Session No. 636

Applications of Cause-Consequence Diagrams in Operational Risk Assessment[1]

Yaneira E. Saud, CSP
ERM Southwest
Houston Texas

Chris Israni
ERM Southwest
Houston Texas

Introduction

Cause-consequence analysis (CCA) combines the inductive and deductive reasoning of logic diagrams (e.g., event-tree analysis (ETA) or fault-tree analysis (FTA)) to identify the basic causes and consequences of potential accidents. Bowtie diagramming, a less formal CCA than ETAs and FTAs, provides a pictorial representation of the risk assessment process, and during the last decade, the use of bowtie diagrams has become increasingly popular, especially in the exploration and production, oil and gas sector. Because of their unparalleled advantages demonstrating that major hazards are identified and controlled, bowties are widely used in Europe to support safety reports and HSE cases for drilling and grassroots onshore projects. Other applications have been reported for healthcare, nuclear, transport, and organizational culture.[2]

This paper discusses the evolution of the risk-based approach in the United States and how the bowtie model would fit in the risk management process, and it shares representative bowtie case study applications in making engineering controls operational for a diverse range of oil and gas facilities.

Regulatory Requirements Versus Best Practices

U.S. Regulatory Background

Onshore U.S.
The process safety regulatory process in the U.S. has been significantly influenced by industry and technical associations. In 1985, the Center for Chemical Process Safety (CCPS) was chartered by the American Institute of Chemical Engineers (AICHE) to develop and disseminate technical information for preventing major chemical accidents.

The premiere process safety reference was a brochure published by CCPS, "A Challenge to Commitment," outlined a comprehensive model characterized by 12 distinct and essential elements. In the midst of outrage and uncertainty by the latest catastrophic events, the brochure was distributed to 1500 chief executive officers. The second CCPS publication, “Guidelines for Technical Management of Chemical Process Safety,” further refined the approach in 1992.[3]

A year later, the American Petroleum Institute (API) published its consensus guideline to assist in the management of process hazards. This was one of the industry practices that the U.S. Occupational Safety and Health Administration (OSHA) referenced when developing the process safety management (PSM) standard (29 CFR 1910.120), which was promulgated in February 1992,[4,5] two years after OSHA’s Notice of Proposed Rulemaking (NPR).

Four months after the publication of 29 CFR 1920.120, the Clean Air Act Amendments (CAAA) were enacted into law. The CAAA required a list of highly hazardous chemicals and minimum preventive elements for employers and outlined specific duties for the Environmental Protection Agency (EPA) in the form of a risk management plan (RMP)[6] related to preventing accidental releases. The EPA’s RMP rule avoided overlap by integrating the process safety elements stated in OSHA’s PSM Standard. Also, The U.S. Chemical Safety Board (CSB) was authorized by the Clean Air Act Amendments of 1990; the CSB became operational in January 1998 to provide objective incident investigative function, independent of the rulemaking, inspection, and enforcement authorities of EPA and OSHA.

Offshore Gulf of Mexico

For offshore operations, the Safety and Environmental Management System (SEMS) was introduced in 1991 to address the finding of the National Research Council’s (NRC’s) Marine Board about the prescriptive approach of the Minerals Management Service (MMS) to regulating offshore operations. The Marine Board recommended a systematic approach to managing offshore operations; therefore, API, in cooperation with MMS, developed API Recommended Practice (RP) 75, “Recommended Practice for Design and Hazard Analysis for Offshore Production Facilities.”[7] Since API RP 75 was published, MMS promoted voluntary implementation of SEMS.

From 1991 to 2006, incident investigation findings and performance reviews identified the need to improve the performance of four key areas: (1) hazard analysis, (2) operating procedures, (3) mechanical integrity, and (4) management of change. The call for adequately addressing human factors is also a persistent topic resulting from audits and investigations. An Advance Notice of Proposed Rulemaking (ANPR) was published in 2006 to request comments and information about how to improve the safety and environmental management regulatory approach. In June 2009, the Bureau of Ocean Energy Management, Regulation, and Enforcement (BOEMRE) published an NPR based upon industry and public feedback for ways to improve the regulatory approach of safety and environmental management. In October 2010, BOEMRE published Final Rule 30 CFR Part 250 Subpart S, which incorporates by reference and makes mandatory API RP 75, 3rd Edition.[8] Only six months earlier (April 20, 2010), one the worst accidents in the Gulf of Mexico had taken place: the Deepwater Horizon blowout in the Macondo field.

Risk Management Evolution and Standardization

According to the CCPS, process safety has evolved from plain regulatory compliance to a continuous improvement process to, most recently, a risk-based approach (see Exhibit 1).[9] Risk-based process safety takes into account that hazards are different, and different levels and intensities of assessments must by applied for every case to efficiently assign resources for tasks that address higher-risk activities. This approach or new framework integrates lessons learned by industry by applying the original process safety management ideas of the late 1980s; applies the plan, do, check, act (PDCA) management system principles; and organizes the practices to be applied throughout the lifecycle of a process or facility.

