis can be performed from any level in the asset indicator hierarchy; for the time being, third level indicators in the asset hierarchy, i.e. element indicators' weight variation, were analyzed. The data of INTECSEA Canada from the benchmark study were used for indicators' weight sensitivity analyses.

Table 4-2: Sensitivity analysis scenarios with leading and lagging risk index outcome

Sl. No.	Scenarios	Assigned Weight	Leading RI	Lagging RI
1	Equal Importance	MI=.33, OI=.33, PI=.33	20	9
2	Maximizing MI	MI=.75, OI=.15, PI=.10	19	10
3	Minimizing MI	MI=.10, OI=.50, PI=.40	20	8
4	Maximizing OI	MI=.15, OI=.75, PI=.10	18	7
5	Minimizing OI	MI=.50, OI=.10, PI=.40	21	10
6	Maximizing PI	MI=.15, OI=.10, PI=.75	23	10
7	Minimizing PI	MI=.50, OI=.40, PI=.10	19	9

Note: Leading baseline RI=20 and Lagging baseline RI=9.

Figure 4-2 and Figure 4-4 represent the leading and lagging risk index outcome corresponding to varying weights according to the mentioned scenarios in Table 4-2. The variation in the final risk index outcome was compared with the baseline leading and lagging risk index, respectively to observe the variation extent of index value. For the leading indicator case, Figure 4-2 showed that with the different assigned weight scenarios the outcome RI is much closer to the baseline value except in two cases. These two cases arose for the scenarios of minimizing OI and maximizing PI weights. When the different scenarios RI outcome were mapped with the asset risk index scale, these two cases change the outcome classes and move to the upper risk class. Figure 4-3 shows the percent variation of RI compared to the baseline index value for different scenarios. Again, the highest variation was found in the case where the PI was maximized. This wide variation in this case is obvious since the study concentrated on the asset integrity and has given most importance on the personal integrity element. Except this value, the other scenario variations are less than 10 percent, which is reasonably in the allowable variation region.

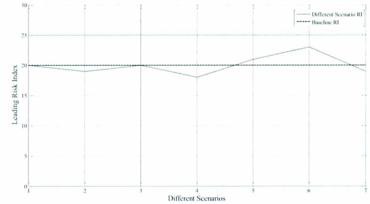

Figure 4-2: Leading risk index variation from baseline risk index value

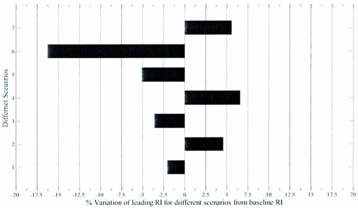

Figure 4-3: Leading indicator sensitivity to parameter weight in the RI outcome

For the lagging indicator case, Figure 4-4 depicts the RI outcome and compares results with the baseline RI. In this case, the variations in outcome compared to leading indicators are widespread. Though the risk class does not change in any of the scenarios, still the variations are extensive within the same risk tier. And, in sensitivity analysis Figure 4-5 showed that the scenario 4 where the OI were maximized provided the highest percentage of variation in outcome while compared with the baseline values. Again, the maximization of MI weight also represents more than 10 percent variation compared to the baseline RI. This could be because of ignoring the influence of OI and PI elements in the asset integrity. Other scenarios also showed allowable variation within 10 percent from the baseline. Analyzing this leading and lagging indicator weight variation it can be concluded that the variations in the outcome are not very significant and are reasonable where variations are significant. So, the subjectivity of the expert judgement diminishes considerably and stability of the estimated weights is achieved. This also ensured the applicability of standardized indicators' weights in different process plant assessments.

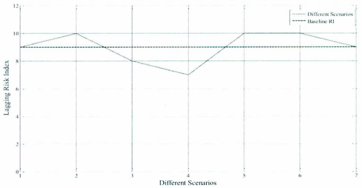

Figure 4-4: Lagging risk index variation from baseline risk index value

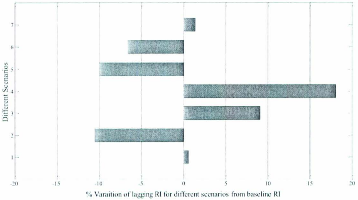

Figure 4-5: Lagging indicator sensitivity to parameter weight in the RI outcome

Whatever the variation in importance or weights, the priority of the mechanical integrity element in asset integrity cannot be overridden by other element. So, with this hypothesis, numerous variations in weights were also checked and compared with the baseline final outcome. The variation of outcome risk index does not shift beyond ±5% of original index value. It is also believed that the same scenario will arise in case of other stages of indicators and for the case of other process plant data too. The arbitrary variation in weight also shows insignificant changes in the final outcome, thus ensuring the viability of standardized weight presented in Table 3-3.

For deriving the next level indicator risk, using aggregation operator still has prominent impact and continues up to the final level of asset integrity. The aggregation operator used here is the weighting average and this operator smoothes out the effect of the highest risk value in each operation until the final outcome. So, the final risk index is a result of smoothed weighting average of basic indicators' risk items. But, this strategy of aggregation does not show eclipsing characteristics. Eclipsing is the phenomenon where high basic risk items are smoothed to a very low risk value. Here, observing all the benchmark study calculations it can be concluded that in most of the cases the input and the outcome risk values have a reasonable variation. One of the reasons is because the weights of all stages' indicators are normalized to a sum of 1.0. These variations are permissible since overall asset performance is estimated instead of individual asset performance. Again, from this model the most risk significant items can easily be determined and action can be taken subsequently for assets' superior future performance.

4.4.2 Model Response to Changing Indicators Inputs

Since the indicators are not yet established in the process facility, the variability of the output corresponding to changing input needs to be analyzed. The benchmark study was conducted by collecting leading and lagging indicator information and analyzed accordingly to get the final risk index. The uncertainty about the collected information is obvious. So, it is imperative to find out how the final risk index derived from the model if the assigned information values were changed to other sets of plausible values. This will also allow assessment of the impact of particular indicators' inputs to the final risk index and to identify the indicators that are the key drivers of outcome results as well. In this case input data variation with a certain percentage shows a linear variation in the outcome. Since fed data to the system are very site specific, the extensive analysis will not be worthwhile. This sensitivity analysis ensured the robustness of the developed model in determining risk-based asset integrity levels.

Chapter 5

5 Additional Work: Risk Based Spare Parts Inventory Management

"For want of a nail the shoe was lost;

for want of a shoe the horse was lost;

and for want of a horse the rider was lost."

Benjamin Franklin (1706-1790)

5.1 Preamble

The implementations and uses of an indicators' system plays a vital role in attaining asset integrity. An indicator system can also assist in managing assets by identifying the vulnerable areas that require improvement to avoid future mishap. For instance, one of them is the managing of spare parts that have been overlooked over the years due to budget constraint. For executing maintenance work effectively, tangible equipment spare parts' availability and adequacy is mandatory. Spare parts unavailability could have the greatest negative impact on plant availability and result in costly downtime of the asset. In process industries, to accomplish the business requirement the availability target is particularly challenging. To meet the availability requirement and to reduce downtime process industries usually maintain large stock of spare parts. So, the non-optimized spare parts stocking reduces the profitability of the overall investment. Even if it optimized due to lack of attention towards the critical equipment, spare requirement and shortage could threat the integrity level of engineering asset. A risk-based approach can be established for the management of spare parts requirement effectively. Risk-based spare parts' management makes sure the adequacy level of spare parts inventory on the basis of equipment criticality without compromising the integrity of the plant's asset. This also allows inventory optimization and effective allocation as well as utilization of limited maintenance resources.

5.2 Introduction

Effective inventory management of spare parts is essential for ensuring asset integrity in a process facility. With the increased mechanization and complexity in process plant, there is a rise in the number of component failure scenarios. Failure of components incurred downtime and unavailability of the plant, which may prolong with the inadequacy of spare parts. Spare parts have great influence on all types of maintenance activities and the availability of process plant. For the case of critical equipment this could lead to severe consequences like excessive downtime costs, idle manpower cost and so on. Modern process plants are required to be available for operation most of the time and unavailability due to spares is not tolerable. Maintenance often depends on the spare parts availability and, thus, the adequacy of spare parts in stock has a direct impact on the operability of the system. It could easily be achieved by storing an adequate quantity of spares in the inventory. However, numbers of issues arises with respect to storing of spare parts. First of all, the quantity of spares to be stored for a particular time period requires a reliable forecasting technique and basis of forecasting. Secondly, among all spare parts which spares should be given priority in storing due to financial constraint. This means to allocate the capital expenditure on spares will be more effective to maintain and maximize plant availability. Thirdly, the optimization of spares parts quantity is based on the consequences of unavailability of the plant. This required an acceptable balance between the available allocated budget for spares and the stock-out consequences. Considering these factors, one may convert the spare parts inventory management into a holistic approach.

Spare parts demand forecasting is one of the most crucial issues for inventory management and also a big challenge in the repair and overhaul industry (Pham, 2006). The vital challenge arises due to the sporadic nature of components' failure and corresponding random demand of spare parts. Spare parts demand forecasting refers to an estimation of the most likely future requirement of spares on components' failure under given conditions. Forecasting of spare parts also has a prominent effect on executing the other issues of spare parts inventory management like procurement and holding policy. Spare parts inventory model differs substantially from regular inventory models since spare parts demands arise with the failure of components. Kennedy et al. (2001) pointed out that inventories of spare parts differ from other manufacturing inventories from functionality as well as from storing strategy point of view.

To resolve the above mentioned issues, numbers of studies have been carried out to investigate the forecasting techniques as well as to resolve other different issues of spare parts inventory management. Among the forecasting model, traditional exponential smoothing is the most popular technique applicable to time series data, where historical demand data are smoothed and extrapolated to formulate forecasts. However, it does not generate required confidence and is usually suitable for short periods of forecasting (Pham, 2006). To overcome the drawback of exponential smoothing, Croston (1972) has proposed a method that predicts the size of the demand peaks and demand intervals separately and also effective intermittent demands. Besides these deterministic approaches, probabilistic approaches are also popular and effective in spare parts forecasting. Nahman et al. (2009) proposed a probabilistic approach where the optimum numbers of spare transformers are forecasted based on the widely used Poisson distribution process in demand prediction, and optimization is performed considering the cost for spares and the outage cost of transformer. Usually, it is considered that component's failure process followed a Poisson process, and historical failure data are used to determine probability of future occurrences for a certain time interval. However, the forecasting of spare requirement using Poisson distribution does not provide reliable estimation and usually ends with overrated estimation. So, there is always a possibility of the spare parts to be remains unused. For probabilistic estimation of spare parts demand forecasting, compounded Poisson and Gamma distribution are also used in different literature (Kumar et al. 1997, Watson 1987, Vereecke et al. 1994, Johnston 1980, Yeh 1997).

