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Risk-Based Process Engineering Framework for Strengthening Reliability Across Complex Natural Gas Infrastructure Systems

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Abstract- ***Natural gas infrastructure is a coupled system of wells, gathering lines, processing units, compressors, transmission pipelines, storage assets, metering stations, and distribution interfaces. Reliability failures within this system rarely arise from one technical defect. They emerge through interactions among degradation, process variability, protection-system performance, human decisions, organizational controls, and external hazards. Existing approaches often treat process safety, asset integrity, inspection, maintenance, and operational risk as separate programs. This paper develops a unified risk-based process engineering framework that connects these programs through a common decision structure. The study uses an integrative review of standards and scholarly literature published to date. The synthesis draws on risk management, risk-based inspection, functional safety, pipeline integrity management, barrier theory, human factors, and reliability engineering. The proposed framework contains eight linked functions: system definition, hazard identification, consequence modelling, failure-likelihood assessment, barrier evaluation, risk aggregation, intervention selection, and performance learning. A bow-tie representation connects initiating causes, preventive barriers, loss-of-containment events, mitigative barriers, and consequences. A dynamic risk register then links each scenario to operating limits, inspection findings, maintenance tasks, management-of-change actions, and leading indicators. The framework replaces isolated equipment rankings with system-level prioritization and treats uncertainty as a decision variable. It also introduces reliability, safety, environmental, and economic criteria into one intervention portfolio. The paper contributes a practical architecture for allocating engineering attention across heterogeneous gas assets while preserving traceability from hazard evidence to action. The framework is suitable for conceptual testing, case-study validation, and later quantitative implementation. Its central proposition is that reliability improves when risk information moves continuously across lifecycle functions rather than remaining within specialist silos.***

Keywords: natural gas infrastructure; risk-based process engineering; reliability; process safety; asset integrity; barrier management; risk-based inspection; functional safety

I. INTRODUCTION

For natural-gas infrastructure, risk analysis must connect credible scenarios with evidence strength, barrier condition, and named decision owners (Kaplan & Garrick, 1981; Reason, 1997; Center for Chemical Process Safety, 2007; International Organization for Standardization, 2018) (Sunday & Omoegun, 2018; Sunday & Omoegun, 2019; Amayo & Popoola, 2017b) (Center, 2012). (Ahammed, 1998; Ale, 2005; American Petroleum Institute, 2016b)

Natural gas supports electricity generation, industrial heat, chemical production, domestic use, and transport. Its value depends on a long physical chain whose elements operate under pressure, temperature variation, cyclic loading, corrosive service, and changing demand. A compressor trip can reduce throughput across downstream facilities. A separator upset can send liquid into equipment designed for gas service. A small leak can escalate when detection, isolation, ignition control, and emergency response fail together. Reliability therefore describes more than equipment availability. It includes the ability of the entire system to deliver its required function without unacceptable harm to people, the environment, assets, or supply continuity (Mbonu & Oluoha, 2019) (Mbonu et al., 2019). (Aven, 2012; Aven, 2016; Aven & Vinnem, 2007)

Traditional engineering programs divide this responsibility. Process engineers manage operating envelopes and throughput. Inspection teams assess

degradation. Maintenance teams restore equipment. Safety specialists study hazards and protective layers. Pipeline integrity groups evaluate threats along linear assets. Operations teams manage daily deviations. Each discipline contributes necessary knowledge, but fragmented decisions produce blind spots. A low-risk equipment item in one register can form a high-risk dependency in the wider network. A maintenance deferral that appears economical can weaken a barrier shared by several accident scenarios. A process change can alter corrosion conditions without reaching the inspection plan. The need is not another isolated method. The need is a decision architecture that joins existing methods. This fragmentation mirrors the systemic-accident perspective developed by Perrow (1984), who showed that interactively complex and tightly coupled systems generate failure modes that no single discipline can anticipate alone, and by Rasmussen (1997), whose dynamic-society model traces how decisions made at separate organizational levels erode safety margins without any single actor intending harm. Leveson (2011) extends this reasoning by treating safety as an emergent system property that must be engineered through control structures rather than assembled from the reliability of separate parts, which is precisely the gap this paper addresses (Lawal & Oduleye, 2019b; Kletz, 1999; Dagodzo, 2018b) (Dagodzo, 2018; Dagodzo, 2018; Leveson, 2011). (Bagheri et al., 2016; Bevilacqua & Ciarapica, 2018; Boschee, 2012)

Risk-based process engineering offers such an architecture. It applies structured risk reasoning to process design, operations, inspection, maintenance, change, and learning. Risk is treated as the combined effect of uncertain events and their consequences, consistent with the general principles of ISO 31000:2018. The approach does not claim that every risk can be reduced to a precise number. Instead, it makes assumptions visible, compares scenarios consistently, directs resources toward the largest risk drivers, and records why an intervention was selected (Ogbete & Ambali, 2019) (Ogbete et al., 2019). (Bransby, 1999; Caleyo et al., 2002; Cheng, 2013)

This paper asks three questions. First, which bodies of knowledge must be integrated to manage reliability across complex natural gas infrastructure? Second, what sequence of engineering decisions connects hazard evidence to prioritized action? Third, which indicators show whether the resulting system is becoming safer and more reliable? The answer is a conceptual framework grounded in literature available by the end of 2019. The paper is country-neutral because gas systems differ in regulation, maturity, climate, terrain, and organizational capacity, while their core engineering relationships remain comparable (Okonkwo & Okeke, 2018a; Aminu-Ibrahim & Ambali, 2018) (Aneke & Adesemoye, 2019; Okonkwo et al., 2018). (Conley, 2005; Cox, 2008; Cozzani & Reniers, 2013)

II. THEORETICAL FRAMEWORK

Natural-gas reliability depends on physical interdependence, operating context, and the quality of asset information used in risk decisions (International Organization for Standardization, 2014, 2018; American Petroleum Institute, 2015). A gas system combines discrete process plants with geographically distributed networks. Upstream flow conditions influence separation and dehydration. Treating and fractionation affect product quality and downstream corrosion. Compression changes pressure, temperature, vibration, and surge exposure. Transmission performance depends on line-pack, station availability, valve function, geohazards, third-party activity, and demand. Storage introduces inventory and deliverability concerns. Metering and control systems connect commercial decisions to physical operation. The full system contains material, energy, information, and organizational flows. This coupling creates three reliability problems. First, local optimization can transfer risk. Increasing throughput can narrow margins to hydrate formation, compressor surge, relief capacity, or product specifications. Second, common dependencies create correlated failures. Shared power, instrumentation air, communications, cooling, or emergency shutdown logic can defeat several units at once. Third, delayed effects conceal causation. A feed-composition change might accelerate damage that becomes visible months later. Reliability analysis must therefore represent dependencies, time, and barriers rather than relying only on equipment failure rates. Comparative accident analyses reinforce this pattern. Papadakis (1999) compared onshore transmission pipeline accidents across multiple national datasets and found that

corrosion, mechanical failure, and third-party interference dominate causation in proportions that shift with pipeline age and operating context, while Restrepo, Simonoff, and Zimmerman (2009) showed that the cost and risk consequences of United States hazardous liquid pipeline accidents are concentrated in a small number of high-severity events, which is why network-level prioritization outperforms uniform equipment-level rules. The useful unit of analysis is the accident or interruption scenario. A scenario begins with a threat or deviation, passes through equipment and barriers, and ends in consequences. Equipment remains important, but its risk derives from its role within scenarios. This scenario-centered view also allows process hazards, integrity threats, cyber-dependent controls, and human action to appear within the same model without forcing them into identical probability techniques (Ilodigwe & Adesemoye, 2019b; International Organization for Standardization, 2015; Sunday & Oluokun, 2019) (International, 2009; International, 2014). (de Ruijter & Guldenmund, 2016; Dey, 2001; Duijm, 2009)

The decision model adopts the scenario, likelihood, and consequence structure established in foundational risk research (Kaplan & Garrick, 1981) and applies organizational controls drawn from accident-causation theory (Reason, 1997). Kaplan and Garrick defined risk through triplets that ask what can happen, how likely it is, and what the consequences are. This formulation remains valuable because it resists the reduction of risk to a single undifferentiated score. ISO 31000:2018 adds governance principles, emphasizing integration, structured analysis, inclusion, change, information quality, human factors, and continual improvement. In process industries, the Center for Chemical Process Safety framed risk-based process safety around commitment, hazard understanding, risk management, and learning. These perspectives share a cycle: establish context, identify scenarios, analyze evidence, evaluate tolerability, treat priorities, monitor performance, and revise decisions. Kaplan (1997) later clarified that the triplet formulation is compatible with both frequentist and subjective interpretations of probability, provided the analyst states which interpretation underlies a given estimate. Aven (2012) situates this choice within a broader foundational debate about whether risk is best treated as an objective property of a system or as a description of uncertainty held by the assessor, and argues that a risk-based framework should make this position explicit rather than leaving it implicit in the choice of method. Risk-based inspection contributes equipment-specific depth. API Recommended Practice 580 describes the elements of an inspection program in which probability and consequence guide inspection planning. API Recommended Practice 581 supplies quantitative methods for pressurized equipment. The value of this logic is prioritization. Inspection does not reduce risk merely by occurring. It reduces uncertainty, detects damage, enables repair, or supports a justified operating decision. An inspection plan should therefore specify the damage mechanism, detection capability, coverage, timing, and decision rule. Earlier applied treatments reach a similar conclusion. Hagemeijer and Kerkveld (1998) proposed one of the first structured methodologies for risk-based inspection of pressurized systems, and Conley (2005) later showed how such inspection outputs can be integrated directly into a facility's broader risk management plan rather than functioning as a standalone technical exercise (Okonkwo & Mayo, 2019; Center for Chemical Process Safety, 2016; Akomolafe & Agu, 2019c) (Obriki & Arumosoye, 2019; Okonkwo et al., 2019; Center, 2007). (Fadayomi et al., 2019; Fang et al., 2019; Ferdous et al., 2011)