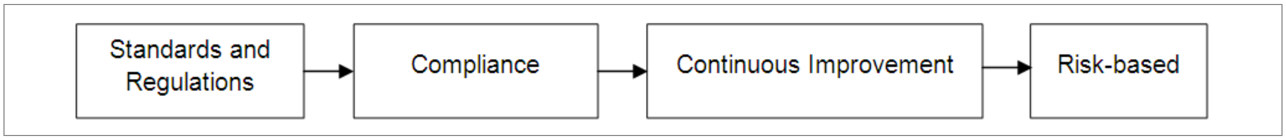

Exhibit 1. Evolution of Risk-based Process Safety

The risk management approach in the literature has moved from the isolated concept (in which the different risks are distinctly administrated) to an all-encompassing, integrated approach (where risk management is optimized throughout the organization). Some of the driving forces for risk integration are:

- Increased number, variety, and interaction of risks
- Accelerated pace of business and globalization
- Tendency to quantify risks
- Attitude of organizations toward the value-creating potential of risk
- Common risk practices and tools shared across the world

The international community has created documents related to the standardization of risk management that cover general guidance, terminology, requirements, and tools.

The International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) standard ISO/IEC 31010:2009 provide guidance for selecting and applying systematic techniques for risk assessment.[10,11,12] During May 2010, the United States Technical Advisory Group to the American National Standards Committee (ANSI) for risk management reached consensus to adopt the ISO documents as American National Standards. Public review of the subject and committee votes for adoption resulted in positive action, and ANSI approved the adoption of ISO/IEC standards in its standard ANSI/ASSE Z690.2-2011.[13,14,15]

Risk Assessment Management Process

Identify, Evaluate, Analyze, and Manage

Risk management is a process that includes hazard identification and evaluation and risk assessment and reduction of events that could impact process safety, occupational safety, environment, and social responsibility.

The ISO Risk Management Principles and Guidelines standardize risk assessment in four parts: (1) risk identification, (2) risk analysis, (3) risk evaluation, and (4) risk treatment. The first step in risk management is risk identification. This is achieved by identifying all hazards and their subsequent consequences.

The risk management process has reached a level of maturity where recent and future improvements are focused to better manage risk and includes review and monitoring checks to ensure desired performance in order to prevent and mitigate major accident events. The risk management process is a key factor in the success and sustainability of oil and gas facilities and must be ingrained into the entire process life cycle.

Where Do Bowties Fit in HIRA?

To understand the use and application of bowties in risk-based process safety, a brief overview of the transition between hazard identification and risk assessment follows. Hazard identification is a key provision in the U.S. regulatory-based safety management systems (e.g., process safety management, safety and environmental management system).

This process includes the orderly, systematic examination of causes leading to potential releases of hazardous substances and safeguards that must be implemented to prevent and mitigate a loss of containment, resulting in occupational exposure, injury, environmental impact, or property loss.

Process hazard analysis (PHA) techniques like hazard identification (HAZID), and hazard and operability (HAZOP) studies are the tabular hazard methods most widely used for operational hazard identification. HAZID studies frequently are used in exploration, production, and mid-stream operations, both onshore and offshore. However, compared to other worldwide best practices, such as HSE cases for onshore and offshore facilities, hazard identification by itself falls short of applying the risk management process.[16,17,18]

Traversing from the identification of hazards to qualitative risk assessment is achieved by the use of semi-quantitative matrices, which is essentially an interaction of the two attributes of risk—severity and likelihood. The exercise amounts to the risk ranking of these undesired events. The hazard evaluation team must identify ways to reduce the consequence or reduce the likelihood of high or medium risks through preventive or mitigation barriers to ensure risk level is either acceptable or as low as reasonably practicable (ALARP). Although ALARP can be demonstrated for any system, regardless of design definition or focus level, complex, costly decisions often require more accurate information about potential consequences and frequency of occurrence.

Bowties effectively include the main elements of the risk management process: identify, prevent, mitigate and assess (refer to Exhibit 2). To enhance a risk-based approach, any tabular hazard identification can be customized to identify preventive and mitigation safeguards (barriers) that can be exported to a cause-consequence diagram, such as a bowtie diagram.