For the optimization between different inventory parameters, like spare quantity, availability, cost, and downtime, there are many studies reported in the literature. Adams (2004) has studied different spares parts analysis methods and optimization techniques to determine the best approach that can meet the cost constrained and availability targets. Poisson and Normal distribution techniques were used here to determine the recommended quantity of spares based on demand rates. To effectively control the spare parts inventory, Dekker et al. (1998) proposed a stocking policy where the plant's critical equipment spares are given more attention as well as priority in storing. Yang et al.

(2004) considered criticality of components as an important issue and uses criticality of spares parts to determine the initial adequate quantity of spares to be stored for executing maintenance effectively. Bharadwaj et al. (2008) proposed a risk-based methodology aiming to maximize the availability of a machine by maintaining a certain level of spare parts in the inventory. It utilizes the risk term in the context of probability of failure to meet the spare demand and the corresponding consequences of the failure to meet the demand. But this approach only deals with spare optimization based on the risk without concerning spare forecasting strategy.

The missing point in all of the spare parts inventory management literature is the comprehensive integration and consideration of the above mentioned three issues. Forecasting the demand of spares is the most difficult task; however, the demand of spares and inventory management depends on issues like i) failure rate of the components/parts over a specified period of time, ii) criticality of the components or spare parts and in this case it is the risk associated with unavailability of components, iii) lead time required for procurement of spare parts, iv) financial consideration and optimizations, and, v) ensuring availability of spare parts in storage condition. Hence, a more precise demand forecasting technique is essential for successful and effective inventory management. In present work, a new risk-based inventory management methodology is proposed that adduces the earlier mentioned three issues. The proposed risk-based inventory management methodology comprises of four steps as depicted in Figure 5-1. Each of the steps of the methodology addresses the above described issues. In a subsequent section of the paper, a detailed description of the methodology with application is presented.

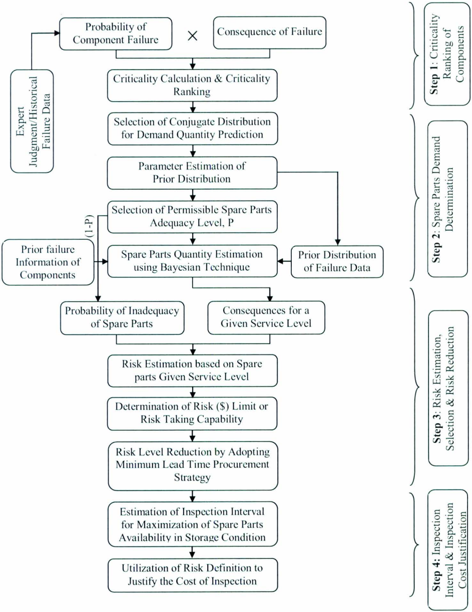

Figure 5-1: Methodology for Risk-based spare parts inventory management

5.3 Criticality ranking of components

The risk-based spare parts inventory management model proposed in this paper is based on the fundamental concept of systematically prioritizing the spare parts corresponding to their criticality. The criticality in this respect is defined with respect to the risk associated with the components of process facility. Critical components are identified based on the failure risk exceeding acceptable risk level and have potential impact on the operational target of the plant.

There are many techniques available to assess risk. The primary factors to calculate risk are the probability of failure and the consequences of failure. There are numerous components in an operating facility that may lead to a number of hazardous events. Therefore, every component is to be evaluated in terms of associated risk. The risk evaluation results are used for criticality ranking. The key purpose of risk assessment is to support management in rational decision making.

Criticality ranking based on components' risk is done by using equation 5-1,

$$\text{Risk (K)} = P_f \times C_f \qquad (5\text{-}1)$$

Where P_f is the probability of component failure and C_f is the failure consequences i.e. cost of a given failure. In the present study, risk is considered in terms of associated economic consequences corresponds to components failure. Scala et al. (2009) pointed out that spare parts inventory-related risk is the revenue loss associated with plant shutdowns or de-rates operations if parts are not available when needed. Components' failure probability information is important in quantification of risks. Historical plant specific data, generic failure data of components, or expert judgment can be used as a basis for determining suitable failure probabilities. Consequences in this context are the financial losses due to the failure of components. The financial loss consequences include several factors, such as loss of production ($), cost of replacement ($), and liability cost ($). The aggregated financial loss associated with the failure of components can be assumed using Equation 5-2.

$$\text{Cost of component failure, } C_f\ (\$) = \sum_{i=1}^{n} C_i \qquad (5\text{-}2)$$

Where C_i is the financial loss due to failure of component'. The financial issue along with the failure probability information assist in quantifying the risk ($) associated with the individual component of the process plant. This way every component has a risk score that will facilitate rationale comparisons between components and decide criticality. Thus, criticality analysis will assist in avoiding plant outage situations and also suggest group of spares to be stored on the priority basis. Based on the estimated risk, the spare parts can be grouped into four categories: high critical, medium high critical, medium critical, and low critical components. This provides an ease in budget allocation for different group of spares.

5.4 Spare Parts Demand Forecasting Technique

Once the spare items to be procured and stored to support maintenance are decided, then the next step is to determine how many spares of each type to be stored. This requires a suitable forecasting technique to specify the future demand of spares. The forecasting of a demand is a complicated task where several issues are involved. The characteristics of spare parts demand is a major issue that determines the technique of forecasting. Ghobber et al. (2002) categorize the spare parts demand patterns into four categories: intermittent, erratic, slow moving, and lumpy demand. Irrespective of the types of demand, forecasting primarily depends on the failure history or failure rate of components. The historical components' data of mean time between failures can provide the failure rate depending on the hazard rate function. The simplest way to forecast the demand explained by Kececioglu (2003) as the expected number of spare parts demand for a finite operating time interval is equal to the expected number of failure; it can be estimated using Equation 5-3.

$$N_F(T_2 - T_1) = \int_{T_1}^{T_2} \lambda(T) dT \tag{5-3}$$

Since the forecasting is based on the failure rate function, $\lambda(T)$, it is not possible to exactly envisage the demand of spare parts. In that case, the concept of spare parts service at a certain confidence level will be more appropriate for forecasting. For forecasting the quantity of spares to be purchased and stored with a desired confidence level, a Poisson distribution can be used. This distribution requires a single parameter that is the mean failure rate and can uphold the randomness of spare demand. Considering the event are exponentially distributed and components fail according to a Poisson process, the probability of 'n' or fewer failures during a time interval of (0, t) can be estimated by Equation 5-4.

$$\text{P}\left(\text{n or fewer failure}\right) = \sum_{i=1}^{n} \frac{(\lambda t)^n}{n!} \exp(-\lambda \text{t}) \tag{5-4}$$

So, based on the desired level of confidence or service level, the quantity of spare parts requirement can be estimated assuming a constant failure rate. Here, the forecasting is solely based on the prior failure information, before demand data has been generated. The forecasted quantity is usually overestimated (assuming constant failure rate) and uncertainty also is not taken into consideration. With the increase of uncertainty the variation in the estimation increases exponentially. To minimize uncertainty, the Bayesian method is most appropriate tool for forecasting and continuous demand updating. The Bayesian approach in demand prediction is suitable for either case of unknown demand with constant or varying demand rate (Popovic, 1987). The utilization of the Bayesian method for demand prediction is not new in inventory management literature. Several studies have illustrated the application of the Bayesian method in demand forecasting that deals with different aspects of inventory management (Silver et al. 1965, Smith et al. 1969, Brown et al.1973, Kamath et al. 2002, Aronis et al. 2004 and Dolgui et al. 2008). Brown et al. (1973) also mentioned that the Bayesian approach can estimate demands at initial provisioning before demand data has been generated, as well as having the capability of progressive updating as data becomes available with time. This is done by incorporating the recent demand information and updating simultaneously.

5.5 The Bayesian Analysis Approach

The Bayesian technique, with respect to spare parts management, combines prior information with actual observed data derived from subsequent events to predict the future demand of spare parts. The Bayesian theorem is used to convert likelihoods into probability. It is considered as one of the best systematic methods for incorporating current demand information and continuous updating of the demand distribution. This is done by revising the prior information about the mean failure rate with the gathered failure information. The uncertainty in failure rate, i.e. demand, is tackled by considering it as a prior probability distribution, which is updated routinely in the form of posterior distribution. Bayes' theorem allows combining the prior demand distribution with a demand process (likelihood function) to estimate a posterior distribution for demand. Considering the failure rate (λ) of components as unknown, a prior assumption is made that failure rates follow a Gamma distribution and, as consequences of failure as a Poisson distribution, the posterior Gamma distribution can be developed. Capability of developing an extensive array of mean and variance's encouraged to employ Gamma distribution as a demand prediction conjugate. The prior Gamma distribution has two parameters; these are α and β, and the posterior Gamma will be with revised parameters α' and β' with generated demand data. These two parameters are positive and real quantities similar to the variable failure rate (λ). The proof of conjugacy between selected prior candidates can be showed as:

$$\text{Posterior} \propto \text{Prior} * \text{Likelihood}$$

$$P(\lambda / k) \propto \left(\frac{\beta^{\alpha}}{\Gamma} \lambda^{\alpha-1} e^{-\beta\lambda} \right) * \left(\lambda^{k} \, e^{-\lambda t} \right)$$

$$\propto \left\{ \lambda^{k+\alpha-1} \, e^{-\lambda(t+\beta)} \right\}$$

The posterior parameters are $\alpha' = k + \alpha$ and $\beta' = t + \beta$, which are same as the Gamma distribution parameter. So, it can be considered as an appropriate pair that can serves spare parts forecasting. The conjugate Gamma-Poisson probability function for 'k' number of demand for spare parts with 'n' operating unit during operating period 't' is given by Equation 5-5 (Brown et al. 1973).

$$p(k/\alpha,\beta)=\int_0^\infty \frac{(n\lambda t)^k e^{-n\lambda t}}{k!}\frac{\beta^\alpha \lambda^{\alpha-1} e^{-\lambda\beta}}{\Gamma(\alpha)}d\lambda \tag{5-5}$$

The Bayesian approach assumes that one has prior information about the demand distribution, which is updated using the observed demand values to obtain the posterior distribution to be employed for forecasting. So, the spare parts quantity requirement will be updated using the Bayesian technique as described earlier and represented by Equations 5-6 and 5-7.