Functional safety contributes lifecycle discipline for instrumented protection. IEC 61511:2016 links hazard assessment, allocation of safety functions, safety integrity requirements, design, validation, operation, proof testing, modification, and decommissioning. The standard shows why a barrier cannot be credited only because hardware exists. Its independence, architecture, diagnostics, proof-test interval, bypass management, and maintenance history affect performance. Uncertainty and evidence quality remain central to this reasoning at every stage. Rausand (2011) frames risk assessment as an evidence-gathering process in which model uncertainty and parameter uncertainty must both be reported alongside a point estimate, and Aven (2016) reviews how this dual treatment of uncertainty has matured across engineering risk fields into an accepted requirement for decision-relevant analysis. Pipeline integrity management adds threat-based reasoning across long assets. Corrosion, material and construction defects, equipment failure, incorrect operations, third-party

damage, and natural forces differ in detectability and control. API RP 1173:2015 extends this logic into a pipeline safety management system shaped by leadership, stakeholder engagement, risk management, operational controls, incident investigation, emergency preparedness, competence, documentation, assurance, and management review. Together, these foundations support an integrated framework (Arumosoye & Obriki, 2018; Obogo & Ozobu, 2019; Obogo & Uduokhai, 2019a) (Obogo et al., 2019; Arumosoye & Obriki, 2018; Obogo et al., 2019). (Guo et al., 2017; Hagemeijer & Kerkveld, 1998; Han & Weng, 2011)

Reliability analysis should connect equipment condition with system function, maintenance strategy, and recovery capability rather than treating failure frequency as a complete measure (Khan & Haddara, 2003; International Organization for Standardization, 2014). Reliability is the probability that an item performs a required function under stated conditions for a stated period. Availability expresses the proportion of time the required function is accessible. Maintainability concerns restoration speed and effort. Resilience concerns the capacity to absorb disturbance, sustain essential function, recover, and adapt. These concepts overlap but are not interchangeable. A highly reliable component can belong to a fragile system if it has no redundancy and creates a severe single-point failure. A plant with high availability can still carry unacceptable major-accident risk if production pressure encourages degraded barriers. These definitions follow the formal treatment of reliability, availability, and maintainability developed by Rausand and Hoyland (2004), who show that system-level availability depends not only on component failure and repair rates but on the logical structure connecting components, including redundancy and common-cause dependencies. Michelsen (1998) cautions, from early industrial experience, that the practical value of reliability technology depends less on model sophistication than on whether its outputs actually reach operating and maintenance decisions, a caution the present framework addresses by specifying where each analytical output enters a decision rather than treating analysis as an end in itself. Yu et al. (2018) illustrate the system-level stakes of this caution for gas supply specifically, showing that transmission network deliverability depends on the interaction of component failure, linepack, and compressor redundancy rather than any single asset's availability. Gas infrastructure requires a layered objective. The first layer prevents fatalities, major releases, and intolerable environmental effects. The second preserves containment and process stability. The third sustains required supply. The fourth controls lifecycle cost and energy loss. Tradeoffs must occur inside explicit constraints. Safety-critical actions should not compete directly with discretionary production improvements through an unconstrained financial score. Reliability modelling methods include reliability block diagrams, fault trees, event trees, Markov models, Bayesian networks, failure-mode and effects analysis, and Monte Carlo simulation. Each method answers different questions. Block diagrams expose series and parallel dependencies. Fault trees trace combinations leading to a top event. Event trees trace outcomes after an initiating event. Bayesian networks update beliefs when evidence arrives. Simulation represents variable demand, repair times, and uncertainty. The framework proposed here does not mandate one technique. It specifies where model outputs enter decisions and requires the method to match data quality and decision stakes. Modarres, Kaminskiy, and Krivtsov (2016) provide a practical synthesis of these techniques and stress that model selection should follow the decision at stake rather than analyst preference, a principle consistent with the framework's refusal to mandate one method. Ferdous et al. (2011) extend fault tree and event tree analysis with explicit uncertainty handling formulations, showing how parameter and model uncertainty can propagate through these classical techniques rather than being suppressed in a single point estimate. Reliability-centered maintenance, as formalized by Moubray (1997), offers a complementary logic for translating failure-mode information into maintenance task selection, asking what function is required, how it can fail, and what task most economically prevents or detects that failure (International Organization for Standardization, 2016; Lawal & Oduleye, 2018a; Amayo, 2017) (Dagodzo, 2018; International, 2006; Dhillon, 2006). (Hopkins, 2005; Jin & Summers, 2015; Jo & Ahn, 2005)

Hazard analysis becomes actionable when each threat is connected to a top event, consequences, preventive barriers, and mitigative barriers (Sklet, 2006; Center

for Chemical Process Safety, 2007, 2018). A common taxonomy allows information from different disciplines to meet. Process deviations include high or low pressure, temperature, flow, level, composition, and liquid carryover. Mechanical threats include corrosion, erosion, fatigue, vibration, fracture, seal degradation, and overpressure. Pipeline threats include external and internal corrosion, stress-corrosion cracking, manufacturing defects, construction damage, equipment failure, incorrect operations, third-party interference, geotechnical movement, flooding, and other natural forces. Utility failures include power, fuel gas, instrument air, cooling, communications, and control-system loss. Khan and Abbasi (1999) similarly analyzed causes and consequences across a large set of process industry accidents and found that mechanical failure and human error together account for the majority of major losses, a pattern consistent with treating both categories as first-class entries in the hazard taxonomy rather than secondary considerations. Marinos, Stoumpos, and Papazachos (2019) demonstrate this geotechnical threat category directly in their landslide hazard and risk assessment of the Trans Adriatic Pipeline, showing how slope-movement probability and pipe strain interact to determine rupture likelihood along a specific corridor. Human and organizational contributors require equal visibility. They include unclear procedures, alarm overload, inadequate shift handover, weak competence assurance, deferred maintenance, contractor-interface gaps, production pressure, poor management of change, and incomplete learning. These contributors often shape the probability that a technical threat develops, remains undetected, or escalates. Hopkins (2005) traces how organizational and cultural conditions, not only technical failures, produced the causal chain behind major process accidents, reinforcing why these contributors deserve equal visibility in the taxonomy rather than being treated as background context. Applied human factors research supports this taxonomy. Kariuki and Löwe (2006) show that structured human factors techniques measurably increase human reliability in chemical process operations, and Bevilacqua and Ciarapica (2018) confirm, in a process industry case study, that workload, competence, and organizational pressure remain the dominant drivers of human factor risk even where instrumented protection is in place. The taxonomy should preserve causal links. Corrosion is not a complete scenario. A defensible scenario might describe water and acid-gas conditions causing internal wall loss in a low point, followed by undetected growth, rupture, delayed isolation, ignition, and harm. This form identifies the data needed at each stage and prevents vague rankings. Kidam and Hurme (2013) analyzed equipment failures across a large set of process accidents and found that design-stage deficiencies and maintenance-related degradation, rather than a single catastrophic material defect, account for most equipment-related losses, which supports representing corrosion and other degradation mechanisms as extended causal chains rather than isolated component ratings. Kletz (1999), whose hazard and operability study method underlies much of the taxonomy applied here, made the same point about process deviations: a deviation is only meaningful once it is traced to a cause and a consequence through the intervening equipment and human response (Akomolafe & Agu, 2018; Arumosoye & Obriki, 2019; Obogo & Uduokhai, 2019b) (Obogo et al., 2019; Arumosoye & Obriki, 2019; Center, 2018). (Kalantarnia et al., 2009; Kaplan, 1997; Kariuki & Löwe, 2006)