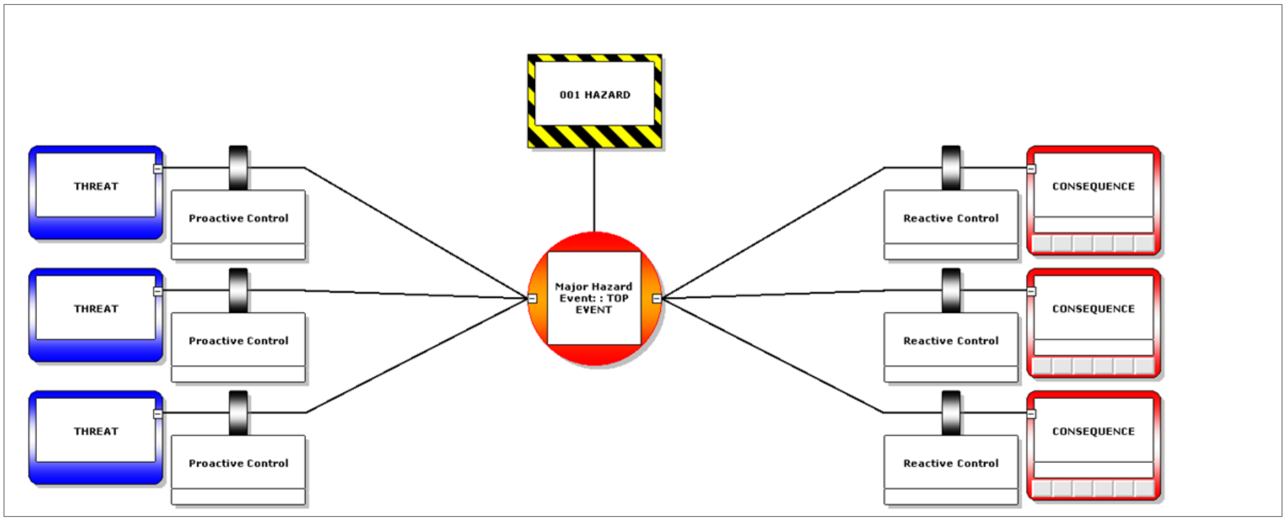

Exhibit 2. Typical Bowtie Diagram

Risk assessment becomes quantitative when accident scenarios need more precise numerical analysis to estimate the extent of a potential damage and its yearly frequency of occurrence. Such quantitative risk assessment often involves the use of existing failure and loss of integrity data, and computational models to simulate accident events. Typical quantitative risk assessments for the oil and gas industry include fire and explosion analysis (FEA), smoke and toxic gas dispersion analysis (S&GDA), fire and gas mapping, and dynamic events study, such as ship collision, helicopter crash, or dropped objects studies (see Exhibit 3).

As illustrated in Exhibit 3, a bowtie diagram may be an optional way to identify hazards and display the risk management process in an illustrative, all-inclusive way; this approach has proved particularly useful for risk communication. It also allows for extracting critical element systems that either prevent or mitigate an accidental event. Even though bowties are considered a *qualitative* risk assessment tool, applications where *quantitative* analysis is necessary can also benefit, by representing within the risk management process exactly where the results refine the consequence and frequency of undesired outcomes.