$$p(\lambda/k)=\frac{p(k/\lambda)f(\lambda)}{\int_0^\infty p(x/\lambda)f(\lambda)d\lambda} \tag{5-6}$$

In a more specific form of updating, in case of conjugate Gamma-Poisson, probability distribution is given by Equation 5-7.

$$p(\lambda|\alpha,\beta)=\frac{(n\lambda t)^k e^{-n\lambda t}}{k!}\frac{\beta^\alpha \lambda^{\alpha-1} e^{-\lambda\beta}}{\Gamma(\alpha)} \tag{5-7}$$

After observing 'r' number of failure of components during the most recent operational period of 't' the parameter of prior distribution will be updated as follows:

$$\alpha' = r+\alpha \text{ and } \beta' = \mathrm{t}+\beta \tag{5-8}$$

These revised parameters will be used as an updated parameter for prior distribution and the posterior distribution will be developed accordingly. Again, pursuing the same strategy of desired levels of confidence or service levels as followed in case of Equation 5-4, the required minimum number of spare parts (S) can be determined for a desired level of confidence (P) using the cumulative format of Equation 5-5 as shown in Equation 5-8. From now, it can be considered that this required service level is the reliability level of spare parts adequacy that is capable of meeting the certain levels of demand.

$$\sum_{k=0}^{S-1} \int_0^{\infty} \frac{(n\lambda t)^k e^{-n\lambda t}}{k!} \frac{\beta^{\alpha} \lambda^{\alpha-1} e^{-\lambda\beta}}{\Gamma(\alpha)} d\lambda \geq p \qquad (5\text{-}9)$$

Here, the two prior Gamma distribution parameters (α, β) are unknown and need to be known to estimate the spare parts demand. If the historical information is available for the components then, using the moment method, the two parameters of Gamma distribution can be evaluate by setting scale parameter, $\alpha = \frac{\mu^2}{\sigma^2}$ and shape parameter, $\beta = \frac{\sigma^2}{\mu}$ (Bevilacqua, 2008). Least square method, the moment method, and maximum likelihood approach are also used in many applications for estimating Gamma distribution parameters (Choi et al. 1969, Fisher, 1992, George, 1999). At time when no prior knowledge is available, this situation of prior distribution is known as non-informative prior. This required some subjective estimation and several literatures have attempted to find out these two parameters. Brown et al. (1973) has chosen a wide range of the parameter α, β to illustrate the prior distributions all having the same mean but with increasing variance also has selected the optimum one. Sherbrooke (2004) has estimated the prior mean of the Gamma distribution and relates this with the observed demand estimated the parameters. Using the expert judgement and statistical method, Aronis et al. (2004) proposed a typical approach to estimate the parameters. The parameters of a prior Gamma distribution 'α' , 'β' are estimated by setting mean $\alpha/\beta = \lambda_0$ and, assuming the actual failure rate does not exceed twice of original estimated failure rate, λ_0 i.e. $\lambda \leq 2\lambda_0$. The prior Gamma distribution can be set as follows and the proposed approach will adopt this to determine prior parameters of α, β.

$$\int_0^{2\lambda_0} \frac{\beta^{\alpha} \lambda^{\alpha-1} e^{-\lambda\beta}}{\Gamma(\alpha)} d\lambda = \text{Spare Adequacy Level, } p \tag{5-10}$$

The failure rate is important to predict the prior distribution parameters. Gamma distribution parameters can be estimated for both cases: where the failure rate information is available and also for the case where sufficient failure information is not available. In case of inadequate failure information, the original estimation of failure rate, predicted during the design or product development testing stage, can be used. On the other hand, a rough estimation based on an expert's opinion for mean failure rate or demand can also be used. In either of the options, the estimation can be refined continuously and will be more certain as additional information is used to update the initial estimation of parameter. Using the estimated prior distribution parameter the minimum quantity of spares to be stored can be determined corresponding to desired reliability level of spares service.

5.6 Risk Estimation for Spare Parts Service Reliability

It is not possible to predict and maintain spare parts that can fulfill the spare parts demands in all conditions. This is constrained by the economic factor as well as by the random nature of the components failure. The proposed technique is an appropriate candidate for forecasting demand corresponds to particular service level. As this approach is also based on the strategy of maintaining a certain level of spare parts adequacy levels, the associated risk with the unavailability of spares cannot be overlooked. There is always a probability that the demand could go beyond the expected or maintained service level of spares. This gives birth to the risk related to maintaining a certain level of spares service reliability level. The risk is corresponds to the spare parts adequacy level and can be estimated using Equation 5-11.

$$Risk(\$) = \text{Probability of inadequacy of spares service level (P')} * \text{Consequences of inadequacy } (C_i) \quad (5\text{-}11)$$

Where, the probability of inadequacy of spare parts service level is determined by,

$$P' = (1 - \text{Spare adequacy Level}, P) \quad (5\text{-}12)$$

Consequence of inadequacy of spare parts includes the cost of procurement of spare parts and the cost of downtime of a unit due to the unavailability of spares. With this information for certain service levels and spare parts quantities, the associated risk can be quantified. At the same time, for different service levels, the quantity of spares and the associated risks can also be determined. This will provide an aid to the management to make a decision of which service level should be selected based on risk. It is to be mentioned here that the service level of spare parts may also vary corresponding to their criticality. This simply means that management can select service levels based on the criticality of the components. For high critical components, higher service level should be chosen and for normal components lower service level can be chosen. So this will allow the management to allocate their limited recourses optimally and place emphasis where it will be more effective. Again, to cope up with the varying characteristics of components they can also select a range of service levels that will provide a zone of risk taking capability. Within this range, the plant management can handle the non-availability of spare parts with respect to the downtime cost. This decision, at the same time, will provide the range of spare parts adequacy level, which will provide more flexibility in inventory control.

5.7 Risk Level Reduction and Procurement Policy

Even after deciding the appropriate service level, there is a fair provision to lower the selected risk level. The risk level can be lowered by changing the procurement policy of spare parts. Instead of purchasing the entire forecasted spares corresponding to service levels it is worthfull to purchase the spare parts in accordance with the minimum lead time for replenishment of spares. With the minimum lead time procurement strategy, the quantity of procured spare parts will be less and the risk will also be less, accordingly. The same technique as described earlier will be used to determine the forecasted quantity of spare parts and risk level with selected service level, and only the period of forecasting will be changed. This period of forecasting will be based on the minimum lead time for manufacturing and supplying the spare parts to the place of use. The overall risk for entire spare parts procurement will be distributed among the several slots of procurement decided by minimum lead time. Lowering the risk level will also develop the concept of maintaining a constant risk level throughout the operating cycle. The spare parts shortage and abundance will be adjusted in the upcoming cycle, and this will assist in maintaining an almost constant risk level throughout the procurement cycle or plant life cycle. Therefore, the risk level can be minimized and maintained by adapting the minimum lead time procurement policy. The mathematical evidence of this strategy is provided in the illustrative example for better understanding.

5.8 Inspection Interval

It is usually assumed that components in operational condition may fail; and, the spare components in the inventory or storage condition are always ready to fit in, onward failures. This assumption could seriously impact the inventory management system. The spare parts failure incident while they are in storage condition has been taken into account in the present work. Failure of spare parts in storage condition can result from either latent manufacturing defect or improper storing. Realizing this, the availability of spare parts can be maintained by performing inspection at a certain optimum interval to maximize the level of availability of components. Assuming that the failed components will be repaired perfectly to as good as new condition, the steady state availability of the components is given by Equation 5-13 (Ebeling, 2009).

$$A(T) = \frac{\int_0^T R(t)dt}{T + t_1 + t_2[1 - R(T)]} \tag{5-13}$$

Where R (T) is the reliability of the dormant failure i.e. failure in storage condition distribution, t_1 is inspection time, t_2 is repair time and T is time between inspections. So, the inspection interval, T, can be estimated from Equation 5-13 for an optimum level of availability of spare parts in storage condition.

5.9 Cost Consideration for Inspection

To maintain the availability of spares in storage, condition by routine inspection will incur extra inspection cost. On the other hand, if the availability of spares in storage condition is not maintained then, at the time of spares requirement, inventory could be out of available workable spares. The maintenance and inventory personnel in believe that the adequate quantity of spare parts available for maintenance intervention could be in trouble. At that time, for the spares parts outage, several adverse consequences may take place. Here also, risk based strategy is followed to justify the extra cost associated with inspection personnel. It is obvious that the probability of failure of spare parts in storage condition will be higher compared to the probability of failure with inspection at storage condition. In both of the cases, the consequences, like emergency spare procurement cost, idle maintenance personnel cost, and downtime cost, are similar. The spares failure at storage condition or shortage of spare parts could have a significant impact on the production performance. So, to avoid downtime, immediate action is necessary for the procurement of the spares. This immediate procurement of spares will cost more than regular procurement costs. At the same time, the assigned manpower for the maintenance job will also be idle which will also incur cost. The higher probability of unavailability of spares with defined consequences will give higher risk value. On the other hand, inspection on routine intervals will reduce the probability of unavailability of spares value`s as low as possible. So the higher risk value will incur higher loss of production. Equation 5-14 is utilized to justify the inspection requirement of spare parts at storage condition. If the risk ($) associated with the application of inspection strategy is less or equal to the risk ($) associated with the strategy of adopting inspection then the implementation of inspection strategy is economically justified.

$$\text{Risk cost without inspection scenario } (R_{NI}) \leq \text{Risk cost with inspection scenario } (R_{WI}) \tag{5-14}$$

In simple words, the cost of the inspection is justified in case of higher penalty cost associated with the unavailability of spares. The scenario is further explained in the illustrative example.

5.10 Illustrative Example

A typical process plant is an oil refinery that consists of numerous equipment of diverse type. It involves several distillation stages along with other processing steps and utilities systems to convert crude oil into useful petroleum products. The entire sub units are required to function for complete operation of the plant. It runs around the clock 365 days a year and the degradation of components occurs more rapidly. Again, corrosion occurs in various forms in the refinery and is considered as one of the major causes of frequent component failures. The type, number, degradation rate, corrosion rate and failure rate of the components varied widely in this type of process plant. Due to the diverse nature of the spare parts demand, it is encourage checking the functionality of the proposed methodology for the case of refinery spare parts inventory management.

Step one: *Criticality Ranking of Components*

The risk-based inventory management strategy is illustrated considering pumps as the most critical component, through criticality analysis components are ranked based on associated risk. The pump is identified to be the most critical component in the process facility.