III. METHODOLOGY

The study followed an integrative conceptual-review method. It combined peer-reviewed research, recognized engineering standards, technical guidance, and an author-supplied citation collection. Sources were eligible when published no later than 31 December 2019 and when they addressed natural gas infrastructure, process safety, pipeline risk, risk-based inspection, reliability, corrosion, functional safety, human factors, barrier management, or enterprise risk. Later editions and retrospective webpages were excluded from the evidentiary synthesis even when they described an earlier standard. The cutoff controls the historical knowledge base rather than the date on which a source was accessed (Agbabiaka & Okeke, 2019; Ladapo & Abolaji, 2019; Akomolafe & Agu, 2019a) (Agbabiaka et al., 2019). (Khakzad, 2015; Khakzad et al., 2012; Khan & Abbasi, 1998)

The review proceeded in four stages. The first stage defined the infrastructure boundary and the reliability problem. The second extracted recurring concepts, including probability of failure, consequence of

failure, safety barriers, operating envelope, degradation mechanism, human and organizational factors, uncertainty, and feedback. The third compared the decision logic of risk management, risk-based inspection, functional safety, and pipeline integrity systems. The fourth translated the shared logic into a unified process-engineering architecture (Badmus & Ozowara, 2018) (Aven & Renn, 2010). (Khan & Abbasi, 1999; Khan & Abbasi, 2001; Khan & Amyotte, 2004)

The review is conceptual, not systematic in the narrow meta-analytic sense. The literature contains different units of analysis, data structures, consequence categories, and sector assumptions. Statistical pooling would create false comparability. The synthesis instead seeks theoretical completeness and operational traceability. It identifies what information a defensible decision requires, where that information originates, and how it should affect design or operating action. This method supports proposition development and later empirical testing. Khan and Abbasi (1998) catalogue the many quantitative and qualitative risk-analysis techniques used across chemical process industries and note that no single technique addresses every scenario type, a conclusion the eight-function framework treats as a design constraint rather than a limitation to be engineered away. Marhavilas, Koulouriotis, and Gemeni (2011) reach a similar conclusion in their classification of risk analysis methodologies applied at work sites, finding that qualitative, quantitative, and hybrid techniques answer different questions rather than competing to replace one another, which supports treating method choice as a design decision tied to the question at hand (Badmus & Ozowara, 2019a) (Gbadamosi & Obogo, 2013; Marhavilas et al., 2011). (Kidam & Hurme, 2013; Landucci et al., 2017; Li et al., 2015)

IV. FINDINGS AND DISCUSSION

The Proposed Framework

The proposed framework combines risk-based process safety, pipeline safety management, risk-based inspection, and functional-safety lifecycle principles (Center for Chemical Process Safety, 2007; American Petroleum Institute, 2015, 2016a, 2016b; International Electrotechnical Commission, 2016). The bow-tie logic that connects these functions has itself matured into a distinct methodological literature: de Ruijter and Guldenmund (2016) trace its development from a qualitative communication tool into a semi-quantitative barrier-based method, while Duijm (2009) shows how safety-barrier diagrams can be built directly from bow-tie elements to support day-to-day barrier management rather than one-time hazard studies (Center for Chemical Process Safety, 2008; Center for Chemical Process Safety, 2010) (Center, 1992; Center, 2000; Center, 1995). (Li et al., 2016; Lu et al., 2015; Macaulay & Singer, 2016)

The proposed Risk-Based Process Engineering Framework contains eight connected functions. Function one defines the system, objectives, boundaries, operating modes, dependencies, and decision authority. Function two identifies hazards and constructs credible scenarios. Function three estimates consequences across safety, environment, supply, asset, reputation, and cost. Function four estimates failure likelihood using mechanism models, inspection data, operating history, reliability data, and expert judgment. Function five identifies barriers and evaluates their effectiveness, independence, degradation, and assurance. Function six aggregates risk without hiding category-specific intolerability. Function seven selects a portfolio of design, operating, inspection, maintenance, and preparedness interventions. Function eight monitors indicators, learns from events and weak signals, and updates the model. Table 1 summarizes the eight functions together with the core question each answers and its primary output (Mbonu & Oluoha, 2019) (Mbonu et al., 2019). (Marinos et al., 2019; Massaiu & Paltrinieri, 2016; Meel & Seider, 2006)

The framework uses three linked records. The scenario register states causes, top events, consequences, assumptions, uncertainty, and risk owner. The barrier register states barrier purpose, performance standard, owner, assurance task, impairment state, and dependencies. The action register states the selected intervention, expected risk reduction, cost, deadline, verification method, and residual risk. A unique scenario identifier links all three. (Meyer, 2011; Michelsen, 1998; Modarres et al., 2016)

The framework also separates inherent risk, current residual risk, and forecast residual risk. Inherent risk

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assumes no credited safeguards. Current residual risk credits barriers whose effectiveness is supported by evidence. Forecast residual risk reflects the condition expected after approved actions. This separation prevents planned work from being treated as completed protection and exposes the risk carried during implementation delay. (Moskowitz et al., 2016; Moubray, 1997; Muhlbauer, 2004)

Figure 1 presents a bow-tie view linking threats, preventive controls, the central loss event, consequences, and recovery measures. Table 1 serves a different purpose by defining performance measures for judging whether the framework improves risk, reliability, resilience, and assurance.

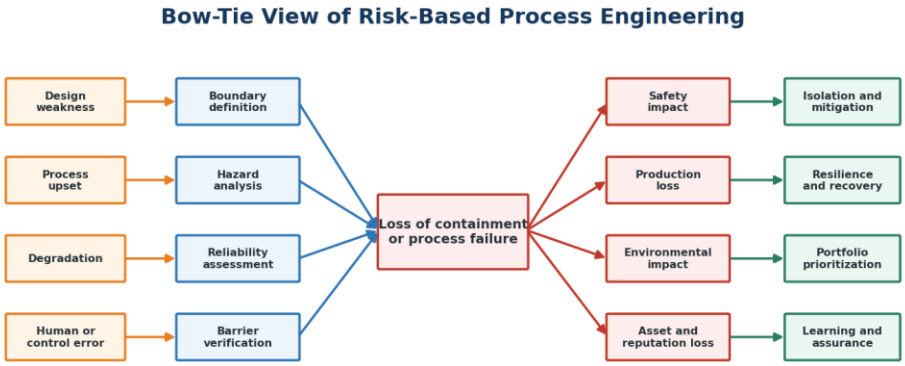

Figure 1. Bow-tie representation of the Risk-Based Process Engineering Framework.

Table 1. Performance Measures for Monitoring Risk-Based Process Engineering Outcomes

Performance dimension	Suggested measure	Interpretation	Management use
Risk exposure	Annualized scenario risk	Combined frequency and consequence	Rank capital and operating controls
Reliability	Critical-equipment availability	Share of required service time achieved	Set reliability improvement priorities
Detectability	Median warning time	Time available before functional loss	Improve sensing and alarm coverage
Resilience	Time to stable recovery	Speed of restoration after disruption	Test recovery resources and procedures
Maintenance	Risk-weighted overdue work	Backlog exposure for critical assets	Direct maintenance resources
Data quality	Verified-data completeness	Evidence strength behind risk estimates	Target measurement improvements
Change risk	Unassessed modifications	Exposure created by unmanaged change	Strengthen management of change

Performance dimension	Suggested measure	Interpretation	Management use
Assurance	Closed actions verified	Effectiveness of completed controls	Confirm sustained risk reduction

System Definition and Boundary Control. A useful assessment begins with a boundary that matches the decision. For a facility study, the boundary might include feed receipt, separation, dehydration, compression, export, utilities, flare, control, and emergency systems. For a corridor study, it might include compressor stations, mainline segments, crossings, valves, communications, and emergency access. Boundary diagrams should show material and energy interfaces, control dependencies, shared utilities, adjacent populations, environmentally sensitive areas, and external stakeholders. (Necci et al., 2015; Nessim et al., 2009; Nivolianitou & Papazoglou, 1998)

Operating modes must be explicit. Startup, shutdown, turndown, recirculation, maintenance, upset, temporary repair, and emergency operation produce different hazards from stable production. Seasonal demand and feed variability can move equipment into rarely tested regions. The assessment should list permitted modes, prohibited combinations, and transition controls. (Nwafor et al., 2019; Paltrinieri et al., 2014; Paltrinieri et al., 2016)

Boundary control also means version control. Process flow diagrams, piping and instrumentation diagrams, cause-and-effect charts, relief studies, line lists, equipment files, procedures, and geographic data must represent the same configuration. A risk model built from outdated drawings gives false precision. Document quality should therefore appear as a leading indicator and as a source of model uncertainty. (Papadakis, 1999; Perrow, 1984; Rasmussen, 1997)