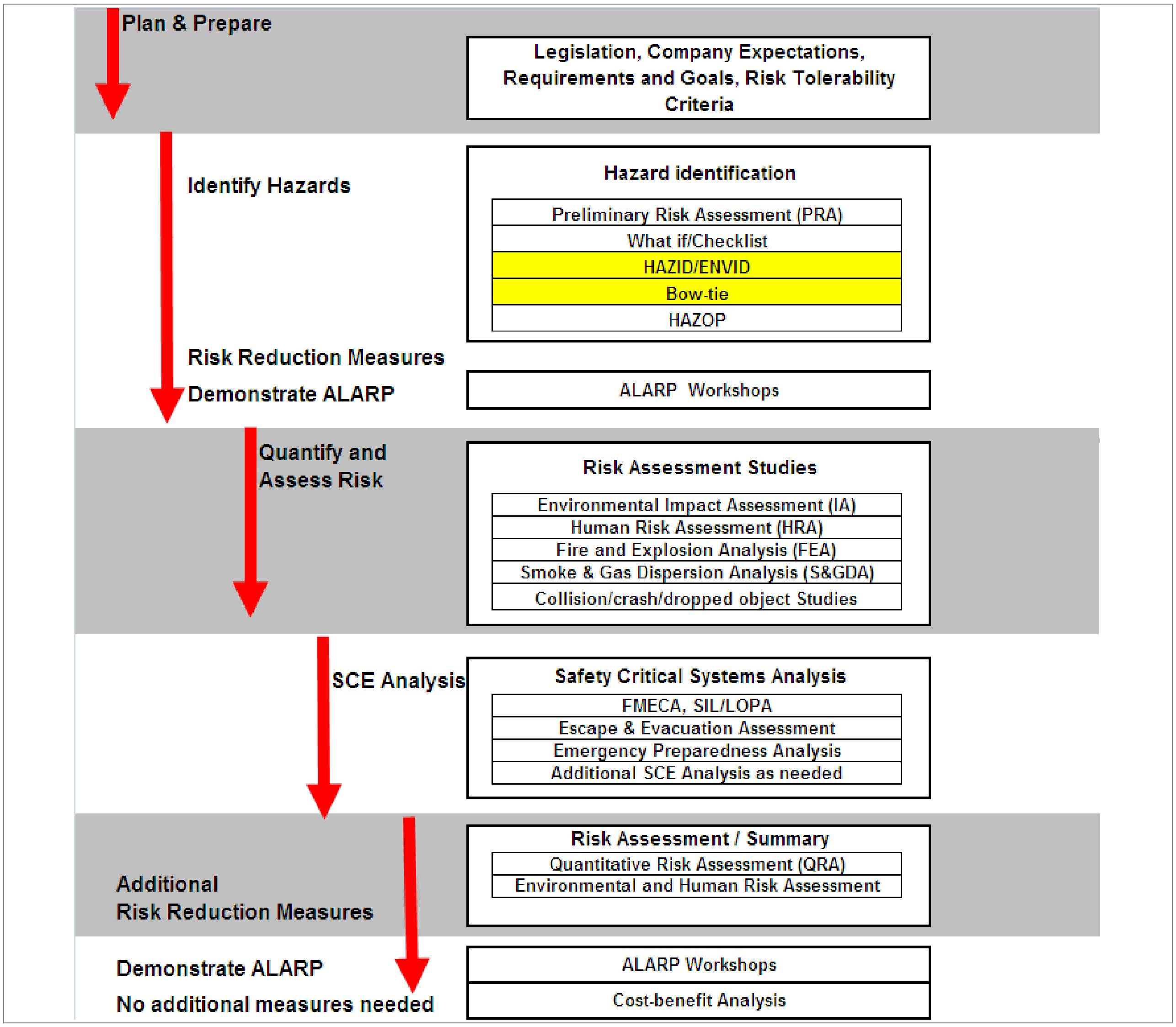

Exhibit 3. Hazard Identification and Risk Assessment Process Flow (*Source:* ERM North America Risk Practice)

CCA Terminology

Essential definitions for conducting CCA techniques are provided for the benefit of the reader to understand the terminology used and to relate it to the case studies:

- *Hazard:* Anything inherent to the business that has the potential to cause harm to safety, health, the environment, property, plant, products or reputation.

- *Threat:* A direct, sufficient and independent possible cause that can release the hazard by producing the top event, leading to a consequence.
- *Top Event:* The moment in which the hazard is released; the first event in a chain of negative events, leading to unwanted consequences.
- *Control*: Any measure taken that acts against some undesirable force or intention in order to maintain a desired state; proactive controls prevent an event (left side of bowtie diagram), reactive controls minimize consequence (right side of bowtie diagram).
- *Escalation Factor*: Condition that leads to increased risk by defeating or reducing the effectiveness of a control.
- *Consequence:* Accident event resulting from the release of the hazard that results directly in loss or damage to persons, environment, assets, or reputation.
- *ALARP:* As low as reasonably practicable. Risk of a business where a hazard is intrinsic; however, it has been demonstrated that the cost involved in reducing the risk further would be grossly disproportionate to the benefit gained. The ALARP definition is linked with risk tolerability and, thus, is different for every organization.
- *Risk Matrix:* Company- or project-defined grid that combines consequence (severity) and frequency (likelihood) to produce a level of risk and defines the risk tolerability boundaries for attributes of interest (people, environment, assets, or reputation).

How Can Bowties Contribute to HIRA?

After a significant investment of time and resources in the HIRA process, it would be unthinkable to lose access to the results in thick binders that are seldom opened again. The knowledge and insight gained through the process of identifying hazards and assessing risks needs to be extracted and kept operationally current and evolving.

In addition to quick and easy access to the HIRA proceedings, it is pertinent that this information be available in an easy-to-understand format. Hence, the key elements to a successful documentation of a HIRA are:

- Ease of access to the information.
- Ease of understanding the information.
- Ease of maintaining the information for the entire lifecycle of the process or facility.

Major Hazard Event

In a process facility, a plethora of hazards exists, but not all hazards have the potential of materializing to an accident or major hazard event (MHE). Likewise, process hazards have numerous controls, but not all controls are considered safety-critical. Bowtie diagramming helps one to understand the top events in a facility, the threats that can be involved in a causation sequence, and the final consequences that the organization will need to face.

The generic definition of MHE involves hazards with the potential to result in "a sudden occurrence (including, in particular, a major emission, loss of containment, fire, explosion or release of energy) leading to serious danger or serious harm to persons, property, or the environment, whether immediate or delayed."[18]

Example MHE categories used for the process industries include:

- *Loss of containment*: Most MHEs will be concentrated in the loss of containment of either hydrocarbons or hazardous substances.
- *Dynamic energy*: Involves any event of traffic (vessel collision) or dropped or swung object.

- *Occupational MHE*: Confined space entry, high elevation, energy sources (stored energy, energized circuits).
- *Adverse weather events*: Earthquakes, bush fires, heavy rains, flash foods.

Safety-Critical Equipment

If risk assessment is to be effective, it must be able to identify the safety-critical equipment, procedures, and activities (safety-critical elements or SCEs) or set of barriers against their effectiveness in reaching a risk-reduction target. SCEs are any part of the installation, plant, or computer programs the failure of which will either cause or contribute to a major accident, or the purpose of which is to prevent or limit the effect of a major accident.[19]

By extracting a list of SCEs, access to the controls and their perceived effectiveness are easier to understand, use, and monitor. A non-exhaustive list of SCEs, proposed by the Energy Institute London, is reproduced in Figure 4.