The following data are considered for the illustrative example:

Number of Pump in the process plant, n: 449; Observed Failure rate, λ: $2.052\text{x}10^{-5}$/hr =79.65 failure per year; Operating time, t: 1 Year; Original Estimate of failure rate, λ_0: 3.076 $\text{x}10^{-5}$/hr =121 failure per year (OREDA, 2002); Minimum lead time required to replenish the inventory, $t_{l=}$ 3 month (Based on manufacturer recommendation); Spares collection cost ($)/unit, C_1= $ 500.00; Downtime cost ($), C_2=$ 50,000.00 (in the case of spare parts unavailability); minimum spare replenishment period of = 3 months (0.25 Year); Failure rate of pump while in storage condition, λ= 0.0001026/hour; Inspection time, t_1= 32 hours; Repair time, t_2= 40 hours (OREDA, 2002).

Step two: *Spare Parts Demand Determination*

For different spare parts adequacy level, the required quantity of spares is calculated using Equation 5-9, and prior initial values of parameters (α, β) are determined using Equation 5-10. After observing 79.65 numbers of failures of components during the operation period of one year, the parameters of prior distribution are updated utilizing Equation 5-8. The result presented in Table 5-1 showed the forecasted spare quantity for one year and the updated demand quantity with the varying level of spare adequacy level. The updated demand quantities of spares are much closer to the observed number of failure. It is observed that with the increase of spare parts adequacy level the forecasted quantity also increases. But, with the higher level of spare adequacy, the gap between the forecasted quantity and the exact observed number of demand also increases. Although the difference will be reduced with the further updating of parameters, suitable adequacy level still have to be selected considering associated risk and minimum spare gap issues.

Step three: *Risk Estimation, Risk Level Selection & Risk Reduction*

Risk Estimation, Risk Level Selection

Risk associated with the different levels of spare parts adequacy levels is calculated using Equation 5-11 and the results are presented in Table 5-2. The results shown confirm the earlier observation that increases of spares service level i.e. with the increasing number of spare parts requirement the associated risk level decreases. Figure 5-2 depicts the risk variation associated with the inadequacy of spare parts service level. The risk ($) linearly increases with the higher spare inadequacy level. Though the risk ($) is low with the higher spare adequacy level, it requires more investment, as well. At the same time, it could also increase the gap between actual demand and forecasted quantity. This results in more numbers of unused spares in the inventory and also increases the holding cost. From Figure 5-2, plant management can decide the zone of risk taking capability based on financial resources, within which range the plant can handle the non-availability of spare parts with respect to the downtime risk ($). This decision provides the range of spare parts adequacy level, which will provide more flexibility in inventory control assuming the plant has the capability of taking a risk ($) in between $ 4,000.00 to $8,000.00 and the corresponding spare parts adequacy level lies in between 92 to 96 percent. So, the risk level will be maintained within the selected region for the forecasted operating period.

Table 5-1: Parameter of prior distribution and spares quantity corresponds to service level

Item Name	Spare Adequacy Level, p	Parameter, α	Parameter, β	Spare Parts Quantity, S	Updated Parameter, α'= α+r	Updated Scale Parameter, β'= β+t	Updated Spare Quantity, S'
Pump	0.85	2	0.0165	205	81.65	1.0165	93
	0.87	3	0.0248	200	82.65	1.0248	95
	0.89	3	0.0248	210	82.65	1.0248	96
	0.91	3	0.0248	222	82.65	1.0248	98
	0.93	4	0.0331	220	83.65	1.0331	100
	0.95	5	0.0431	214	84.65	1.0431	103
	0.97	6	0.0496	232	85.65	1.0496	107
	0.99	8	0.0661	246	87.65	1.0661	114

Table 5-2: Risk determination based on the spare parts adequacy level for one year

Probability of adequacy of Spares, p	Quantity of spares, S	Spares collection cost($)/unit,C1	Total cost of spares, C3=S* C1	Probability of inadequacy of spares POIS= (1-p)	Cost of downtime ($), C2	Consequence of inadequacy ($), C=C2+C3	Risk, R($)=POIS* C
0.85	93	500	46500	0.15	50000	96500	14475
0.87	95	500	47500	0.13	50000	97500	12675
0.89	96	500	48000	0.11	50000	98000	10780
0.91	98	500	49000	0.09	50000	99000	8910
0.93	100	500	50000	0.07	50000	100000	7000
0.95	103	500	51500	0.05	50000	101500	5075
0.97	107	500	53500	0.03	50000	103500	3105
0.99	114	500	57000	0.01	50000	107000	1070

Table 5-3: Initial spare parts requirement quantity determination

Item Name	Spare Adequacy Level, p	Parameter, α	Parameter, β	Spare Parts Quantity, S	Updated Parameter, $\alpha' = \alpha + r$	Updated Scale Parameter, $\beta' = \beta + t$	Updated Spare Quantity, S'
Pump	0.94	4	0.0331	58	24	0.2831	32

Table 5-4: Risk Determination following minimum replenishment time interval

Probability of adequacy of Spares, p	Quantity of spares, S	Spares collection cost($)/unit,C1	Total cost of spares, C3=S* C1	Probability of inadequacy of spares POIS=(1-p)	Cost of downtime ($), C2	Consequence of inadequacy ($), C=C2+C3	Risk, R($)= POIS*C
0.94	32	500	16,000	0.06	50,000	66,000	3,960

Table 5-5: Spare parts quantity & risk level corresponds to spare supply lead time

Desired service level of spare parts	Spare parts at hand in last interval	Spare parts consumed in this interval	Spare parts in hand	Spare parts to be procured in the next interval (Predicted)	Exact quantity of spares procured	Corresponding Risk ($)
0.94	32	28	4	34	30	3,900
	34	36	-2	38	40	4,200
	38	37	3	38	35	4,050
	38	35	3	39	36	4,080

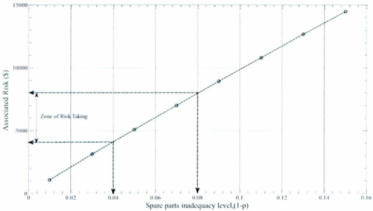

Figure 5-2: Risk level corresponds to spare parts service inadequacy level

Risk Level Reduction and Procurement Policy

Now, instead of purchasing all the spares corresponding to the selected range service level, it is advised to purchase the spare parts in accordance with the minimum lead time for replenishment spares. In this way, the risk level is minimized and maintained at that level for the subsequent cycle. Using the same procedure as followed for spares quantity determination described above, the minimum spare replenishment period of 3 months (0.25 Year) for the initial spare parts requirement is calculated and presented in Table 5-3. Considering the observed number of failures, r= 20, during the replenishment period, t_{rp}=0.25 years the forecasted spare quantity and risk is presented in Table 5-4. The risk value shown in Table 5-4 corresponds to a selected service level of 94 percent. The result showed that the risk level is reduced significantly to a lower value, while the purchasing policy of spare parts has been on the basis of minimum replenishment lead time. So, for the first interval, 32 numbers of spares are procured that will ensure 94 percent of service levels with the risk value of only $3,960. Now, the target is to maintain this risk level throughout the plant's operating life.

Now, if the observed number of failure of components in the next time interval turns out to be 28 then using this number of failure the requirement of spares for the next cycle is predicted. This time the prediction showed that a total of 34 spare parts will be required to maintain the desired service level. But, at this point 4 numbers of spares are on hand that were not used. So, the exact number of spares for the upcoming cycle will be 30, but the ultimate service level will remain constant. The risk levels with this policy for consecutive cycle are calculated using same procedure as described earlier, and result are presented in Table 5-5. The result showed that forecasted quantity is determined by ensuring the desired service level constant. But, the procurement quantity of spares is adjusted based on the earlier cycle scenario of shortage or excess of spares. Accordingly, the risk is calculated for the consecutive procurement cycle. As the service level is maintained constant and the actual procured quantity is adjusted, the risk level in the different cycles remains almost the same as the initial cycle risk. Again, the forecasted quantity for a one year period is 103 spares with adequacy level of 0.95. And, with this lead time procurement policy, the procured quantity is a total of 105 with the adequacy level of 0.94. This policy represents a very small variation in requirement and is considered to be justifiable with the significant decrease in risk level.

Figure 3 shows the exact quantity procured and on hand spare parts quantities at different intervals. The interval is set depending on the minimum replenishment time. The variation in demand, uses, and the procurement allows the risk level to be within the marginal tolerances.

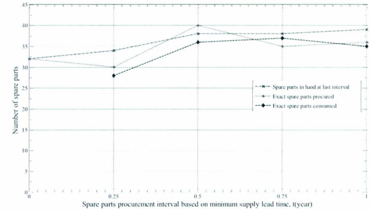

Figure 5-3: Spare parts quantity with minimum lead time interval procurement strategy

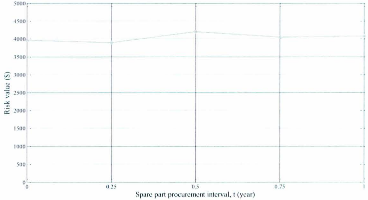

Figure 5-4: Risk level variation throughout the observation period

Figure 5-4 shows the variation of risk levels corresponding to the spares procurement and uses strategy. From the plot`, it is clear that the variation of risk level is not significant and is instead within the tolerable limits and can be considered constant risk throughout the cycle. This ensured the stability in spare parts forecasting and corresponding risk too.

Step four: Inspection Interval

Step four: *Inspection Interval& Inspection cost Justification*

Inspection Interval

Considering the exponential failure tendency while the spares are in inventory Equation 5-13 can be written as:

$$A(t) = \frac{1 - e^{-\lambda T}}{\lambda[T + t_1 + t_2\{1 - e^{-\lambda T}\}]} \qquad (5\text{-}15)$$

Using Equation 5-15, optimum level of spare parts availability at storage condition can be determined and presented in Figure 5-5.

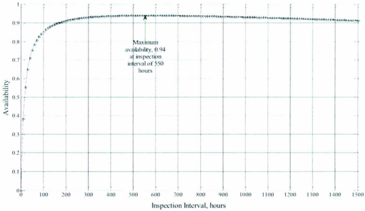

Figure 5-5: Optimum inspection interval that maximizes the availability of spares parts

The optimum inspection interval corresponds to maximum availability of 0.94 at 550 hours. The availability showed increasing trends until it reached the inspection interval of 550 hours. After this time interval, the availability of spare parts in inventory condition followed downward trend. So, inspection has to be performed following this time interval to ensure the availability of spares in storage condition.