Scenario Construction and Bow-Tie Logic. Hazard identification methods serve different purposes. Hazard and operability study examines deviations from design intent. What-if analysis tests structured questions. Failure-mode and effects analysis starts from component failures. Fault-tree analysis works backward from a top event. Event-tree analysis works forward through protection successes and failures. Job and task analysis exposes human interactions. No single method covers the entire gas system. These methods are catalogued comprehensively in Mannan's (2012) edition of Lees' Loss Prevention in the Process Industries, which remains a standard reference for hazard identification and consequence modelling techniques across the process industries (Mannan, 2012) (Baybutt, 2015; Ericson, 2015). (Rathnayaka et al., 2011; Rausand, 2011; Rausand & Hoyland, 2004) The framework uses bow-tie logic as an integration layer. The top event represents loss of control, such as loss of containment, compressor surge, off-specification export, or loss of critical supply. Threats and preventive barriers appear on the left. Consequences and mitigative barriers appear on the right. Escalation factors explain how a barrier might fail, and escalation controls protect the barrier. Khakzad, Khan, and Amyotte (2012) demonstrate that a bow-tie diagram can be mapped onto a Bayesian network to compute how the probability of the top event changes as barrier-performance data accumulate, and their later work (Khakzad et al., 2013) extends this mapping to update barrier and escalation-factor probabilities dynamically as inspection and monitoring evidence arrives, which is the same updating logic this framework assigns to function eight. This mapping has since extended to other formalisms. Yazdi and Kabir (2017) combine fuzzy set theory with Bayesian networks to handle imprecise probability inputs in process industry risk analysis, Li, Chen, and Zhu (2016) apply a Bayesian network formulation specifically to leakage failure of submarine oil and gas pipelines, and Zarei et al. (2017) show that a Bayesian network representation of dynamic safety risk can be updated in near real time as process data accumulate, a capability increasingly relevant to modern gas processing control systems. (Reason, 1990; Restrepo et al., 2009; Skogdalen & Vinnem, 2011)

Bow-ties should not become decorative diagrams. Each credited barrier needs a performance standard. The standard should define function, availability, reliability, survivability, response time, capacity, and assurance. An alarm is not automatically a barrier. Credit depends on detection, operator response time, procedure quality, workload, and available control action. Likewise, an isolation valve requires detection logic, closure capability, leak tightness, power, and testing. Alarm system performance illustrates the same point. Bransby (1999) shows that reliable operator response depends on alarm system design being matched to realistic response times and workload, Li et al. (2015) demonstrate that distributed alarm management strategies can materially reduce alarm floods without sacrificing detection of genuine deviations, and Moskowitz et al. (2016) model process and operator response time jointly, showing that credited alarm performance should reflect realistic human response rather than an idealized instant reaction. (Stack, 2009; Teng et al., 2012; Vianello & Maschio, 2014)

Consequence Analysis. Consequence analysis should begin with realistic release or interruption cases. Process inventory, pressure, temperature, composition, hole size, isolation time, blowdown, terrain, ventilation, congestion, and ignition affect physical outcomes. Models may estimate dispersion, fire radiation, explosion overpressure, toxic exposure, environmental reach, repair duration, and supply loss. The analyst should document assumptions and sensitivity rather than present a single deterministic output as fact. (Villa et al., 2016; Wieczorek & Basu, 1997; Xing et al., 2009)

Multiple consequence dimensions should remain visible. Fatality risk and major environmental harm require threshold treatment. Supply and financial effects support prioritization after mandatory constraints are met. Monetizing every outcome into one figure can obscure ethical and regulatory differences. A practical risk matrix may support screening, but high-stakes scenarios need quantitative or semi-quantitative analysis with uncertainty bounds (Kaplan & Garrick, 1981). (Yazdi & Kabir, 2017; Younsi & Smati, 2017; Yu et al., 2018)

System consequences include propagation. A failed compressor may constrain upstream wells, destabilize downstream processing, increase flaring, and reduce delivery. A pipeline isolation can shift flow into another corridor and consume redundancy. The assessment should therefore model dependency and recovery, not only immediate damage. Consequence studies at network scale illustrate this propagation logic. Guo et al. (2017) modeled how submarine pipeline instability propagates into span-length-dependent failure consequences that extend well beyond the initiating geotechnical event, and Vianello and Maschio (2014) showed, in a quantitative risk assessment of the Italian gas distribution network, that consequence estimates for urban distribution systems are highly sensitive to population-density assumptions near the failure point, which argues for documenting these assumptions explicitly rather than treating a single consequence figure as fact. Escalation between adjacent units, commonly termed the domino effect, has attracted a substantial dedicated literature. Khan and Abbasi (2001) provided an early quantitative assessment of domino likelihood and damage potential within a typical industrial cluster, Cozzani and Reniers (2013) trace how this literature matured into a distinct methodological field, and Necci et al. (2015) review the resulting state of the art and identify data availability as the main remaining constraint (Vinnem, 2014). (Zarei et al., 2017; Zarei et al., 2016; Zhang et al., 2019)

Likelihood and Degradation Assessment. Degradation estimates require mechanism-specific inspection evidence, measurement uncertainty, and updating after new findings (American Petroleum Institute, 2016a, 2016b; Yuhua & Datao, 2005). (Dagodzo, 2018a)

Likelihood combines initiating-event frequency, conditional barrier failure, and exposure. Historical failure rates provide a starting point but require adjustment for design, age, environment, operation, and data quality. Damage-mechanism models offer causal information. For internal corrosion, relevant evidence includes water content, carbon dioxide or hydrogen sulfide partial pressure, temperature, velocity, solids, microbial activity, inhibitor delivery, pigging, and inspection measurements. For fatigue, cycles and stress range matter. For external interference, land use, burial, marking, patrol, and

stakeholder activity matter. Dey (2001) developed one of the earlier risk-based inspection and maintenance models for cross-country petroleum pipelines, combining likelihood and consequence scoring with an analytic hierarchy process to prioritize inspection resources, an approach whose logic persists in current risk-based inspection practice. Reliability-based approaches extend this logic further. Ahammed (1998) developed one of the earlier probabilistic models for estimating remaining pipeline life from active corrosion defects, Caleyo, Gonzalez, and Hallen (2002) refined the reliability assessment methodology for pipelines carrying such defects, and Nessim et al. (2009) establish target reliability levels for the design and assessment of onshore natural gas pipelines that translate these defect-level estimates into system-level acceptance criteria.

Risk-based inspection should target the mechanisms that dominate uncertainty and risk. Inspection effectiveness depends on technique capability, coverage, sizing error, access, and analyst competence. A negative finding does not prove absence of damage. Detection probability and measurement error should inform remaining-life estimates and reinspection intervals (Ilodigwe & Adesemoye, 2019a).

Bayesian updating offers a disciplined way to combine prior knowledge with new evidence. Exact Bayesian models are not required for every decision. The principle is that inspection, monitoring, near misses, and process excursions should change the assessed likelihood. A static annual score that ignores new evidence is not risk based in practice. Kalantarnia, Khan, and Hawboldt (2009) operationalize this updating principle by combining failure and repair data through Bayes' theorem to revise accident likelihood after each new observation, and Paltrinieri, Khan, Amyotte, and Cozzani (2014) show, through retrospective analysis of the Hoeganaes metal dust accidents, that near misses and process deviations recorded before the final event carried the statistical signal needed to have revised the risk estimate in time. Villa, Paltrinieri, Khan, and Cozzani (2016) review this dynamic risk analysis literature and caution that its practical adoption remains limited by data infrastructure rather than by the underlying statistical method, a limitation this framework's governance and data architecture functions are intended to address. Rathnayaka, Khan, and Amyotte (2011) formalize a parallel predictive accident-modelling approach, later applied to an LNG processing facility (Rathnayaka, Khan, & Amyotte, 2012), that traces how deviations propagate through safety functions before culminating in loss of containment, offering a template for scenario-linked likelihood updating in gas-processing assets. Meel and Seider (2006) independently developed a plant-specific dynamic failure assessment method using Bayesian theory, reinforcing the case that likelihood estimates should update continuously as operating evidence accumulates rather than resetting at fixed review intervals (Adeyelu, 2018) (Adeyelu, 2018).

Barrier Performance and Functional Safety. Barrier management converts hazard analysis into operational control. Preventive barriers reduce top-event frequency. Mitigative barriers reduce escalation or consequence. Examples include materials selection, corrosion control, process control, relief, shutdown, isolation, drainage, ventilation, gas detection, ignition control, fire protection, emergency response, and land-use measures (Atta & Adenuga, 2018).

IEC 61511:2016 supplies a lifecycle for safety instrumented functions. Hazard analysis defines the required function and integrity. Design provides architecture and diagnostics. Validation confirms implementation. Operation and proof testing sustain performance. Management of change controls modification. The broader framework applies similar lifecycle logic to all critical barriers. This lifecycle logic descends from the generic functional-safety standard IEC 61508 (International Electrotechnical Commission, 2010), which established the safety-lifecycle and safety-integrity-level concepts that IEC 61511 subsequently adapted to the process sector (Amayo & Popoola, 2017a) (International, 2009; International, 2018).