Performance Standards

The role of an SCE has to be clearly defined in terms of the following attributes: functionality, availability, reliability, survivability, and interactions with other systems. A performance standard document contains essential information for the performance of each of these attributes for the SCE:

- *What* are the function, pre and post-accident event?
- *How* likely is it to perform on demand?
- *Who* is accountable?
- *What* are associated interactions?
- *When* are inspection, maintenance, and testing required?

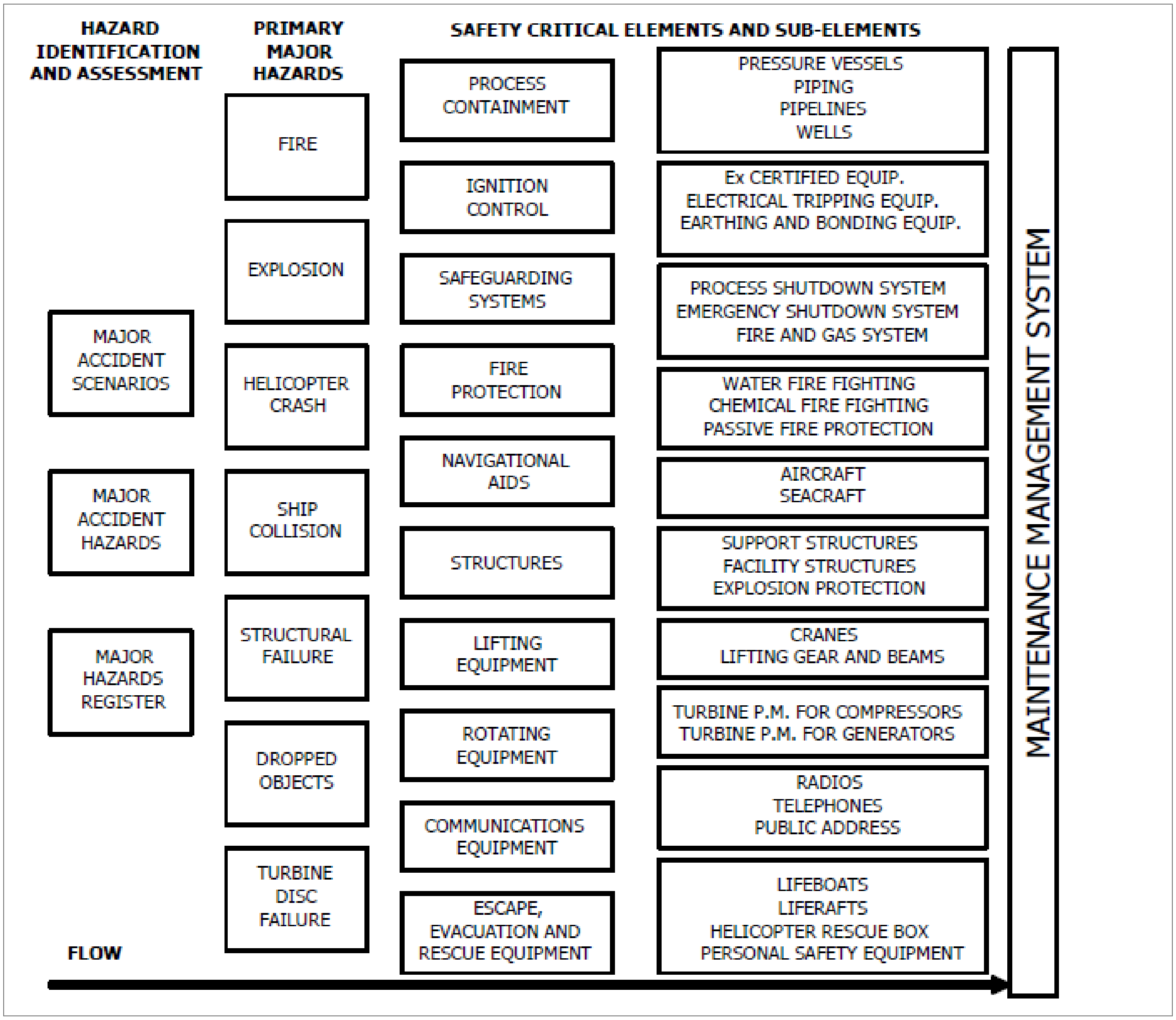

Exhibit 4. Risk Identification and Risk Assessment Process Flow (*Source:* Guidelines for the Management of Safety Critical Elements, Energy Institute, London, March 2007)

SCE Lifecycle

Unless an SCE is inspected, maintained, and tested, it will deteriorate over time. Most of the accident investigations conducted in the industry reveal broken or degraded barriers, where a complex sequence of unfortunate events resulted in a major accident.