Inspection Cost Justification

Risk associated with both of the strategies should be analyzed, and inspection strategy is to be justified by the cost of the inspection personnel. Since the availability of the spares with inspection is 0.94, the probability of unavailability of spare parts with this strategy is P'_{WI}=0.06. On the other hand, the probability of unavailability of spare parts in storage condition without inspection strategy will be more and is considered as P'_{NI}=0.15. The consequences in this case are downtime cost ($), C_2=$ 50,000.00; emergency spare parts procurement cost, C_E = $ 750/unit; and idle manpower cost, C_M = $ 1,000, for both of the scenarios. The cost for the inspection including the man-hour cost is C_I = $ 60,000/year.

$$\text{Risk cost associated without inspection scenario}, R_{NI} = \text{Probability of unavailabilty of spare parts} * \text{Consequences of unavailability}$$

Consequences of unavailability of spare parts= C_2+ C_E+ C_M

So, the risk cost without inspection is R_{NI}=$ 7,765.00

$$\text{Risk cost with inspection scenario}, R_{WI} = \text{Probability of unavailabilty of spare parts} * \text{Consequences of unavailability}$$

Consequences of unavailability of spare parts= C_2+ C_E+ C_M+ C_I

So, the risk cost with inspection is R_{NI}=$ 6,705.00

So, the calculated risk satisfies the Equation 5-14, and the risk without inspection is more comparable to risk with inspection. The inspection cost is justified with the higher risk associated without utilizing inspection in storage condition. Therefore, from this example, it is evident that it is profitable to perform routine inspection of spare components in storage condition.

5.11 Conclusion

The current attempt is a risk-based spare parts inventory management in consideration with the objective of maintaining the equipment of a process plant in optimum operating conditions. Upon failure of components in the process facility, spare parts are required to support the maintenance activity. The inventory is to be maintained adequately and effectively. This requires a dynamic technique for forecasting demands along with updating capability to cope up with the diverse nature of components. The appropriate candidate used in this paper is the Bayesian method that predicts the demands in conjunction with the associated risk. The risk concept also permits developing balance between the costs of downtime of equipment or service to the cost of stocking spares parts. Risk associated with components also used to classify the components instead of using traditional Pareto rules of 80/20 in the criticality analysis. Besides accurate forecasting, the proposed methodology also attempted to lower the risk level. For lowering the risk level, this paper explored the functionality procurement policy and executed spare procurement based on the minimum lead time of supply. The result presented in the illustrative study shows the direct impact of this policy that drastically reduces the risk level from a higher risk. The total forecasted spares quantity following lead time interval strategy is also almost the same as the quantity as forecasted for an entire period. Both scenarios are analyzed mathematically for better illustration and to make comparisons between strategies outcome`s. This also makes sure that, without increasing the number of spares the risk level is reduced only by changing the procurement policy. The introduction of spare inspection strategy also strengthens the proposed methodology by ensuring the maximum availability of the spares in storage condition. The cost for the inspection is also justified, and its requirement for better inventory management is established. The presented illustrative example shows the potentiality and the applicability of this approach in a capital sensitive process plant.

Chapter 6

6 Summary, Conclusion and Future Research Suggestions

6.1 Summary

The underlying causes for recent process industry accidents identified by several investigations were reported as due to the lack of asset integrity. Considering, assessing, and maintaining the occupational safety performance only is not adequate now-a-days. Asset integrity should also be achieved, assessed, and maintained along with those traditional performance measurement systems. Asset integrity is a versatile area, and it is very difficult to measure asset performance and maintain subsequently. In most of the cases where indicators are used for performance measurement, they seem to be developed in the absence of underlying rationale. This implies the lack of rationale linking the strategic goals and measured or observed parameters.

To overcome the hurdle risk based the asset integrity indicator system is proposed with the methodology for identifying multilevel indicators for monitoring asset performance and for assessing asset performance level risk-based performance quantification strategy is also illustrated. For establishing an indicator system, a hierarchical framework is developed that is capable of integrating the top level strategy with functional activity. The hierarchical structure also acts as supporting models or frameworks and assists in identifying four level indicators: element indicators, activity indicators, key indicators, and, finally, specific indicators. The selection of element indicators: mechanical integrity, operational integrity, and personnel integrity in the specified areas of coverage is asset integrity issue. Instead of considering the overall asset's life cycle, the functional period of process plant assets are taken into account. The central purpose is to assist in identifying sets of functional leading and lagging indicators in the specific indicator level that provides risk information. The risk information is used as fed data for the evaluation of risk based asset integrity performance. To convey the risk information to the apex of the asset hierarchy through a multilevel indicator system, the analytical hierarchy process technique is used. Based on the importance level of one indicator over other, i.e. by pair-wise comparison, the weights of different indicators are determined. To neutralize the subjectivity of pair-wise comparison and weight allocation, comparisons of data were collected from numerous experts. The comparison data from the experts' were geometrically averaged to determine the final comparison value that leads to weights of indicators. At the same time, consistency in the experts' judgements was also checked to determine the applicability of assigned indicators' weights. In this way, standardized indicator weights are developed for diverse process plant asset performance measurement application. So, the important indicators' data are given more priority while transferring the risk information to the next level by taking weighted average. A universal four stage risk index scale is also developed to map both leading and lagging indicator values and to locate the risk class accordingly.

The multilevel indicators are developed meticulously, considering every possible risk scenarios. But, the indicators are not yet established in a process plant to observe asset performance and to collect risk information. Even when indicators are implemented, it requires considerable observation periods in order to gain valid results. So, to visualize the proposed model outcome and to validate the methodology, a benchmark study is conducted. To carry out the benchmark study, the leading and lagging indicators were converted to sets of questionnaires to collect the risk information. The questionnaires were conveyed to five different process plants seeking leading and lagging risk information. This risk information was aggregated separately, and, final leading and lagging risk indexes were determined for each participant process plant. These risk indexes were mapped with the risk index scale to determine the performance level of assets.

Finally, a sensitivity analysis was also performed to check the variability of the outcome risk index with the variation in the weight of indicators. The variations in the outcome are reasonably satisfactory and considered to be feasible for any process plant risk based performance determination.

These risk-based indicators can be employed to illustrate the current status of plant assets and also to identify future needed tasks for maintaining plant integrity. The hierarchical structure is developed in such a way so that, at the end with risk information, it will turn out to be a risk based index tool of asset performance. And, the benchmark study also proved the applicability and functionality of the risk based asset integrity system for performance measurement.

6.2 Conclusion

The fate of an asset integrity indicator system depends mostly on the identification of a handful indicators and rationale linking between multilevel indicators. Accident investigation reports and several process plant accident analyses were studied extensively to determine the areas and activities that are mostly responsible for incident occurrences. These analyses assist in developing appropriate and generic hierarchical indicator structure that correlate the overall goal with functional activities. The developed hierarchical structure provides a strong base for integrating and identifying a comprehensive set of indicators. In the specific level, the utilization of both leading and lagging indicators also makes the risk based asset integrity approach more robust. For the aggregation of risk information, appropriate techniques were used and sensitivity was also analyzed to check the variability. The standardized set of indicator weights were also developed by taking indicators pair-wise comparison feedback from experts. A benchmark study has been presented, in order to have an idea of real life applicability of risk based asset integrity indicator methodology. The feedback of the study determined that the developed indicators are practicable and appropriate for assessing asset integrity. It is to be mentioned that these indicators are selected in such a way that all the risk enhancing scenarios are involved. Again, the indicators should not be static and have to be updated continuously depending on the present situation to avoid any kind of accident scenarios. Eventually, this handful of indicators and risk based asset integrity indicator methodology will decrease the operating and maintenance cost of a process facility irrespective of the aging effect. So, the idea of higher operating and maintenance cost for an aging facility can be proved as wrong, and it could even decreases with time. The thinking process should be changed in a way that the outcome of maintaining asset integrity is the reliability that results in more productivity. Thus, the asset integrity is achieved through the appropriate application of an indicator system and keeping all records for all of these activities so that performance can be measured and quantified.

6.3 Future Research Suggestions

A number of future research possibilities to support continuous improvements in a risk based asset integrity indicator system follow from the findings presented in this thesis:

- Development of a more comprehensive, generic, and user friendly indicator development framework having adequate rationale linking between different stages of indicators.
- Risk based indicator selection strategy development for identification of most important parameters that have the most impact on asset integrity.
- Development of more adequate aggregation techniques and the selection of most appropriate aggregation operators so that basic risk fed data exaggeration or eclipsing tendency can be avoided.
- Overcome the inadequacy in dealing with inherent uncertainty and subjectivity of AHP pair-wise comparison fuzzy pair-wise comparison can be utilized for standardized indicators' weight determination.
- Asset integrity trend analysis strategy development.

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Appendixes

Appendix A : Consequence Class Rating

Consequence Class	Health & Safety	Production Loss	Environment Damage	Repair Cost	Reputation loss
0 (Negligible)	No health impact/injury	No loss of Production	No effect	No damage	No impact
1(Slight)	Slight injury, First aid, Slight medical Treatment	Slight loss of production	Slight effect with the fence & very quick remediation	Slight damage	Within Plant Confines
2(Marginal)	Health effect/injury causes lost time & hospital attention	Minor damage and potential downtime causes minor loss of production	Minor effect within the fence & short term remediation	Minor damage	Surrounding Areas of Plant
3(Critical)	Significant health effect/injury causes irreversible damage	Local damage leads to downtime causes more production loss	Localized significant effect also crosses the fence with medium range remediation	Significant damage	Local Territory of the plant
4(Severe)	Permanent total disability or single fatality	Major damage causes several days downtime leads major loss of production	Serious offsite impact , long term impact with extended period for remediation	Major Damage	National impact
5(Catastrophic)	Multiple fatalities	Extensive damage causes shutdown of whole production facility	Massive impact with long term effect and very long time for remediation	Extensive damage	International impact

Appendix B: Questionnaires for data collection and pair-wise comparison

Questionnaire for Asset Integrity Indicators

Basic idea about model:

The following section which is part of ongoing research on "Risk based asset integrity indicators", is intended to validate and to determine the accuracy of the developed model. A hierarchical framework is followed to develop indicators for ensuring asset integrity in a process facility. This hierarchical structure eventually becomes an integrity monitoring system. Asset integrity mainly arises from technical issues like maintenance, inspection and engineering assessments, which are grouped as mechanical integrity followed by operational integrity and personnel integrity. These three are considered the main elements to ensure asset integrity. The on site view of asset health helps to predict, detect and correct conditions that can lead to equipment failure or process upset, before they result in an unplanned downtime. Functional indicators are developed called 'leading' and 'lagging', using criteria such as: relevancy, selectivity, availability of data, changes over time, statistical quality and scope of coverage etc. Data corresponding to related risk information will be collected using the following developed questionnaires along with the relative importance of different level indicators. Then, using the bottom-up strategy, the indicator risk information will be converted and will be mapped with the risk index. Risk based indexing of asset indicators is used as an asset information tool. This asset information tool monitors the asset performance and alerts the plant personnel if parameters exceed certain levels or follow an undesired trend.