Barrier health should be visible to decision makers. Status categories might include healthy, degraded, bypassed, failed, unknown, and under test. Aggregation should recognize shared dependencies. Three shutdown functions using one transmitter do not provide three independent layers. Barrier dashboards must avoid counting devices without testing

independence and common-cause exposure. Skogdalen and Vinnem (2011) found, in a review of offshore quantitative risk analyses, that human and organizational factors are frequently represented only as generic multipliers on hardware failure rates, which understates their influence on barrier availability; a defensible barrier dashboard should instead trace how staffing, competence, and workload affect the specific barriers they support. Domino-specific barrier credit raises a similar concern. Landucci et al. (2017) develop a method for assessing mitigated domino scenarios once protective measures are credited, and Khakzad (2015) shows that a dynamic Bayesian network can update domino risk estimates as barrier performance evidence accumulates during operation, extending the same updating logic this framework assigns to its learning function.

Risk Evaluation and Tolerability. Risk evaluation compares analyzed risk with criteria and identifies treatment priorities. Criteria should be approved before results are known. They should address individual and societal safety, environmental harm, supply interruption, regulatory duties, asset loss, and organizational risk appetite. The as-low-as-reasonably-practicable principle supports further reduction between broadly acceptable and intolerable regions, but it does not excuse weak analysis. Aven and Vinnem (2007) describe how ALARP judgments in the offshore petroleum industry combine risk analysis results with cost-benefit reasoning and broader managerial judgment, and caution that the principle can be misapplied if it is used to justify inaction rather than to structure a genuine search for further risk reduction. Ale (2005) compares how the United Kingdom and Dutch regulatory regimes operationalize the boundary between tolerable and acceptable risk, showing that even mature regulatory systems draw this line differently, which is why the framework treats tolerability criteria as an organizational decision to be approved explicitly rather than assumed from external practice (Akomolafe & Agu, 2019b) (Aven & Zio, 2014).

Ranking methods should distinguish screening from final decisions. A risk matrix is efficient for a large population but can suffer category compression and arbitrary boundaries. Cox (2008) demonstrates formally that risk matrices can rank risks inconsistently with the underlying likelihood and consequence values they are built from, reinforcing why the framework treats the matrix as a screening aid rather than a substitute for quantitative or semi-quantitative analysis in high-stakes scenarios. Quantitative risk analysis supports major scenarios but depends on uncertain inputs. Layer-of-protection analysis offers a structured middle ground for process scenarios when initiating frequencies and independent protection layers are defined consistently. The Center for Chemical Process Safety (2015) sets out the elements this analysis should contain, but the credibility of the middle ground it offers depends on how independence is judged. Stack (2009) and Jin and Summers (2015) both show that protection layers sharing sensors, logic solvers, or maintenance crews are not truly independent and can be significantly overcounted if evaluated only at the device level, while Meyer (2011) illustrates, across three representative chemical processes, how a disciplined independent protection layer analysis changes the credited risk reduction compared with a naive layer count (Center for Chemical Process Safety, 2007) (Center, 2001; Center, 2015; Center, 2003).

Uncertainty should influence priority. Two scenarios with equal central estimates need not receive equal action when one rests on weak data or unverified barriers. The framework adds an uncertainty class and an evidence-quality score. High uncertainty can trigger inspection, testing, engineering study, or conservative temporary control (Michael & Ogunsola, 2019a).

Intervention Portfolio Selection. Risk treatment follows a hierarchy. Elimination and inherent safety remove or reduce hazards at source. Engineered prevention reduces event frequency. Engineered mitigation limits escalation. Administrative controls guide human action. Emergency response limits remaining consequences. Inspection and monitoring produce information and enable timely treatment. The strongest portfolio combines measures rather than relying on one layer. This hierarchy follows the same logic as the integrated inherent safety index proposed by Khan and Amyotte (2004), which scores design options on inherent safety, hazard, and cost criteria to identify where elimination or substitution offers more durable risk reduction than added protective layers.

Optimization should respect mandatory constraints. After intolerable risks and compliance obligations are addressed, remaining options can be compared by risk reduction, cost, schedule, downtime, feasibility, uncertainty reduction, and lifecycle benefit. A portfolio view matters because resources, shutdown windows, engineering capacity, and spare parts are shared.

Every approved action needs a closure standard. Completing a work order does not prove risk reduction. Verification might require testing, updated drawings, revised procedures, training, inspection evidence, or performance monitoring. Deferred actions require an explicit risk owner, interim controls, expiry date, and escalation threshold.

Management of Change and Operational Discipline. Natural gas systems change continuously. The Center for Chemical Process Safety (2008) sets out the elements a management-of-change program should contain, including technical review, authorization, and time-limited temporary changes, and Wieczorek and Basu (1997) show, in an early pilot-plant application, that even small-scale facilities benefit from formal change screening once change frequency and technical diversity exceed what informal review can reliably track. Feed composition, throughput, chemicals, control logic, alarm settings, equipment duty, staffing, inspection intervals, suppliers, software, and procedures can alter risk. Management of change should screen technical, organizational, and temporary changes. The review must connect the proposed change to affected scenarios, barriers, documents, training, and startup authorization (Ogbete & Ambali, 2018) (Ogbete et al., 2018; Center, 2011).

Operating envelopes translate design and integrity assumptions into daily control. Limits should cover variables that drive damage, protection demand, and product quality. Excursions require recording, technical review, corrective action, and model update. Repeated excursions are evidence of a mismatch between design, operation, and maintenance.

Operational discipline depends on usable procedures, competence, supervision, shift handover, alarm management, permit systems, and field verification. Human reliability is shaped by system design. Blaming an operator after an event obscures workload, interface design, conflicting goals, missing information, and latent organizational conditions. Reason (1990) distinguishes active failures, the unsafe acts of people at the point of operation, from latent conditions built into procedures, training, and supervision long before an event, and argues that organizations that focus corrective action only on the former will keep encountering the same latent conditions in new circumstances. Applied human reliability analysis offers complementary tools for this diagnosis. Massaiu and Paltrinieri (2016) review the main qualitative and quantitative human reliability analysis methods available for process applications, and Paltrinieri, Massaiu, and Matteini (2016) show how these methods adapt to petroleum industry operating conditions, while Zarei et al. (2016) link control room operators' decision making style directly to predicted task efficiency, reinforcing the case for treating operator performance as a modelled variable rather than an unexplained source of variance (Ladapo & Abolaji, 2018) (Zio, 2009).

Performance Measurement and Learning. Leading indicators, near-miss records, and hazard observations support earlier intervention than lagging outcome measures alone.

Lagging indicators measure outcomes such as releases, fires, injuries, shutdowns, repair cost, and lost delivery. They matter but arrive after control has failed. Leading indicators measure the condition of barriers and management processes. Examples include overdue proof tests, inspection coverage against plan, corrosion-monitor availability, alarm-system performance, safety-critical maintenance backlog, temporary repairs, overdue management-of-change actions, operating-envelope excursions, emergency-drill findings, and closure quality.

Indicators should connect to scenarios. A corporate count of overdue tasks has limited meaning unless decision makers know which barriers and consequences are exposed. Risk-weighted backlog provides more information than raw backlog. Indicator thresholds should trigger defined actions.

Learning includes incidents, near misses, successful recoveries, audit findings, inspection discoveries, and

weak signals. The update process should ask whether the scenario set, frequencies, consequences, barrier assumptions, and intervention rules remain valid. Management review then tests whether risk is moving in the intended direction.

Governance and Data Architecture. Plant uptime and project delivery depend on materials readiness, procurement controls, and traceable risk ownership across engineering and operational functions. Nwafor et al. (2019) find that an explicit analytical framework for scheduling and resource allocation improves efficiency in public infrastructure delivery, a logic consistent with treating governance and data architecture as delivery critical rather than administrative overhead (Okonkwo & Okeke, 2018b) (Okonkwo et al., 2018).

Integration requires governance. Senior leadership sets risk criteria and resources. Asset owners accept residual risk within delegated authority. Technical authorities define minimum engineering rules. Scenario owners maintain risk records. Barrier owners maintain performance standards and assurance. Teng, Thekdi, and Lambert (2012) show that risk and safety organizations often struggle to identify which of their own business processes most deserve prioritized attention, underscoring why the framework assigns scenario and barrier ownership explicitly rather than leaving priority setting to informal organizational judgment. Independent assurance tests whether the system works as described. Nivolianitou and Papazoglou (1998) illustrate one applied approach to this assurance function, developing an auditing methodology that scores safety management performance across a national process industry sector rather than relying on plant by plant self-assessment (Adeyelu, 2019) (Adeyelu, 2019; Center, 2009).

A minimal data architecture links asset hierarchy, process tags, pipeline segments, scenarios, barriers, work orders, inspection results, changes, incidents, and documents. Unique identifiers and controlled vocabularies matter more than an elaborate dashboard. Poor master data can create duplicate assets, lost history, and misleading aggregation.