Leading and lagging key performance indicators (KPI) show that if an SCE is given adequate importance and attention with respect to the hazard it prevents or mitigates, along with evidence of its maintenance cycles, then the SCE typically works and performs as intended. Moreover, changes of technology, raw materials, systems, and components will be persistent throughout the facility’s lifecycle. All modifications must be assessed and managed to establish their impact on the SCEs, and to ensure that changes are incorporated to the maintenance and verification regime.

Application of CCA techniques

Several real application cases for a variety of oil and gas facilities, either in design or operation, are summarized in this section to illustrate the use of bowties in the risk management process.

Operational Process Hazard Analysis for an LNG Plant

Bowties are presently being developed for a new coal seam LNG facility in Australia. According to Australian regulations, the LNG plant is expected to be classified as major hazard facility (MHF) and, within the scope of engineering, procurement, and construction (EPC), a safety case report must be submitted to the MHF regulator.[18]

A condensed list of MHEs was developed, including loss of containment, occupational exposure, and global adverse events. SCE were extracted from the formal safety studies (i.e., HAZIDs, HAZOPs, and project hazard register) that were completed during front-end engineering and design (FEED). During the bowtie workshop, SCEs, such as design, hardware, and procedures, were validated and classified.

The bowtie method allowed the team to assess the appropriateness and robustness of the preventive and mitigation controls. Also, lessons learned from other LNG projects were applied to challenge the barriers proposed in the design. Identified action items aimed to confirm and improve SCEs are being incorporated in the project execution phase. Figures 5 and 6 (illegible) are provided only as an illustration of the resulting diagrams.

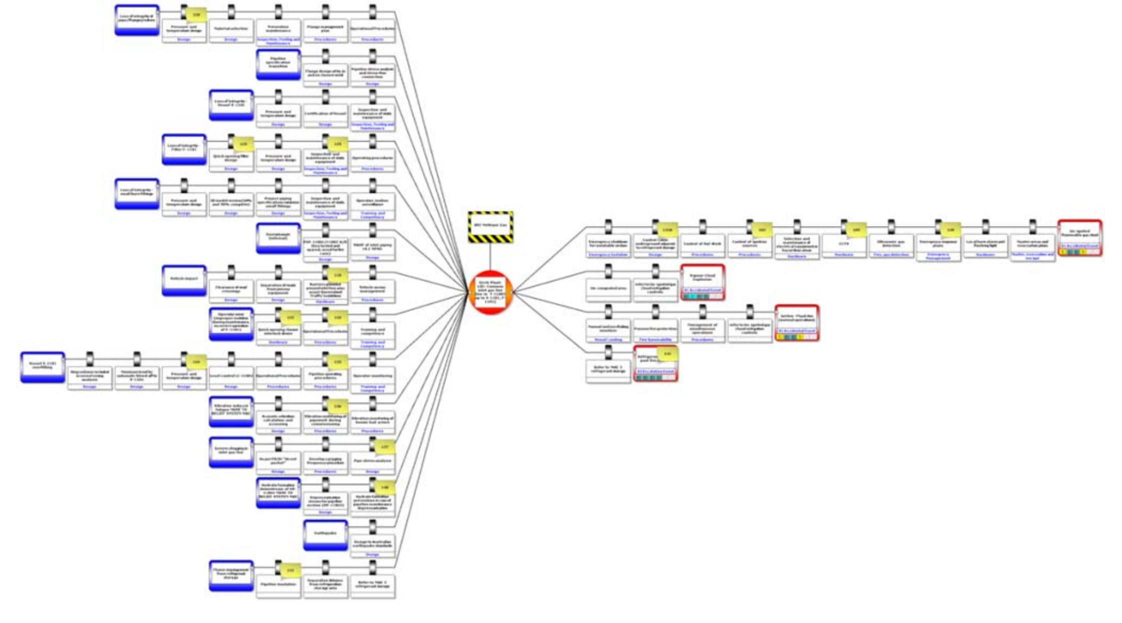

Exhibit 5. Sample Bowtie Loss of Containment (*Source:* ERM North America Risk Practice)

Source: ERM North America Risk Practice

Exhibit 6. Sample Bowtie Dynamic Energy (*Source:* ERM North America Risk Practice)

Incident Investigation

An accident investigation review was performed for a fatal accident aboard an offshore drilling unit in the Gulf of Mexico. The bowtie method was used to organize and analyze accident causes gathered from the Kelvin Top-Set® investigation process. Black BowTieXP software was used to record relevant accident information and to identify active failures and preconditions (underlying causes) and latent failures (root causes). The Tripod Beta analysis tool was used to identify the organizational failures that were the main causes or contributors to the accident.

The uncovered underlying and root causes pointed to latent failures within the drilling contractor's management system, evidenced by failing protection barriers that were underperforming several months before the fatal accident. As the team completed the analysis process, a number of actions, including drilling contractor corrective actions and operator diligence improvement opportunities, were identified to prevent the accident from reoccurring. Exhibit 7 (illegible) is provided only to illustrate the resulting Black BowTieXP diagram.