Questionnaire:

There are two sets of questionnaires developed for this research program. The first questionnaire is specially developed to get feedback on the specific indicators from the personnel directly involved in the functional area. The second questionnaire is developed to collect information related to the relative importance of element indicators, activity indicators and key indicators in the hierarchy of an asset integrity tree. This is done to integrate specific indicators to an overall asset integrity indicator.

Set 1 Questionnaire:

The following questionnaires is developed for activities and actions performed in the plant area as well as for plant equipment. This set of questionnaires is divided into two sections. The first section deals with the issues related to the proactive or leading information and the second section deals with reactive or lagging information. In both sets two types of information are asked, about the likelihood of success & importance level of success for the leading indicator, and the likelihood of occurrence & consequence of an event for the lagging indicator.

Questionnaire related to Leading Indicators

Instructions:

If the answer to the following questions in the second column is 'no', then place '0' in the corresponding third column, and if 'yes', in your judgement, depending on the extent of use, comprehensiveness, coverage, availability, effectiveness etc. give a value between '1-100'. At the same time, for each of the following questions, based on the importance of subject matter's success in the process facility provide a value between '0-100' in the fourth column. In some cases the questions are formatted in such a way so that the answer could be either 'yes' or 'no', with nothing in between. Then you are requested to give '0' for each 'no' answer and '100' for each 'yes' answer.

For example, if it is asked, "does the young driver obey the signs while he drives the car?"

- If the answer is 'no' place '0'. If the answer is 'yes', according to the judgement, as he is a young driver and usually obeys the road signs 80% of the time, the score here is '80' (indicated in boldface) and have to place '80' in the third column of the matrix.
- If obeying only road signs while driving is considered as an important issue that helps to avoid an accident scenario, then on a scale of 0-100%, '75' (indicated in boldface) importance level can be given for this event's success in the fourth column of the matrix.

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Does the young driver obey the road signs while he drives the car?	80	75

Fill in the arrow indicated spaces by putting a value in the scale of 0-100

Area: Mechanical Integrity

Group: Inspection

Measure: Inspection Strategy

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any standard inspection strategy or recommended practices followed?		
2	Is a written scheme & guideline available for periodic inspection & test?		
3	Comprehensiveness of inspection for safety critical equipment & safety system.		
4	Are inspections performed by 3^{rd} party specialized inspection team?		

Measure: Inspection Effectiveness

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Are overall inspection procedure, interval & checklist followed?		
2	Are appropriate inspection tools & logistic support available for inspection?		
3	Is any strategy followed for the pending inspection related jobs?		
4	Percentage of inspection task completed on schedule.		
5	Safety critical equipment inspected & tested on schedule.		
6	Percentages of different local gauges/ regulators/ indicators calibrated and found consistent.		
7	Is any asset inspection database maintained that covers the equipment to be inspected along with assets' condition information and their inspection history?		

Measure: Compliance to Statutory Requirement

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is systematic appraisal available to determine the inspection compliance with applicable standards & legislation?		
2	Is inspection performed by qualified & certified personnel?		
3	Are Inspection data & information documented for future use?		

Group: Maintenance

Measure: Preventive Maintenance Performance

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any method and technique used to establish preventive maintenance program?		
2	Percentage of preventive maintenance work compliance with instructions & work request guideline.		
3	Percentage of preventive maintenance work order completion.		
4	Percentage of preventive maintenance work order completion on schedule.		
5	Percentage of preventatively maintained equipment found in good condition on testing after maintenance.		

Measure: Corrective Maintenance Performance

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Percentage of corrective maintenance work compliance with instructions & work request.		
2	Corrective maintenance work order completed successfully beyond the coverage area of inspection & preventive maintenance.		
3	Corrective maintenance work order completed within allocated time.		
4	Percentage of maintained equipment found in good condition on testing after corrective maintenance.		

Measure: Reliability Perspective of SSC

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any strategy followed for corrective work order completion of highly critical equipment of plant?		
2	Compliance of inspection & preventive maintenance for system, structure & components.		
3	Are there quantified target reliability sets for system, structure & components performance assurance?		
4	Percentage of maintenance work for safety critical equipment completed in allocated time.		
5	Percentage of equipment having either active or standby redundancy.		

Measure: Availability of Equipment

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Equipment having provision for maintainability.		
2	Logistic support level for carrying out maintenance.		
3	Percentage of equipment with prior knowledge of mean time to failure & mean time to repair.		
4	Emergency or unplanned repair work order completed successfully.		

Measure: Compliance with Rules & Regulations

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any safety practice followed during maintenance work execution?		
2	Are any written maintenance rules & guidelines available?		
3	IS documentation of risk significant events performed?		

Group: Inspection & Maintenance Management

Measure: Planning & Scheduling

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Percentage of work (maintenance & inspection) executed through planning & scheduling?		
2	Is any strategy followed for contingency work planning & scheduling?		
3	Quality level and responsiveness strategy of the planning & scheduling activity.		
4	Percentage of work completed within the allocated time.		
5	Percentage of planned activities (maintenance & inspection) completed on schedule.		
6	Percentage of work order for which execution is not delayed due to logistics and manpower support.		
7	Is preventive maintenance history used to correct future preventive maintenance scheduling?		
8	Is any written procedure developed for carrying out inspection & tests, critical repairs and preparation for maintenance?		

Measure: Correspondence with Operational Activity

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any correspondence maintained with the operational department during inspection and maintenance of equipment?		
2	Emergency work order response system performance level.		
3	Assistance & cooperation level of operational department with maintenance team during work execution.		

Measure: Work Flow Monitoring

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any strategy followed for monitoring the work execution process as well as progress?		
2	Is work order turnover rate monitoring system in place?		
3	Manpower and logistics support effectiveness in work execution.		
4	Is wrench time (staff physical effort to a tool, equipment or material to accomplish assigned work) taken into consideration in determining the maintenance performance of staff during work execution?		

Measure: Procurement & Inventory Management

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any methodology followed for maintaining spare parts inventory management?		
2	Adequacy level of spare parts to support PM, CM and emergency maintenance.		
3	Effectiveness of emergency spare parts procurement policy.		
4	Is any strategy followed to maintain the availability of spares in storage condition?		

Group: Engineering Assessment

Measure: Financial Optimization & Control

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is comparison carried out between repairs to replacement cost during maintenance decision?		

2	Is any optimization technique followed to maintain inventory, allocate manpower & distribution of time to perform the work?		
3	Effectiveness of statistical financial optimization technique.		

Measure: Quality of Work Execution

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any computerized maintenance & inspection management system available?		
2	Percentage of internal manpower & facilities usage for different types of work execution.		
3	Is gathered experience used to improve the PM & CM work?		

Area: Operational Integrity

Group: Operating Performance

Measure: Operating Procedure

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Does the operating manual have a clear structure and organization?		
2	Are standard operating procedures reviewed and updated, or staff hours spent in updating procedures?		
3	Are operating procedures revalidated per schedule/plan/period?		
4	Percentage of equipment operated by the written operating procedure.		
5	Are written operating procedures followed during all operation related activities and situations?		
6	Is any trouble shooting procedure available to handle upset situation?		
7	Are readiness reviews performed before start-up of plant?		
8	Percentage of equipment with completed task analysis to indentify the requirements in operational procedures.		
9	Are the operators often in the field to visually inspection the condition of the offline assets?		
10	Percentage of equipment without interlocking system that have alarms & trips option for safety operation.		

Measure: Forced Outages

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Are any special operating procedures developed to formalize the methods for completing infrequent or unusual tasks during operation?		
2	Is written forced shutdown procedure available & followed during unit up-set condition?		
3	Percentage of time operating within the safe operational design limit?		

Group: State of Structures, System and Components

Measure: Corrective Work Order

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Percentage of corrective work order completion for SSCs along with safety critical & safety components?		
2	Completion of work order on SSCs within allocated time to avoid unnecessary downtime.		
3	Is any strategy adopted to carry out work order completion for safety critical and safety components?		

Measure: Corrosion & Fatigue Condition

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Reliability of inspection method followed for monitoring the corrosion and fatigue condition?		
2	Effectiveness level of the corrosion control technique used.		
3	Percentage of welded connections in the structure and components with fatigue lives less than the designed life?		
4	Percentage of SSC found in good condition on inspection with CP readings within acceptable range.		
5	Percentage of SSC painting and coating within allowable range.		

Measure: Ageing Condition of SSC

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is the information related to the design life of SSCs are available?		

2	Is any strategy followed for the over age SSCs?		
3	Is remaining life analysis carried out for SSCs?		
4	Is fitness for service analysis carried out for safety critical SSCs?		

Group: Plant Configuration & Modification

Measure: Plant Design

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Percentage of start-up, operating & shutdown procedure revised that related to plant design.		
2	Are the deviation from the codes & standard justified?		
3	Percentage of plant personnel involved with reviewing and updating plant design.		

Measure: Modification Effectiveness

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any amassment process followed for justifying the requirement of modification?		
2	Percentage of modification to risk significant SSCs.		
3	Modification compliance level with the current design standard.		
4	Are modifications reported for the necessary changes in all related areas?		

Measure: Modification Assessment

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Are modification to plant design & configuration performed after due risk assessment?		
2	Are Modifications performed so that limiting condition for operation doesn't arise?		
3	Post-modification test performed for ensuring synchronization with existing system.		

Group: Engineering Safety System

Measure: Safety System Performance

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Percentage of safety system demand fulfilled during requirement.		
2	Percentage of time safety system performed successfully.		
3	Safety system actuated successfully during test run.		

Measure: Safety System Related Backlog

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any strategy followed for performing safety system related work order completion on priority basis?		
2	Percentage of safety system related work order completion in allocated time.		

Group: Emergency Management

Measure: Emergency Response System Performance

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Safety and emergency response procedure are in place and adequate.		
2	Success of emergency response system during trial run.		
3	Emergency response equipment performs successfully.		
4	Percentage of work orders for emergency response equipment completed on time.		
5	Tendency of learning from previous emergency situation.		

Measure: Emergency Preparedness

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Strategic policy for responding to any kind of emergency situation.		
2	Emergency situation planning organized based on the nature of the identified and analyzed potential emergency situation.		

