Bow-Tie Diagrams in Downstream Hazard Identification and Risk Assessment

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INTRODUCTION

Bow-tie diagrams are emerging as a very useful tool to depict and maintain an up-to-date, real-time, working risk management system embedded in daily operations. They are a proven concept in the worldwide offshore industry. These diagrams provide a pictorial representation of the risk assessment process. This article introduces the bow-tie concept to the downstream and chemical process industries in the United States. The authors believe that bow-tie diagrams can be a resourceful method in the safety and risk practitioner’s toolkit to improve performance of the hazard identification and risk assessment process and to demonstrate that major hazards are identified and managed to as low as reasonably practicable. Because of their graphical nature, the biggest advantage of bow-tie diagrams is the ease to understanding. Risk management by upper management and operations groups. © 2013 American Institute of Chemical Engineers Process Saf Prog 000: 000–000, 2013

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REGULATORY REQUIREMENTS VERSUS BEST PRACTICES

U.S. Regulatory Background

The evolution of the process safety approach for the onshore industry within the United States has been driven primarily by the regulatory agencies. However, it was industry who produced one of the earliest process safety references—a brochure published in 1985 by AIChE-CCPS; “A Challenge to Commitment.” The article outlines a comprehensive model characterized by 12 distinct and essential elements to avoid catastrophic events. Other publications, American Petroleum Institute Recommended Practice (API RP) 750, Management of Process Safety Hazards (1990), further refined the approach ultimately leading to the U.S. Occupational Safety and Health Administration (OSHA) promulgation of the Process Safety Management (PSM) standard in February 1992 [3].

In addition, the U.S. Environmental Protection Agency (EPA) formulated a Risk Management Plan (RMP) rule [4] related to preventing accidental releases. The EPA’s RMP rule avoided overlap by integrating the process safety elements stated in OSHA’s PSM Standard.

Along similar lines but for offshore operations, the Safety and Environmental Management System (SEMS) was introduced in 1991 by the Minerals Management Service, but this was deemed voluntary. Eventually, in late 2010, the Bureau of Ocean Energy Management, Regulation, and Enforcement published Final Rule 30 CFR Part 250 Subpart S that incorporates by reference and makes mandatory API RP 75, 3rd Edition [5,6], today enforced by the Bureau of Safety and Environmental Enforcement.

Irrespective of where the site is located within the U.S. or vicinity—onshore or offshore—the approach to risk has predominantly been regulatory driven. However, the 2010 Macondo accident manifested evidence that the right path to follow is a performance-driven approach to risk with operators actively demonstrating that facilities have the appropriate barriers to place to manage risks to as low as reasonably practicable (ALARP) [7].

Trends in Global Risk Management Standardization

The risk management approach has moved in the literature from the isolated concept (where the different risks are distinctly administered) to an all-encompassing, integrated
approach (where risk management is optimized throughout an organization). Some 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 (Figure 1).

The international community has created documents related to the standardization of risk management that cover general guidance, terminology, requirements, and tools. Among them, documents worth mentioning are:

- CCPS latest publications on the evolution of PSM to a risk-based management approach [8] and updated process hazard methods that include bow-tie diagrams [1];
- International Association of Drilling Contractors Safety Case guidelines where risk management is the centerpiece of a comprehensive major hazards ALARP assessment [9,10];
- The International Organization for Standardization (ISO) and the International Electrotechnical Commission guidance for selecting and applying systematic techniques for risk assessment [11–13].

We are moving toward standardized, operational risk management, emphasizing:

- The importance of a formal safety assessment roadmap, instead of isolated hazard identification studies.
- A compilation of identification and assessment results, describing critical barriers that avoid major accidents in a tangible, ALARP demonstration report.
- Bow-tie diagrams appear as the tool of excellence to visualize the risk management process and transmit specific accountability.

**Figure 1.** Evolution of risk-based process safety [8].

**HAZARD IDENTIFICATION AND RISK ASSESSMENT (HIRA)**

**Identify, Evaluate, Analyze, and Manage**

HIRA includes hazard identification and evaluation, 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: risk identification, risk analysis, risk evaluation, and risk treatment. The first step—risk identification—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 include 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 Bow-Tie Diagrams Fit in HIRA?**

To understand the use and application of bow-tie diagrams in downstream, risk-based process safety, a transition must be made from hazard identification to risk assessment. Hazard identification is a key provision in the U.S. regulatory-based safety management systems (e.g., PSM, SEMS).

This process includes the orderly, systematic examination of causes leading to potential releases of hazardous substances and what safeguards must be implemented 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 hazards identification. HAZID studies frequently are used in exploration, production, and mid-stream operations, both onshore and offshore. However, comparing 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 [7].

Moving from identifying hazards to qualitative risk assessment is achieved using semiquantitative matrices, which is essentially an interaction of the two attributes of...
risk—severity and likelihood. The exercise amounts to risk ranking 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 that the risk level is either acceptable or ALARP. Although ALARP can be demonstrated for any system regardless of design definition or focus level, complex, and costly decisions often require more accurate information about potential consequences and frequency of occurrence.