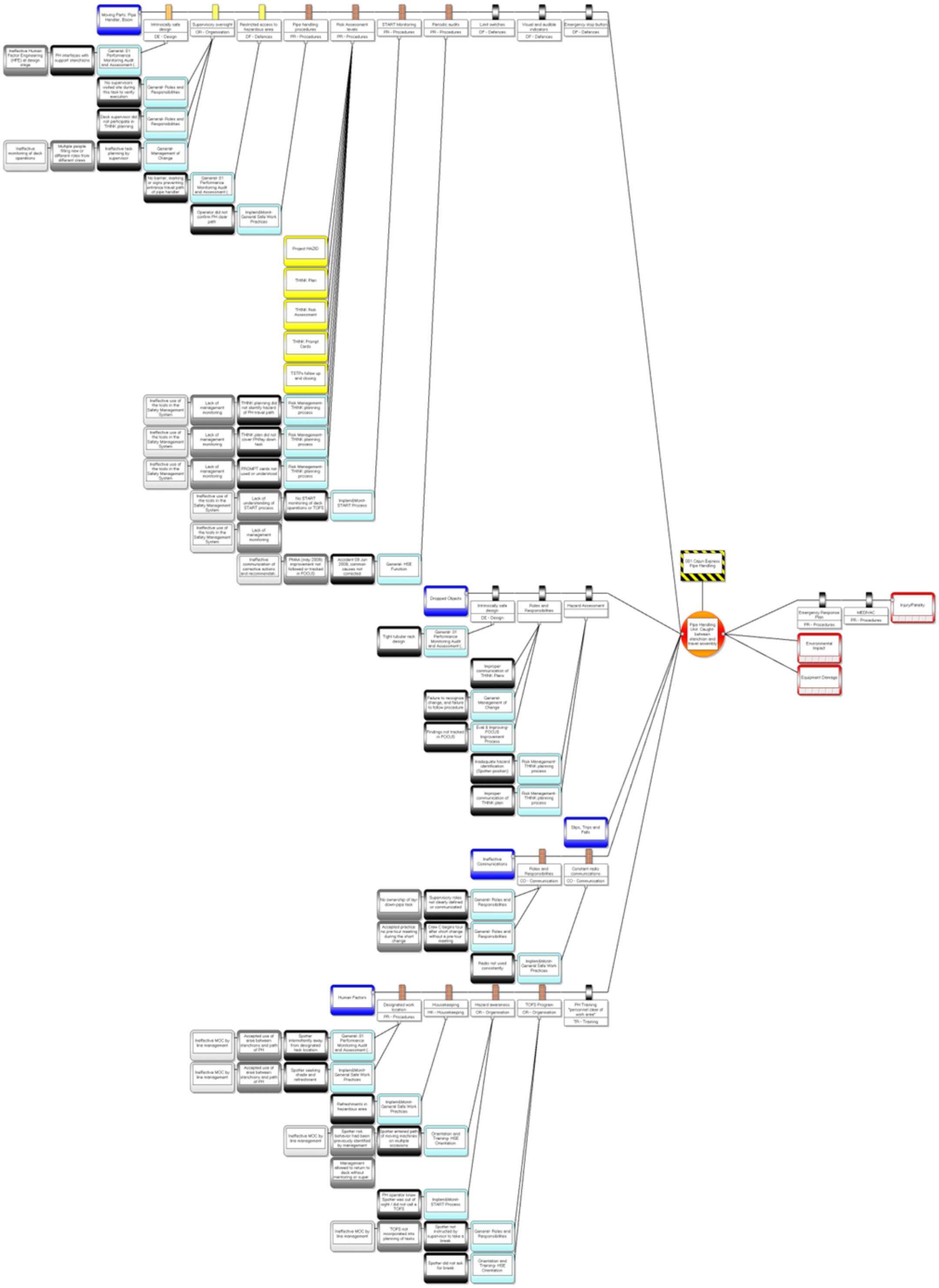

Exhibit 7. Sample Bowtie Incident Investigation (*Source*: ERM North America Risk Practice)

Environmental Applications

The bowtie concept was tested for an environmental identification (ENVID) study that was in progress for an offshore platform. The ENVID was conducted independently of the HAZID.[20] In order to remain consistent to the HAZID approach, the authors applied the bowtie technique to the conventional ENVID method.

A typical bowtie originates at the center, beginning with the hazard identified, and then the diagram is extended to either side for cause and consequence, respectively. Similarly, an environmental event was chosen to be the center of the bowtie. The left-hand side was populated with the causes identified, along with the environmental consequences on the right-hand side.

Conventionally, an ENVID is another brainstorming type of technique that lists existing barriers or safeguards. In this case, using the bowtie approach, the safeguards identified were classified as either being preventive measures that would eliminate the cause, or measures the purpose of which was to mitigate the undesired environmental consequence. The study was conducted in a brainstorming type of setup, and was documented in a tabular/spreadsheet type of format, using the bowtie type of sequential approach for the thought process. For each of the scenarios discussed, the team proposed recommendations wherever it was deemed necessary.