Access, audit trails, validation, and cybersecurity protect decision integrity. Fadayomi et al. (2019) note that risk-based cybersecurity assurance must also address data availability limitations across control and business systems, and Dosunmu and Ogundele (2019) similarly argue that security auditing and enterprise risk assessment frameworks are necessary to keep decision-support information resilient against both technical failure and malicious interference. Macaulay and Singer (2016) provide a comprehensive treatment of the SCADA, distributed control, and safety instrumented system vulnerabilities that this governance layer must anticipate. The framework does not require a digital twin. A governed relational database and disciplined workflow can support initial implementation. Technology should follow the decision model rather than define it. Boschee (2012) surveys how emerging monitoring and data technologies are extending asset integrity management offshore, illustrating both the opportunity and the temptation to substitute new technology for disciplined decision architecture; the framework treats such tools as inputs to, not replacements for, the governance structure described here (Mbonu & Oluoha, 2018; Dosunmu & Ogundele, 2019; Dogbatsey & Oyeleye, 2019) (Mbonu et al., 2018).

Application Across Asset Classes

The following application analysis demonstrates how the same eight-function logic changes across six asset classes. Each paragraph is a decision prompt for case-study validation rather than a claim about a specific installation.

Gathering Pipelines. For gathering pipelines, system definition should begin with the required function of containment and feed continuity. The responsible team should map boundaries, operating modes, interfaces, and shared utilities. The analysis must consider internal corrosion, external interference, unstable multiphase flow, and terrain movement. Evidence should come from approved drawings and an asset hierarchy, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For gathering pipelines, hazard identification should begin with the required function of containment and feed continuity. The responsible team should construct cause-to-consequence scenarios for normal and abnormal modes. The analysis must consider internal corrosion, external interference, unstable multiphase flow, and terrain movement. Evidence should come from multidisciplinary workshops and operating history, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For gathering pipelines, consequence analysis should begin with the required function of containment and feed continuity. The responsible team should estimate safety, environmental, supply, and asset effects. The analysis must consider internal corrosion, external interference, unstable multiphase flow, and terrain movement. Evidence should come from release models, inventory data, and recovery studies, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For gathering pipelines, likelihood assessment should begin with the required function of containment and feed continuity. The responsible team should connect credible degradation and failure mechanisms to exposure. The analysis must consider internal corrosion, external interference, unstable multiphase flow, and terrain movement. Evidence should come from inspection, monitoring, and failure records, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review. Muhlbauer (2004) offers a widely used scoring framework for exactly this class of asset, combining third-party damage, corrosion, design, and incorrect-operations indices into a single relative-risk score that gathering-system operators can build from routinely available records.

For gathering pipelines, barrier evaluation should begin with the required function of containment and feed continuity. The responsible team should test function, independence, availability, and assurance. The analysis must consider internal corrosion, external interference, unstable multiphase flow, and terrain movement. Evidence should come from performance standards and test evidence, with dates, ownership, and configuration status recorded. The assessor should

distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For gathering pipelines, risk evaluation should begin with the required function of containment and feed continuity. The responsible team should compare current risk with category-specific criteria. The analysis must consider internal corrosion, external interference, unstable multiphase flow, and terrain movement. Evidence should come from approved tolerability rules and uncertainty classes, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For gathering pipelines, intervention selection should begin with the required function of containment and feed continuity. The responsible team should choose design, operating, inspection, maintenance, or preparedness actions. The analysis must consider internal corrosion, external interference, unstable multiphase flow, and terrain movement. Evidence should come from portfolio ranking with mandatory constraints, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For gathering pipelines, learning should begin with the required function of containment and feed continuity. The responsible team should update assumptions after changes, excursions, findings, and events. The analysis must consider internal corrosion, external interference, unstable multiphase flow, and terrain movement. Evidence should come from indicator review and model revision, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

Separation and Treating Units. For separation and treating units, system definition should begin with the required function of phase control and contaminant removal. The responsible team should map boundaries, operating modes, interfaces, and shared utilities. The analysis must consider level-control failure, foaming, corrosion, overpressure, and off-specification chemistry. Evidence should come from approved drawings and an asset hierarchy, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For separation and treating units, hazard identification should begin with the required function of phase control and contaminant removal. The responsible

team should construct cause-to-consequence scenarios for normal and abnormal modes. The analysis must consider level-control failure, foaming, corrosion, overpressure, and off-specification chemistry. Evidence should come from multidisciplinary workshops and operating history, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review (Amayo & Oshevire, 2015).

For separation and treating units, consequence analysis should begin with the required function of phase control and contaminant removal. The responsible team should estimate safety, environmental, supply, and asset effects. The analysis must consider level-control failure, foaming, corrosion, overpressure, and off-specification chemistry. Evidence should come from release models, inventory data, and recovery studies, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review. Rathnayaka, Khan, and Amyotte (2012) applied a related predictive accident-modelling approach to an LNG processing facility, tracing how a level-control deviation propagated through interlocks and relief systems before contributing to loss of containment, a pathway consistent with the deviation types considered here. Bagheri, Alamdari, and Davoudi (2016) similarly use computational fluid dynamics to refine consequence estimates for sour gas transmission downstream of treating units, showing that simplified point-source dispersion models can understate near-field toxic exposure where hydrogen sulfide is present (Khan et al., 2015).

For separation and treating units, likelihood assessment should begin with the required function of phase control and contaminant removal. The responsible team should connect credible degradation and failure mechanisms to exposure. The analysis must consider level-control failure, foaming, corrosion, overpressure, and off-specification chemistry. Evidence should come from inspection, monitoring, and failure records, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For separation and treating units, barrier evaluation should begin with the required function of phase control and contaminant removal. The responsible team should test function, independence, availability, and assurance. The analysis must consider level-control failure, foaming, corrosion, overpressure, and off-specification chemistry. Evidence should come from performance standards and test evidence, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For separation and treating units, risk evaluation should begin with the required function of phase control and contaminant removal. The responsible

team should compare current risk with category-specific criteria. The analysis must consider level-control failure, foaming, corrosion, overpressure, and off-specification chemistry. Evidence should come from approved tolerability rules and uncertainty classes, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For separation and treating units, intervention selection should begin with the required function of phase control and contaminant removal. The responsible team should choose design, operating, inspection, maintenance, or preparedness actions. The analysis must consider level-control failure, foaming, corrosion, overpressure, and off-specification chemistry. Evidence should come from portfolio ranking with mandatory constraints, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For separation and treating units, learning should begin with the required function of phase control and contaminant removal. The responsible team should update assumptions after changes, excursions, findings, and events. The analysis must consider level-control failure, foaming, corrosion, overpressure, and off-specification chemistry. Evidence should come from indicator review and model revision, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

Compressor Trains. For compressor trains, system definition should begin with the required function of pressure delivery and throughput. The responsible team should map boundaries, operating modes, interfaces, and shared utilities. The analysis must consider surge, vibration, seal failure, lube-oil loss, and driver trips. Evidence should come from approved drawings and an asset hierarchy, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For compressor trains, hazard identification should begin with the required function of pressure delivery and throughput. The responsible team should construct cause-to-consequence scenarios for normal and abnormal modes. The analysis must consider surge, vibration, seal failure, lube-oil loss, and driver trips. Evidence should come from multidisciplinary workshops and operating history, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work

connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For compressor trains, consequence analysis should begin with the required function of pressure delivery and throughput. The responsible team should estimate safety, environmental, supply, and asset effects. The analysis must consider surge, vibration, seal failure, lube-oil loss, and driver trips. Evidence should come from release models, inventory data, and recovery studies, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For compressor trains, likelihood assessment should begin with the required function of pressure delivery and throughput. The responsible team should connect credible degradation and failure mechanisms to exposure. The analysis must consider surge, vibration, seal failure, lube-oil loss, and driver trips. Evidence should come from inspection, monitoring, and failure records, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review. Reliability data for rotating equipment such as compressor trains benefit from the structured treatment of censored and time-dependent failure data described by Modarres, Kaminskiy, and Krivtsov (2016), which supports realistic estimates of surge and seal-failure likelihood even when maintenance records are incomplete.

For compressor trains, barrier evaluation should begin with the required function of pressure delivery and throughput. The responsible team should test function, independence, availability, and assurance. The analysis must consider surge, vibration, seal failure, lube-oil loss, and driver trips. Evidence should come from performance standards and test evidence, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For compressor trains, risk evaluation should begin with the required function of pressure delivery and throughput. The responsible team should compare current risk with category-specific criteria. The analysis must consider surge, vibration, seal failure, lube-oil loss, and driver trips. Evidence should come from approved tolerability rules and uncertainty classes, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For compressor trains, intervention selection should begin with the required function of pressure delivery and throughput. The responsible team should choose design, operating, inspection, maintenance, or preparedness actions. The analysis must consider surge, vibration, seal failure, lube-oil loss, and driver

trips. Evidence should come from portfolio ranking with mandatory constraints, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For compressor trains, learning should begin with the required function of pressure delivery and throughput. The responsible team should update assumptions after changes, excursions, findings, and events. The analysis must consider surge, vibration, seal failure, lube-oil loss, and driver trips. Evidence should come from indicator review and model revision, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

Transmission Pipelines. For transmission pipelines, system definition should begin with the required function of long-distance containment and deliverability. The responsible team should map boundaries, operating modes, interfaces, and shared utilities. The analysis must consider corrosion, cracking, construction defects, third-party damage, and geohazards. Evidence should come from approved drawings and an asset hierarchy, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review. Long-distance transmission systems are also governed by dedicated integrity-management standards. API Recommended Practice 1160 (American Petroleum Institute, 2013) and ASME B31.8S (American Society of Mechanical Engineers, 2018) both require operators to define covered segments, high-consequence areas, and integrity-assessment intervals as part of system definition, and NACE SP0502-2010 (NACE International, 2010) specifies how indirect inspection tools such as close-interval surveys should be combined to assess external corrosion along uninspectable segments. Stress corrosion cracking receives particular attention in this literature; Cheng (2013) provides a comprehensive treatment of its mechanisms, detection, and management along pipeline steels, complementing this direct assessment guidance (American Petroleum Institute, 2016; American Petroleum Institute, 2016; American Petroleum Institute, 2014).