Bow-tie diagrams effectively include the main elements of the risk management process: identify, prevent, mitigate, and assess (refer to Figure 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 bow-tie 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 plus computational models to simulate accident events. Typical quantitative risk assessments for the oil and gas industry include fire and explosion analysis, smoke and toxic gas dispersion analysis, fire and gas mapping, and dynamic events study such as ship collision, helicopter crash, or dropped objects studies (refer to Figure 3).

As illustrated in Figure 3, a bow-tie diagram may be an optional way to identify hazards and display the risk management process in an illustrative, all-inclusive way; this approach has proven particularly useful for risk communication. It also allows for extracting critical element systems that either prevent or mitigate an accidental event. Even though bow-tie diagrams 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.

**BOW-TIE TERMINOLOGY**

Essential definitions while conducting bow-tie analyses are provided here 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 bow-tie diagram), Reactive Controls minimize consequence (right side of bow-tie 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 a hazard that results directly in loss or damage: persons, environment, assets, or reputation.

ALARP: 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, reputation).

Operational excellence includes producing with no harm and no leaks, and it is not possible unless the operator manages, as a critical routine, the specific elements or components that eliminate or minimize risk (i.e., preventive or mitigation barriers; Refer to Figure 4).

Hence the successful documentation of a HIRA, for operational excellence, includes:

- Access to the information: the right level of detail at the operator's fingertips
- Understanding the information: pictorial bow-tie representation that can be grasped as a whole or by threats or consequences
- Individual accountability for the barriers
- Systems to ensure barrier integrity assurance actions are adequate, timely, and maintained throughout the life cycle of the process or facility.

**Identify Major Hazard Events**

In a process facility, although a plethora of hazards exists, not all hazards have the potential of materializing to an accident or major hazard event (MHE). Likewise, process hazards have numerous risk control systems, but not all controls are...
considered safety-critical. Bow-tie 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 an uncontrolled event with immediate or imminent exposure leading to serious risk to the health and safety of persons, environmental impact, or property loss [14]. A bow-tie session will generate MHE candidates from the HIRA process that will be validated by key discipline team members and subject-matter experts. A consensus MHE list (10 to 15 items, typically) clearly defines the events capable of catastrophic losses in your facility and constitutes the starting point of a bow-tie study.

**Describe Risk Control Systems and Safety-critical Equipment**

The next step is to identify the key barriers that either prevent or mitigate an MHE. These barriers are risk control systems, and within them are vital elements known as safety-critical elements (SCEs). 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 [15]. 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 5.

SCEs can be hardware, software, or human intervention tasks. They can be intrinsic to the design, added as risk reduction measures, or consist of administrative procedures. The bottom line is that the set barriers for each threat need to be legitimate to achieve a risk-reduction target; by blocking the threats or providing timely control and mitigation once top events materializes. For a barrier to be valid it must:
- Be able to stop a threat
- Be effective in minimizing a consequence
- Be independent from other barriers in same threat line

A common finding in accident investigations is the excessive reliance on procedures. Procedural barriers should be considered as complementary, and evaluation of escalation factors due to human error must also be part of the bow-tie study. Therefore, barrier documentation must include an assessment of the number and quality rating of the barriers for the overall risk control effectiveness.
Elaborate Performance Standards and Procedures

Now that risk control systems (SCEs) have been identified, they will be of no value unless they consistently perform when needed, as expected. Performance standards for each SCE define and document the attributes (e.g., functionality, availability, reliability, survivability, and interactions with other systems). The following questions must be answered by an SCE performance standard:

- **What?** function must the SCE perform, before and after a major event
- **How?** will the SCE produce intended outcome on demand

- **Who?** is the individual or position accountable for the SCE integrity
- **What?** are associated interactions with other SCEs
- **When?** is inspection, maintenance, and testing required to ensure a specific SCE attribute

Set Key Performance Indicators

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.

To ensure that SCEs perform as intended, the outcome must be described along with a lagging indicator to show that the outcome has been achieved [16]. Leading indicators must also be set to monitor the effectiveness of the SCE within the risk control system. Systems to define tier control levels, tolerance, data collection, and follow-up outcome deviations must also be established and kept throughout the facility’s life cycle [17]. Moreover, facility modifications must be assessed and managed to establish their impact on the SCEs and to ensure that changes are incorporated into the performance and verification regime.

Assure Competence and Training

Human factors continue to be recognized as an important contributor to major hazard events and need to be appropriately addressed. Human intervention is pervasive in the process industries. SCEs are invented, designed, constructed, fabricated, installed, maintained, tested, and replaced by people. Bow-tie analysis facilitates the assignment of individual roles for risk control systems and SCE by providing clear performance expectations and monitoring outcomes through leading and lagging indicators. By incorporating this valuable information, the competencies are better delineated, training programs, and instructions are accurately designed, the operational procedures are better designed and communicated; resulting in an operator better equipped to fulfill his duties for safe and clean operations. Bow-tie diagrams have been successfully applied in human organizational change and optimization [18].