An advantage of using this approach for the team members was that they were able to correlate the preceding HAZID results, which were part of the scope and conducted in a manner emulating the bowtie approach, to the ENVID, thereby understanding the contribution of the various barriers. This assisted in populating the SCE for the project. In addition, a clear mapping of the undesired environmental events facilitated a robust understanding of the environmental hazards for the team. This method is amenable to early phase environmental impact assessment (EIA) development, design phases, project startup and review of changes and new events, and startup operations.

Table 1 is an example of the application of bowtie to ENVID, based on a current study being carried out by ERM for an oil and gas facility, details of which will be published at a later stage.[20]

Table 1. Altered ENVID Table to Fit the Bowtie Approach (Based on a Recent Study)

Cause	Prevention and Detection Barriers	Environ-mental Event	Controls/ Mitigation	Conse-quence	Risk Ranking (removed for this example)			Recommendations
1. Diesel engine exhaust	1. Routine maintenance and inspection	1. Air Emissions	1. Monitoring for black smoke	1. Release of pollutants to surrounding environment (Particulates, SOx, NOx, CO2)				2. Review helicopter exhaust parameters in later stages
2. Third-party equipment	2. Engineering							3. Review supply boat exhaust properties in later stages
3. Specific equipment	3. Equipment selection to code							8. Verify that drilling contractor equipment will not exceed emissions limits.
4. Supply Boat exhaust	4. Shut down equipment							
5. Helicopter exhaust								
1. Release of gas from drilling mud	1. Gas detection	1. Air emissions	1. Monitoring equipment	1. Release of pollutants to surrounding environment (Increased GHG because of unburned gases)				No recommendation proposed
2. Leaks from flanges, valves, tanks, vents etc. (fugitive emissions)	2. Mud conditioning		2. Mud conditioning					

Group Dynamics

The applications discussed above were based on real studies conducted by the ERM Risk Practice. Each of these was conducted in presence of a team environment, with the participation of several disciplines. It was observed that the graphical nature of the bowtie was a major contributor to the success of the studies.

This visual approach also enhanced the brainstorming for the analyses, minimizing the confusion that a tabular analysis would otherwise tend to cause. Four areas have been identified where the bowtie model is very useful during workshops:

- The clear distinction of the functionality of the controls contributes to either eliminating the causes or mitigating the consequences, assisting the team members in a better perception of the analysis. This in turn brought about a clear distinction amongst the controls that required varied emphasis on maintenance and inspection of the respective devices.
- Using a risk assessment matrix, when ranking a potential ultimate consequence, especially when the team is reluctant to assign valid likelihood and consequence resulting in "high" risk, bowtie helps illustrate the importance of using the matrix correctly by assigning realistic semi-quantitative values and making a recommendation that will yield the most risk reduction.
- Incident investigation, by building upon any investigation method, enables the team to analyze immediate, intermediate, and root causes in a holistic approach by comparing the barrier in places where ones that were degraded or broken, and its connection to the driller and operator-integrated HSE management system. For example, in the case study presented in this paper, the bowtie method helped quickly demonstrate that the joint management system was under-performing some time before the fatal accident.
- Human factors, where interesting discussions are taking place with different clients about integrating human failure analysis with bowties. Human error is being developed as specific "threat," documenting specific instances where inappropriate design, unclear operational instructions or unrealistic emergency response procedures can lead to failure, contributing with the frequency or consequence of a top event.

Certainly, the success of any of these group efforts also depends on the capabilities of an able facilitator; but the visualization also provides an overall view of the risk management process, and a welcomed workshop dynamic change to the participants.

Conclusion

The authors have successfully applied the CCA technique with this diagrammatic approach to several oil and gas facilities, both existing and during design. As the process safety practice continues evolving to a risk-based approach, CCA and bowties have an enormous contribution potential. Some of the advantages of bowties to the risk management process are:

- Application and understanding of the risk management process, from identification to assessment.
- Focus on MHEs, differentiating highly hazardous releases (e.g., loss of containment) from other workplace hazards, occupational health or environmental aspects.
- Synthesis, extraction of what is critical to prevent or mitigate an MHE.
- SCE integrity assurance as the basis for identification of KPIs.
- Unparalleled communication of MAEs and their controls, demonstration of ALARP.
- Integrated risk management, safety, occupational, and environmental (with flexibility to any other hazards security, community, financial).

- Integration of human and organizational factors, by identifying specific barriers for the prevention and management of human error.

A few disadvantages have also been identified:

- Depending on diagram size and complexity, there is a requirement to acquire bowtie software
- A need for a robust risk-assessment matrix to appropriately screen MHEs and arrive at a representative set of bowtie diagrams per facility or business unit.

The authors' use of bowtie so far points towards the application of this tool as a complement to, instead of substitute for, traditional tabular process hazard analysis (e.g., HAZOP). On the other hand, other applications (e.g., LOPA), although feasible and promising, are too incipient to report lessons learned. The future of bowties across industry, to complement, enhance, and operationalize hazard identification and assessment with the incorporation of human factors at a practical level, does look promising and will rapidly evolve.

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