For transmission pipelines, hazard identification should begin with the required function of long-distance containment and deliverability. The responsible team should construct cause-to-consequence scenarios for normal and abnormal modes. The analysis must consider corrosion, cracking, construction defects, third-party damage, and geohazards. Evidence should come from multidisciplinary workshops and operating history, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For transmission pipelines, consequence analysis should begin with the required function of long-

distance containment and deliverability. The responsible team should estimate safety, environmental, supply, and asset effects. The analysis must consider corrosion, cracking, construction defects, third-party damage, and geohazards. Evidence should come from release models, inventory data, and recovery studies, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For transmission pipelines, likelihood assessment should begin with the required function of long-distance containment and deliverability. The responsible team should connect credible degradation and failure mechanisms to exposure. The analysis must consider corrosion, cracking, construction defects, third-party damage, and geohazards. Evidence should come from inspection, monitoring, and failure records, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review. Jo and Ahn (2005) and Han and Weng (2011) both developed quantitative likelihood models for gas transmission pipelines that combine damage-mechanism frequency with population and land-use data, while Lu et al. (2015) integrate a bow-tie model with a risk matrix specifically for long-distance natural gas pipelines, offering a template close to the scenario and barrier structure adopted here. An earlier quantitative index-based method proposed by Xing, Ren, and Liu (2009) combines frequency and consequence scoring specifically for long-distance transmission lines and remains a reference point for these later quantitative pipeline-risk models.

For transmission pipelines, barrier evaluation should begin with the required function of long-distance containment and deliverability. The responsible team should test function, independence, availability, and assurance. The analysis must consider corrosion, cracking, construction defects, third-party damage, and geohazards. Evidence should come from performance standards and test evidence, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review. Zhang, Qin, and Wang (2019) show that pipelines laid together in a single corridor carry correlated risk from shared excavation exposure and third-party threats, which requires joint quantitative risk analysis rather than independent per-line assessment.

For transmission pipelines, risk evaluation should begin with the required function of long-distance containment and deliverability. The responsible team should compare current risk with category-specific criteria. The analysis must consider corrosion, cracking, construction defects, third-party damage, and geohazards. Evidence should come from approved tolerability rules and uncertainty classes, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network

consequences. It also creates a repeatable audit trail for future review.

For transmission pipelines, intervention selection should begin with the required function of long-distance containment and deliverability. The responsible team should choose design, operating, inspection, maintenance, or preparedness actions. The analysis must consider corrosion, cracking, construction defects, third-party damage, and geohazards. Evidence should come from portfolio ranking with mandatory constraints, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For transmission pipelines, learning should begin with the required function of long-distance containment and deliverability. The responsible team should update assumptions after changes, excursions, findings, and events. The analysis must consider corrosion, cracking, construction defects, third-party damage, and geohazards. Evidence should come from indicator review and model revision, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

Storage and Inventory Systems. For storage and inventory systems, system definition should begin with the required function of seasonal balancing and emergency supply. The responsible team should map boundaries, operating modes, interfaces, and shared utilities. The analysis must consider well integrity loss, valve leakage, inventory uncertainty, and withdrawal constraints. Evidence should come from approved drawings and an asset hierarchy, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For storage and inventory systems, hazard identification should begin with the required function of seasonal balancing and emergency supply. The responsible team should construct cause-to-consequence scenarios for normal and abnormal modes. The analysis must consider well integrity loss, valve leakage, inventory uncertainty, and withdrawal constraints. Evidence should come from multidisciplinary workshops and operating history, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For storage and inventory systems, consequence analysis should begin with the required function of seasonal balancing and emergency supply. The responsible team should estimate safety, environmental, supply, and asset effects. The analysis

must consider well integrity loss, valve leakage, inventory uncertainty, and withdrawal constraints. Evidence should come from release models, inventory data, and recovery studies, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For storage and inventory systems, likelihood assessment should begin with the required function of seasonal balancing and emergency supply. The responsible team should connect credible degradation and failure mechanisms to exposure. The analysis must consider well integrity loss, valve leakage, inventory uncertainty, and withdrawal constraints. Evidence should come from inspection, monitoring, and failure records, with dates, ownership, and configuration status recorded. Younsi and Smati (2017) apply a Bayesian updating approach to intrinsic availability assessment of aging gas infrastructure, combining stochastic process modelling with inspection evidence to track how withdrawal reliability evolves over an asset's service life, a method directly transferable to aging storage and withdrawal systems. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review (Aminu-Ibrahim & Ambali, 2019) (Aminu-Ibrahim et al., 2019).

For storage and inventory systems, barrier evaluation should begin with the required function of seasonal balancing and emergency supply. The responsible team should test function, independence, availability, and assurance. The analysis must consider well integrity loss, valve leakage, inventory uncertainty, and withdrawal constraints. Evidence should come from performance standards and test evidence, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review. Well-integrity barrier philosophy for storage assets parallels the submarine-pipeline integrity-management logic of DNV-RP-F116 (Det Norske Veritas, 2009), which specifies condition-based reassessment intervals rather than fixed calendar intervals, and NORSOK Z-013 (NORSOK, 2010) similarly requires that emergency-preparedness assessment for storage and withdrawal facilities be tied explicitly to defined accidental-event scenarios rather than generic response plans.

For storage and inventory systems, risk evaluation should begin with the required function of seasonal balancing and emergency supply. The responsible team should compare current risk with category-specific criteria. The analysis must consider well integrity loss, valve leakage, inventory uncertainty, and withdrawal constraints. Evidence should come from approved tolerability rules and uncertainty classes, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For storage and inventory systems, intervention selection should begin with the required function of seasonal balancing and emergency supply. The responsible team should choose design, operating, inspection, maintenance, or preparedness actions. The analysis must consider well integrity loss, valve leakage, inventory uncertainty, and withdrawal constraints. Evidence should come from portfolio ranking with mandatory constraints, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For storage and inventory systems, learning should begin with the required function of seasonal balancing and emergency supply. The responsible team should update assumptions after changes, excursions, findings, and events. The analysis must consider well integrity loss, valve leakage, inventory uncertainty, and withdrawal constraints. Evidence should come from indicator review and model revision, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

Metering and Pressure-Regulation Stations. For metering and pressure-regulation stations, system definition should begin with the required function of custody transfer and pressure control. The responsible team should map boundaries, operating modes, interfaces, and shared utilities. The analysis must consider regulator failure, measurement drift, icing, control loss, and overpressure. Evidence should come from approved drawings and an asset hierarchy, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For metering and pressure-regulation stations, hazard identification should begin with the required function of custody transfer and pressure control. The responsible team should construct cause-to-consequence scenarios for normal and abnormal modes. The analysis must consider regulator failure, measurement drift, icing, control loss, and overpressure. Evidence should come from multidisciplinary workshops and operating history, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For metering and pressure-regulation stations, consequence analysis should begin with the required function of custody transfer and pressure control. The responsible team should estimate safety, environmental, supply, and asset effects. The analysis

must consider regulator failure, measurement drift, icing, control loss, and overpressure. Evidence should come from release models, inventory data, and recovery studies, with dates, ownership, and configuration status recorded. Fang et al. (2019) show that gas infrastructure routed through confined spaces such as underground utility tunnels can produce sharply higher explosion consequences than open-air corridors, a geometry consideration equally relevant to vaulted metering and regulation installations. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review (Obriki & Arumosoye, 2018).

For metering and pressure-regulation stations, likelihood assessment should begin with the required function of custody transfer and pressure control. The responsible team should connect credible degradation and failure mechanisms to exposure. The analysis must consider regulator failure, measurement drift, icing, control loss, and overpressure. Evidence should come from inspection, monitoring, and failure records, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review (Lawal & Oduleye, 2019a).