EXAMPLE OF DOWNSTREAM BOW-TIE DIAGRAMMING

A study case developed for a new coal seam LNG facility in Australia is presented here. According to Australian regulations, the LNG plant is classified as major hazard facility (MHF) and, within the scope of engineering, procurement, and construction, a Safety Case Report must be submitted to the MHF regulator [14].

A condensed list of MHEs (including loss of containment, occupational exposure, and global adverse events) and their associated SCEs were extracted from the formal safety studies (i.e., HAZIDs, HAZOPs, and project Hazard Register) that were completed during front-end engineering and design. During a bow-tie workshop, SCEs such as design, hardware, and procedures were validated and classified.

The list of identified MHEs included:

- Loss of containment: Most MHEs will be concentrated in the loss of containment of either hydrocarbons or hazardous substances.
The bow-tie method allowed the team to assess the appropriateness and robustness of the preventive and mitigation controls for each identified MHE. Also, lessons learned from other LNG projects were applied to challenge the barriers proposed in the design. Identified action items aimed at confirming and improving SCEs were incorporated during the project execution phase. Figures 6–8 of this article are provided as an illustration of the resulting diagrams.

ENVIRONMENTAL APPLICATIONS

The bow-tie concept was tested for an environmental hazard identification (ENVID) study that was in progress for an offshore platform. The ENVID was conducted independently of the HAZID. To stay consistent the HAZID approach, the authors applied the bow-tie technique to the conventional ENVID method.

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

Conventionally, an ENVID is another brainstorming technique that lists existing barriers or safeguards. In this case, using the bow-tie approach, the safeguards identified were classified as either preventive measures that would eliminate the cause or mitigation measures that would alleviate the undesired environmental consequence. The study (brainstorming session) was documented in a tabular spreadsheet format using the bow-tie type of sequential approach for the thought process. For each of the scenarios discussed, the team proposed recommendations, where deemed necessary.

An advantage for the team members of using this approach was that they were able to correlate the preceding HAZID results to the ENVID, thereby, understanding the contribution of the various causes and barriers to environmental risk. This assisted in identifying critical environmental compliance elements for the project. In addition, a clear mapping of the undesired environmental events facilitated a robust understanding for the team of the environmental hazards. This method is amenable to early phase environmental impact assessment development, design phases, project start up and review of changes and new events, and startup operations.

Lessons learned

The ERM Risk Practice has conducted a significant number of bow-tie workshops in a team environment with the participation of relevant disciplines. The graphical nature of bow-tie diagrams 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 tends to cause. Four areas have been identified where the bow-tie model is very useful during workshops:

- Distinction of the functionality of the controls: Understanding each barrier’s contribution to either eliminating the causes or mitigating the consequences, provided the team members a better perception of the barrier effectiveness and the requirements to retain its integrity over time.
- Correct use of the risk matrix: When ranking consequence using a risk assessment matrix, especially, when the team is reluctant to assign valid likelihood and consequence resulting in “high” risk, the bow-tie diagram illustrates the importance of using the matrix correctly by assigning realistic qualitative values and aim at a recommendation to yield the most risk reduction.
- Incident investigation: Building upon any investigation method, the team can analyze immediate, intermediate, and root causes in a holistic approach by comparing the barriers in place and the ones that were degraded or broken and their connection to the HSE management system.
- Accurate inclusion of human factors: Human error must not be addressed as another generic threat but as a specific escalating factor or vulnerability that can lead to the barrier failure; for example, human error triggered by unclear operational instructions or unrealistic emergency response procedures.

Figure 8. LNG loss of containment—expanded view, consequences. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
CONCLUSION

The authors have successfully applied the bow-tie diagrammatic approach to downstream oil and gas facilities, both greenfield and brownfield projects. As the process safety practice continues evolving to a risk-based approach, bow-tie diagrams have enormous potential to complement process safety initiatives [20,21]. Some advantages of applying the bow-tie approach 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 risk control systems, and SCEs to prevent or mitigate an MHE.
- Provision of stand-alone performance standards to document SCE integrity assurance plan.
- Setting leading and lagging performance indicators.
- Unparalleled communication of MHEs and their controls, demonstration of ALARP.
- Assessment of barrier strength to achieve the desired risk control effectiveness.
- Integration of human and organizational factors by identifying specific barriers to prevent and manage human error.
- Fine-tuning competency and training requirements for individuals accountable for risk-control systems and SCEs.

A few disadvantages have also been identified:

- Requirement to acquire bow-tie software to better document and visualize the resulting large bow-tie diagrams.
- Need to have a robust risk-assessment matrix to appropriately screen MHEs and arrive at a representative set of bow-tie diagrams per facility or business unit.

The authors’ use of the bow-tie concept points toward the application of this tool as a complement, instead of a substitute, to traditional tabular process hazard analysis (e.g., HAZID). Moreover, other semiquantitative applications (e.g., LOPA) are feasible and being used experimentally at this stage. The future of bow-tie diagrams 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.

LITERATURE CITED