3	Emergency plan reviewed to schedule for emergency preparedness.		
4	Percentage of staff who received training on emergency preparedness.		
5	Emergency preparedness exercises completed on schedule.		

Area: Personnel Integrity

Group: Training

Measure: Safety Culture

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Commitment & involvement of top level management in safety related issues.		
2	Are safety related issues given highest priority?		
3	Continuous observation of safety system and striving for safety improvement.		
4	Is the work environment blame free?		
5	Adequacy level of training/seminars on safety culture and safety related issues.		
6	Percentage of staff who believes training is appropriate and effective.		
7	Are lockout/tagout procedures followed for each piece of equipment during maintenance?		
8	Percentage of incidents/near miss events investigated successfully.		

Measure: Technical & Interpersonal Training

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Extent of staff training on interpersonal & technical matters.		
2	Compliance to training successfully as planned.		
3	Percentage of personnel trained prior to start-up of process plant unit.		
4	Percentage of staff trained in standard activities.		

Group: Staff Competence

Measure: Staff Performance

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Percentage of staff that completed mandatory training & other specialized training.		
2	Knowledge, skill & physical capability level of staff.		
3	Willingness of staff to participate in different trainings/seminars.		

Measure: Assessment of Competence

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any assessment process followed to determine the competence level of staff?		
2	Is there any provision of sequential training & routine follow-up?		
3	Percentage of staff who satisfied the competence assurance requirements.		
4	Staff tendency to maintain the competency level.		

Group: Permit to Work

Measure: Effectiveness of PTW

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is there any guideline available for issuing PTW?		
2	Comprehensiveness of permit to work where major hazards are taken into consideration & control measures to be taken are specified clearly.		
3	Is the content of permit to work easy to understand & follow?		
4	Is there any follow up procedure for determining the effectiveness of PTW?		
5	Is PTW guideline managed, routinely inspected & reviewed?		
6	Are all types of PTW issued with due concern of both operations and maintenance personnel involved in the work?		

Measure: Compliance with PTW

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Are permit to work guidelines followed while carrying out maintenance work?		
2	Willingness of the staff to follow the PTW guideline effectively.		
3	Percent of work permits completed correctly.		

Group: Communication

Measure: Reporting Incidents

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Are incidents reporting guidelines & formats available?		
2	Staff tendency towards reporting all kinds of incidents along with near miss events.		
3	Communication of senior management to the general workforce of promoting requirements.		

Measure: Communication System

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Is any structured communication system available?		
2	Are process upsets & emergency conditions communicated for further action?		
3	Is any strategy followed for revision of communication system?		
4	Successful communication among plant personnel that results in avoidance of an unwanted incident.		

Measure: Management of Change

Sl. No.	Questions	% age likelihood of success	Importance level of success
1	Percentages of MOCs reviewed were in full compliance with the site's MOC procedure?		
2	MOCs decision taken with adequate hazard/risk analysis.		
3	Level of MOCs review documentation?		
4	Level of MOC organization and authorization strategy.		

Questionnaire related to Lagging Indicators

Instructions:

In the case of questions for lagging indicators, corresponding to the number of event occurrences, you are requested to give a value between '0' to '100'. Using the guideline below you are requested to provide values in the third column of the following matrix based on in which slot the numbers of occurrences are placed. At the same time provide a value between '0' to '100' in fourth column depending on the severity/impact level of the incident which occurred.

Number of Event Occurrences	% age Likelihood of Occurrences
0-2	0-20
2-4	20-40
4-6	40-60
6-8	60-80
>8	80-100

For example, if it is asked that, number of incidents due to not obeying the road signs while driving car is asked:

If the answer is four (4) incidents due to not obeying the road signs, then '40' (indicated in boldface) will be the value as per above table in the third column of the following matrix.

Corresponding severity based on judgement could be given '60' (indicated in boldface) in the fourth column.

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incident occurred due to not obeying the road signs while driving car.	40	80

Fill in the arrow indicated spaces by putting a value in the scale of 0-100

Area: Mechanical Integrity

Group: Inspection

Measure: Inspection Strategy

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to the incorrect selection of inspection technique & tools.		
2	Number of incidents that are related to an incorrect inspection interval selection.		

Measure: Inspection Effectiveness

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents or loss of containment incident due to inspection deficiency.		
2	Number of incidents in uninspected equipment due to lack of inspection.		
3	Number of incidents due to inspection & testing deficiency.		
4	Number of incidents due to overrun inspection period.		
5	Number of incidents due to the incorrect indication of gauges/regulators/indicators.		

Measure: Compliance to Statutory Requirement

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to avoidance of rectification recommendation related to inspection.		
2	Number of incidents due to the non-compliance of inspection with the legal requirement.		

Group: Maintenance

Measure: Preventive Maintenance Performance

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents in the equipment due to PM errors.		

2	Number of incidents in the equipment where preventive maintenance was not performed on schedule.		
3	Number of incidents due to PM backlog issue.		
4	Number of incidents due to improper selection of equipment in the preventive maintenance plan.		

Measure: Corrective Maintenance Performance

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents in the equipment due to CM errors.		
2	Number of incidents while performing corrective maintenance.		
3	Number of incidents due to delay in CM.		

Measure: Reliability Perspective of SSC

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to significant deterioration of SSC's.		
2	Number of incidents due to the maintenance errors of SSCs.		
3	Number of incidents due to temporary repair works of SSCs.		
4	Number of incidents where poor reliability is found as a root cause.		
5	Number of incidents due to unsafe engineering practices for the purpose of improvement in the reliability.		

Measure: Availability of Equipment

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents in the over maintained (equipment having more/frequent work orders) equipment.		
2	Number of incidents due to the unavailability of equipment or accessories.		
3	Number of incidents due to non-routine work flaws.		

Measure: Compliance with Rules & Regulations

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to violation of technical specifications and requirements in maintenance work.		
2	Number of incidents due to the non-compliance of inspection with the legal requirement.		

Group: Inspection & Maintenance Management

Measure: Planning & Scheduling

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to planning & scheduling deficiency (order of work execution).		
2	Number of incidents due to work order backlog in the planning & scheduling stage.		
3	Number of incidents due to multiple works planning and scheduling in the same area at the same time.		
4	Number of incidents due to incorrect maintenance procedure/methods.		
5	Number of incidents due to temporary repairs or in service deficient equipment.		

Measure: Correspondence with Operational Activity

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to workarounds at the time of maintenance.		
2	Number of incidents due to temporary modification.		
3	Number of incidents due to unauthorized maintenance intervention.		
4	Number of incidents due to omission of overdue schedule SRS maintenance activities.		
5	Number of incidents due to the lack of co-ordination between different teams or work groups.		

Measure: Work Flow Monitoring

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to non- compliance to scheduled time for work completion.		
2	Number of incidents due to failure of work flow monitoring system.		

Measure: Procurement & Inventory Management

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to the unavailability of spare parts on demand.		
2	Number of incidents due to unavailability of tools and logistics for maintenance and inspection.		
3	Number of incidents due to procurement delay of spare parts & components that are mandatory for maintenance.		

Group: Engineering Assessment

Measure: Financial Optimization & Control

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to the deficiency of the optimization technique.		
2	Number of incidents due to the inadequate maintenance for allocated budget & manpower constraints.		
3	Number of incidents due to unavailability of budget & manpower during the emergency work schedule.		

Measure: Quality of Work Execution

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to errors in technique for determining the quality of work execution.		
2	Number of incidents occurred in components for which rectifications		

	were recommended by the audit team.		
3	Number of incidents occurred due to weak links between performance standards and work orders.		

Area: Operational Integrity

Group: Operating Performance

Measure: Operating Procedure

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents related to the inadequate operating procedures.		
2	Number of incidents related to procedures that were unclear, not available, or not widely understood.		
3	Number of incidents for which the operational readiness reviews were not performed.		
4	Number of incidents that occurred during start-up of unit.		
5	Number of incidents due to human-machine interface deficiency.		
6	Number of incidents due to faulty trouble shooting procedure.		
7	Number of incidents during the steady-state operating condition.		
8	Number of incidents at the time of shift change in operation.		

Measure: Forced Outages

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to spurious or unplanned shutdown after start up.		
2	Number of incidents due to external causes for forced outages.		
3	Number of incidents due to internal causes for forced outages.		
4	Number of incidents due to an operational condition that exceeded the design limit.		
5	Number of incidents due to accumulation of transient stresses on equipment because of frequent shutdowns and restarts.		

Group: State of Structures, System and Components

Measure: Corrective Work Order

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents related to errors during corrective work order completion.		
2	Number of incidents due to noncompliance to corrective work order instructions for safety critical components.		
3	Number of incidents due to outstanding work order on SSCs.		
4	Number of incidents due to non functionality of SSCs.		

Measure: Corrosion & Fatigue Condition

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to fatigue failure of SSCs.		
2	Number of incidents due to inaccurate corrosion allowances.		
3	Number of incidents due to incorrect measurement of corrosion and fatigue condition.		
4	Number of incidents due to inadequate corrosion control technique.		
5	Number of incidents due to corrosion rate exceeding the predicted rate.		

Measure: Ageing Condition of SSC

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents where over age equipment is contributing issue.		
2	Number of incidents arose due to the ageing process of SSC's.		
3	Number of incidents due to incorrect analysis of fitness for service & remaining life analysis.		
4	Number of incidents due to lack of proper monitoring of ageing components.		

Group: Plant Configuration & Modification

Measure: Plant Design

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to the deficiency in plant design.		
2	Number of incidents due to noncompliance of design standards & guideline.		
3	Number of incidents due to faulty design configuration issues.		

Measure: Modification Effectiveness

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents in the modification area.		
2	Number of incidents due to plant design modification issues.		
3	Number of incidents due to lack of peer-checking of modification.		
4	Number of incidents due to delay or ignorance of necessary modification.		

Measure: Modification Assessment

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to lack of risk identification and evaluation of any modification.		
2	Number of incidents due to errors in post checking process.		

Group: Engineering Safety System

Measure: Safety System Performance

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to the dormant failure of safety system.		
2	Number of incidents due to safety system not performing successfully after actuation.		

3	Number of incidents due to faulty safety system actuation.		
4	Number of incidents due to safety system being bypassed.		

Measure: Safety System Related Backlog

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to the unavailability of safety system.		
2	Number of incidents due to extended maintenance period of safety system.		
3	Number of incidents due to not performing safety system inspection routinely.		

Group: Emergency Management

Measure: Emergency Response System Performance

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to the failure of emergency response system related equipment.		
2	Number of incidents due to not performing the necessary recommended changes to the response tactics or logistics which arose from trial result.		
3	Number of incidents due to overdue maintenance work on emergency response system.		