For metering and pressure-regulation stations, barrier evaluation should begin with the required function of custody transfer and pressure control. The responsible team should test function, independence, availability, and assurance. The analysis must consider regulator failure, measurement drift, icing, control loss, and overpressure. Evidence should come from performance standards and test evidence, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For metering and pressure-regulation stations, risk evaluation should begin with the required function of custody transfer and pressure control. The responsible team should compare current risk with category-specific criteria. The analysis must consider regulator failure, measurement drift, icing, control loss, and overpressure. Evidence should come from approved tolerability rules and uncertainty classes, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For metering and pressure-regulation stations, intervention selection should begin with the required function of custody transfer and pressure control. The responsible team should choose design, operating, inspection, maintenance, or preparedness actions. The analysis must consider regulator failure, measurement drift, icing, control loss, and overpressure. Evidence should come from portfolio ranking with mandatory constraints, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score

without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

For metering and pressure-regulation stations, learning should begin with the required function of custody transfer and pressure control. The responsible team should update assumptions after changes, excursions, findings, and events. The analysis must consider regulator failure, measurement drift, icing, control loss, and overpressure. Evidence should come from indicator review and model revision, with dates, ownership, and configuration status recorded. The assessor should distinguish confirmed facts from assumptions and should state how uncertainty affects the decision. A high score without a causal explanation is insufficient. The record should identify the scenario, the barrier or dependency that controls it, the action threshold, and the person authorized to accept residual risk. This application keeps local technical work connected to system delivery and prevents an isolated equipment judgment from obscuring network consequences. It also creates a repeatable audit trail for future review.

V. PHASED IMPLEMENTATION ROADMAP

1. Leadership and criteria. Approve risk categories, tolerability limits, escalation rules, and delegated authority. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.

2. Asset hierarchy. Create stable identifiers for plants, systems, equipment, pipeline segments, and safety-critical elements. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.

3. Scenario register. Record threats, top events, consequences, barriers, assumptions, and owners. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.

4. Barrier standards. Define required function, capacity, response, reliability, survivability, and assurance. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.

5. Integrity linkage. Connect damage mechanisms, inspection tasks, findings, remaining life, and repair decisions. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.

6. Maintenance linkage. Map preventive and corrective tasks to barriers and functional failures. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.

7. Operating envelope. Define limits, excursion workflows, technical review, and recovery requirements. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.
8. Management of change. Screen permanent, temporary, technical, and organizational changes against scenarios. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.
9. Action governance. Assign deadlines, interim controls, verification, closure evidence, and residual-risk acceptance. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.
10. Indicator design. Use a small set of scenario-linked leading and lagging measures. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.
11. Assurance. Test data, calculations, barrier status, action closure, and governance independently. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.
12. Learning cycle. Update the model after incidents, near misses, inspections, tests, and operational changes. Begin with major-accident and major-interruption scenarios, assign a named owner, establish baseline evidence, and set a review date. Implementation evidence should show both completion and effectiveness. Where data are weak, adopt conservative interim controls and commission the measurement needed for the next decision cycle.

VI. THEORETICAL AND PRACTICAL IMPLICATIONS

The framework contributes integration at three levels. Conceptually, it joins risk triplets, barrier theory, reliability, risk-based inspection, functional safety, and management systems. Operationally, it links scenarios to barriers and actions. Governably, it assigns ownership and learning loops. The result is a traceable path from evidence to decision (Aye & Tawose, 2016).

The framework also resolves a recurring tension between equipment and system views. Equipment condition enters the likelihood model, while scenario and dependency analysis determine its wider importance. This prevents maintenance criticality from being based only on replacement cost or local downtime.

Implementation will face limitations. Data scarcity, model uncertainty, incompatible taxonomies, specialist boundaries, and resource constraints can weaken integration. Simplification is necessary, but hidden simplification is dangerous. Organizations should begin with major scenarios, critical barriers, and a small indicator set, then deepen models where decisions justify the effort.

VII. LITERATURE SYNTHESIS

The synthesis also incorporates plant-uptime, project-risk, occupational-safety, and near-miss evidence from the supplied literature collection.

A risk-based process engineering system needs evidence from operations, maintenance, projects, and workforce behavior.

Risk controls also depend on human and organizational signals.

Research Propositions

- P1: Linking equipment records to scenario and barrier identifiers improves the consistency of maintenance and inspection priority decisions.
- P2: Explicit separation of current and forecast residual risk reduces premature risk closure.
- P3: Risk-weighted barrier indicators predict major interruption more effectively than unweighted activity counts.
- P4: Treating uncertainty as an intervention trigger increases the value of inspection and monitoring expenditure.
- P5: Cross-functional review of operating-envelope excursions improves degradation-model accuracy.
- P6: Portfolio selection under safety constraints yields greater system risk reduction than isolated departmental ranking.

VIII. LIMITATIONS AND FUTURE RESEARCH

The paper remains conceptual. Empirical studies should test whether framework adoption improves barrier availability, reduces unplanned interruption, changes inspection allocation, or strengthens action closure. Comparative case studies across facilities and network types would identify contextual factors.

Evidence on system integrity and failure control supports explicit links between condition data, risk ranking, and intervention timing (Liang et al., 2012; Khakzad et al., 2011; Li et al., 2018; Zabihi et al., 2016; Rathnayaka et al., 2014; Mondal et al., 2019; Trucano et al., 2006; de Waard et al., 1991; Ismail et al., 2012; Korppoo, 2018; Yang et al., 2017; Allen et al., 2015).

Reliability studies also support the use of lifecycle evidence when operators compare preventive, predictive, and corrective actions (Skogdalen et al., 2012; Khan et al., 2004; Sitorus et al., 2018; Ossai et al., 2015; Witkowski et al., 2014; Singh, 2017; Helton et al., 2003; Gas Processors Suppliers Association., 2017; Skogestad, 2008; Osiki, 2018; Ismail et al., 2016; Marchese et al., 2015).

Research on energy infrastructure highlights the need to treat technical, organizational, and supply risks within one governed decision process (Bevilacqua et al., 2000; Askari et al., 2019; Kukadiya et al., 2017; Rahmanian et al., 2015; Ossai, 2012; Cai et al., 2012; Venkatasubramanian et al., 2003; Bahadori, 2014; Chebbi et al., 2019; Ramasamy, 2018; Ojijiagwo et al., 2016; Roscioli et al., 2015).

Asset-management literature reinforces the value of traceable assumptions, performance indicators, and periodic model review (Bian et al., 2011; Li et al., 2019; Neagu et al., 2017; Yang et al., 2015; Popli et al., 2012; Roy et al., 2011; Venkatasubramanian et al., 2003; Gas Processors Suppliers Association., 2012; Qin et al., 2019; Balcombe et al., 2017; Promoppatum et al., 2016; Sonawat et al., 2014).

Process-safety evidence supports escalation rules tied to uncertainty, consequence severity, and the strength of available safeguards (Baybutt, 2018; Listou Ellefsen et al., 2019; Zavala-Araiza et al., 2017; Howarth, 2014; Remeljej et al., 2006; Venkatasubramanian et al., 2003; Gas Processors Suppliers Association., 2012; Elbashir, 2018; Umukoro et al., 2017; Tavakkoli et al., 2016; Wetenhall et al., 2014).

Further evidence supports the framework's treatment of condition monitoring, system failure, energy integration, digital risk, and subsurface uncertainty (Adaramola et al., 2018; Gideon et al., 2019; Shittu et al., 2019; Akeju et al., 2018; Lamidi et al., 2018).

Ewim's energy-systems research supports the framework's emphasis on safety analysis and managed infrastructure performance (Ibrahim et al., 2013; Nnaji et al., 2019).

IX. CONCLUSION

Complex natural gas infrastructure requires a system-level approach to reliability. Separate safety, integrity, inspection, maintenance, and operational programs create gaps at their interfaces. The proposed Risk-Based Process Engineering Framework aligns these functions around scenarios, barriers, evidence, interventions, and learning.

Eight functions structure the approach: system definition, hazard identification, consequence modelling, likelihood assessment, barrier evaluation, risk aggregation, intervention selection, and performance learning. Three linked registers preserve traceability. Inherent, current residual, and forecast residual risk prevent planned safeguards from being mistaken for existing protection. Uncertainty becomes a basis for action rather than a footnote.

The framework's practical value lies in disciplined connection. Operating changes inform damage models. Inspection results update likelihood. Barrier impairment changes risk. Actions carry verification requirements. Indicators connect to scenarios. Management review tests whether reliability and safety improve. This architecture offers a basis for future quantitative models and field validation (Smith, 2011).

Field-development evidence further supports a risk framework built around integrated surveillance, knowledge transfer, and disciplined lifecycle decisions (Babadagli, 2005; Bresnen et al., 2003; Clayton et al., 1998; Faseemo et al., 2009; Perrin et al., 2005).

Declarations

Ethics approval and consent to participate: This engineering framework used published sources and involved no research participants or animals.

Consent for publication: Not applicable.

Availability of data and materials: The evidence base consists of the publications listed in the references; the study produced no primary dataset.

Competing interests: The author declares no competing interests.

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