Measure: Emergency Preparedness

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to faulty exercises on emergency preparedness.		
2	Number of incidents due to not performing the recommended corrective action from emergency drill.		
3	Number of incidents due to lack of up to date emergency response training.		
4	Number of incidents due to the deficiency of emergency operating procedure.		

Area: Personnel Integrity

Group: Training

Measure: Safety Culture

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to lack of appreciation of risk involved in safety issues.		
2	Number of incidents due to unsolved safety system related issues.		
3	Number of incidents due to degradation of safety culture & practice.		
4	Number of incidents due to lack of adequate worker protecting strategy/mechanism.		
5	Number of incidents due to work performed without adequate equipment or personnel protection.		
6	Number of incidents due to accepting increasingly poor performance along with overlooking weak signals in critical areas.		

Measure: Technical & Interpersonal Training

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to training deficiency.		
2	Number of incidents due to the overdue staff training.		
3	Number of incidents due to errors in simulator training program.		
4	Number of incidents due to negligence of training.		
5	Number of incidents which are related to the issue of not following proper sequence in training.		

Group: Staff Competence

Measure: Staff Performance

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to staff errors.		
2	Number of incidents due to not having appropriate training.		
3	Number of incidents with root cause of insufficient process training/knowledge.		
4	Number of incidents due to operator overlooking control signals.		

Measure: Assessment of Competence

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents due to incorrect assessment of competence level.		
2	Number of incidents due to engagement of non competent personnel.		

Group: Permit to Work

Measure: Effectiveness of PTW

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents where errors in PTW are identified as contributing reason.		
2	Number of incidents due to faulty guidelines & ignorance of reviewing guidelines.		
3	Number of incidents due to not understanding the guideline instruction.		

Measure: Compliance with PTW

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Numbers of incidents due to violation of work permit instruction.		
2	Number of incidents due to failure to properly apply a safe work permit.		

Group: Communication

Measure: Reporting Incidents

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents related to the scenario of not reporting the earlier near miss event in those areas.		
2	Number of incidents due to improper reporting of event		

Measure: Communication System

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents occurred due to lack of proper communication system.		
2	Number of incidents occurred due to not updating the communication system as required.		
3	Number of incidents due to poor communications within the plant management hierarchy.		

Measure: Management of Change

Sl. No.	Questions	% age likelihood of occurrences	Severity level
1	Number of incidents with MOCs as a root cause.		
2	Numbers of incidents due to temporary MOCs conditions were not corrected /restored to the original state.		
3	Number of incidents due to MOCs for which the drawings or procedures were not updated.		
4	Number of incidents due to backlog of MOCs issues.		

Set 2 Questionnaire:

Weighted factors estimation for each level indicator by pair wise comparison to evaluate relative importance of indicators

Instructions:

The following section aims to develop a weighting scheme for the three level elements of asset integrity hierarchy. The questionnaires are designed in such a way so that they will eventually collect data depending on the pairwise importance comparison of different elements. In the questionnaire you are asked to come up with your judgment for prioritizing an element by indicating a score in the blank spaces. The element in the first column has to be compared to each of the elements along the first row of the table, and you have to weight the relative importance of one element to another.

For example, if you are planning to purchase a car and you have set reliability, fuel economy and price as the factors for decision making, now you need to prioritize the factors using your judgment.

If you think that reliability is two times as important as fuel efficiency, place a 2 (indicated in boldface) in the fuel efficiency column of the reliability row (as shown below).

Similarly if you think that reliability is as important as price, place 1 (indicated in boldface) in the price column of the reliability row (as shown below).

If you think that the fuel efficiency is half times less important than the price of the car, place 0.5 (indicated in boldface) in price column of the fuel efficiency row (as shown below).

	Reliability	Fuel Efficiency	Price
Reliability	1	**2**	**1**
Fuel Efficiency		1	**0.5**
Price			1

Fill in only the white matrix elements indicating by arrow by comparing the row elements (right side of the matrix) to the column elements (left side of matrix element) in the indicated places following the instruction

N: B: You need only to fill in the white blank spaces, and the same procedure can be followed for following matrixes. You are allowed to put any weighting values according to your own judgement.

Level 1: Pair wise importance comparison of Key Indicators for all three major areas of Asset Integrity

Area: Mechanical Integrity

	Inspection Strategy	Inspection Effectiveness	Compliance to Statutory Requirement
Inspection Strategy	1		
Inspection Effectiveness		1	
Compliance to Statutory Requirement			1

	Preventive Maintenance Performance	Corrective Maintenance Performance	Reliability Perspective of SSC	Availability of Equipment	Compliance with Rules & Regulations
PM Performance	1				
CM Performance		1			
Reliability Perspective of SSC			1		
Availability of Equipment				1	
Compliance with Rules & Regulations					1

	Planning & Scheduling	Correspondence with Operational Activity	Work Flow Monitoring	Procurement & Inventory Management
Planning & Scheduling	1			
Correspondence with Operational Activity		1		
Work Flow Monitoring			1	
Procurement & Inventory Management				1

	Financial Optimization & Control	Quality of Work Execution
Financial Optimization & Control	1	
Quality of Work Execution		1

Area: Operational Integrity

	Operating Procedure	Forced Outages
Operating Procedure	1	
Forced Outages		1

	Corrective Work Order Issued	Corrosion & Fatigue Condition	Ageing Condition of SSC
Corrective WO Issued	1		
Corrosion & Fatigue Condition		1	
Ageing Condition of SSC			1

	Plant Design	Modification Effectiveness	Modification Assessment
Plant Design	1		
Modification Effectiveness		1	
Modification Assessment			1

	Safety System Performance	Safety System Related Backlog
Safety System Performance	1	
Safety System Related Backlog		1

	Emergency Response System Performance	Emergency Preparedness
Emergency Response System Performance	1	
Emergency Preparedness		1

Area: Personnel Integrity

	Safety Culture	Technical & Interpersonal Training
Safety Culture	1	
Technical & Interpersonal Training		1

	Staff Performance	Assessment of Competence
Staff Performance	1	
Assessment of Competence		1

	Effectiveness of PTW	Compliance with PTW
Effectiveness of PTW	1	
Compliance with PTW		1

	Reporting Incident	Communication System	Management of Change
Reporting Incident	1		
Communication System		1	
Management of Change			1

Level 2: Pair wise importance comparison of Activity Indicators for all three major areas of Asset Integrity

Area: Mechanical Integrity

	Inspection	Maintenance	Inspection & Maintenance Management	Engineering Assessment
Inspection	1			
Maintenance		1		
Inspection & Maintenance Management			1	
Engineering Assessment				1

Area: Operational Integrity

	Operating Performance	State of SSC	Plant Configuration & Modification	Engineering Safety System	Emergency Response Arrangement
Operating Performance	1				
State of SSC		1			
Plant Configuration & Modification			1		
Engineering Safety System				1	
Emergency Response Arrangement					1

Area: Personnel Integrity

	Training	Staff Competence	Permit to Work	Communication
Training	1			
Staff Competence		1		
Permit to Work (PTW)			1	
Communication				1

Level 3: Pair wise importance comparison of Element Indicators for Asset Integrity

	Mechanical Integrity	Operational Integrity	Personnel Integrity
Mechanical Integrity	1		
Operational Integrity		1	
Personnel Integrity			1

Please Provide the following General Information

Company Name :	
Contact :	
Position :	
Telephone :	
E-mail :	
Comments : (Optional)	

Appendix C: List of Experts provided feedback on pair-wise comparison for multilevel weight determination

Sl. No.	Organization	Position
1	Dubai Electricity & Water Authority (DEWA)	Engr.-Mechanical Maintenance
2	Acuren Group Inc	Mechanical Engineer
3	Lafarge Surma Cement Ltd	Assistant Manager-Production
4	Memorial University of Newfoundland	PhD candidate
5	Memorial University of Newfoundland	PhD candidate
6	Memorial University of Newfoundland	PhD candidate
7	Memorial University of Newfoundland	PhD candidate
8	Memorial University of Newfoundland	Graduate Student
9	INTECSEA Canada	Director of Operations
10	Lloyd's Register Kazakhstan LLP	Kashagan IVB Project Manager
11	QATARGAS	Sr. Reliability Engineer

Appendix D: List of process plant participate in benchmark study

Sl. No.	Participating Organization
1	Dubai Electricity & Water Authority (DEWA), Dubai, UAE
2	Lafarge Surma Cement Ltd, Chattak, Sunamgonj, Bangladesh
3	INTECSEA Canada, NL, Canada
4	Lloyd's Register Kazakhstan LLP, Kazakhstan
5	QATARGAS, Qatar

Appendix E: Definitions

Error: an action that unintentionally departs from an expected behavior.

Event: an unwanted, undesirable change in the state of plant structures, system, process or components or human/organizational conditions (health, behavior, administrative control environment, production, safety and so forth) that exceed established criteria and which occurs due to either failure of asset i.e. equipment or improper functioning of components.

Safety critical plant and equipment: Plant and equipment relied upon to ensure safe containment of hazardous chemicals and stored energy, and continued safe operation. This will typically include those items in a plant's preventative maintenance program, such as: Pressure vessels, Piping systems, Relief and vent devices, Instruments, Control systems, Interlocks and emergency shutdown systems, Mitigation systems, Emergency response equipment.

Safety Critical Equipment Inspection: Percent of inspections of safety critical equipment completed on time. This may include pressure vessels, storage tanks, piping systems, pressure relief devices, pumps, instruments, control systems, interlocks and emergency shutdown systems, mitigation systems, and emergency response equipment.

Safety Culture: The safety culture of an organization is the product of individual and group values, attitudes, perceptions, competencies, and patterns of behavior that determine the commitment to, and the style and proficiency of, an organization's health and safety management [Glendon et at, 1995].

Risk-based: The adjective `risk-based` is used to portray one or more risk attributes of a process, activity, or facility. For simplicity, rather than use the independent terms hazard-based, consequence –based, or frequency-based, the single term *risk-based* is used to mean any one or combination of these terms.

LOTO: Lock-out and tag-out (LOTO) is a critical part of a strong all-around safety program. It is a safety procedure which is used in industry and research settings to ensure that dangerous machines are properly shut off and not started up again prior to the completion of maintenance or servicing work. It refers to the specific practices and procedures to protect workers from injury due to the unexpected energization during maintenance or operation. In LOTO, maintenance employees work with production employees to positively prevent all forms of hazardous energy from causing harm.