Integrating HAZOP, Reliability Analysis, and Risk-Based Decision-Making into Critical Energy Infrastructure Design

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Abstract
This paper develops a common scenario model that translates HAZOP findings into reliability structures, risk priorities, and verified design actions. The study responds to the problem that design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. It uses an integrative conceptual review of scholarly and professional literature published to date, drawing on peer-reviewed journal articles, guideline documents, and international standards synthesized within this manuscript. The framework organizes eight decision functions: design-basis confirmation, HAZOP deviation review, failure-mode analysis, fault and event tree modelling, barrier assessment, risk evaluation, design action prioritization, closeout assurance. It applies those functions across feed and transfer systems, separation and treating units, compression systems, storage systems, pipeline interfaces, utilities and control systems. The analysis treats uncertainty, process safety, reliability, environmental performance, resource efficiency, economics, and organizational control as connected requirements. The proposed architecture links a system definition, evidence register, model assumptions, intervention portfolio, verification plan, and learning cycle. Its central proposition is that connect deviation analysis, failure logic, barrier performance, consequence evaluation, and design decisions through one traceable workflow when decisions preserve traceability from measured conditions to selected actions and verified outcomes. The paper offers testable propositions, an implementation roadmap, asset-specific application protocols, and a research agenda. The framework supports case-study testing and quantitative extension without claiming universal performance before field validation.

Keywords: *integrated HAZOP and reliability analysis; process engineering; reliability; process safety; risk management; asset integrity; environmental performance; decision framework*

Introduction

Integrated HAZOP and reliability work require credible deviation scenarios, defensible failure evidence, barrier checks, and documented decision ownership (Kaplan & Garrick, 1981; Reason, 1997; Center for Chemical Process Safety, 2007; International Organization for Standardization, 2018). The theoretical basis for treating risk as a dynamic property of interacting technical and organizational levels, rather than a fixed attribute of equipment, is well established (Rasmussen, 1997; Aven, 2016), and regulatory regimes increasingly codify this systems view through mandatory process safety management and major-accident prevention programs (Occupational Safety and Health Administration, 1992; European Union, 2012) (Atta & Adenuga, 2020; Obogo & Arumosoye, 2021; Orise & Niniola, 2022) (Obogo et al., 2021; Obogo et al., 2020; Obriki et al., 2023). (Center for Chemical Process Safety, 2014; International Electrotechnical Commission, 2016; Khakzad et al., 2013) Safe infrastructure design links hazard review, equipment reliability, safeguard adequacy, consequence analysis, and investment selection from the earliest design stage. In the context of integrated HAZOP and reliability analysis, design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. Local actions affect adjacent equipment, utilities, product quality, emissions, workforce exposure, and supply continuity. A defensible framework must therefore define both the physical process and the decision system through which evidence becomes action. Introduction is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should define the industrial problem, explain its system consequences, and state the paper objectives. For storage systems, the decision model must represent loss of containment, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Fault and event tree modelling supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Public inquiries into major process accidents repeatedly trace the causal chain back to hazard evaluations, reliability estimates, and layer-of-protection decisions that were documented in separate, poorly cross-referenced records (Cullen, 1990; Hopkins, 2000; Paté-Cornell, 1993) (Okonkwo & Mayo, 2023; Akin-Oluyomi & Akokodaripon, 2023; Nnabueze & Akokodaripon, 2021) (Okonkwo et al., 2023; Ogunwole et al., 2021). (Kletz, 1999; Mannan, 2012; Sklet, 2006)
Introduction is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should define the industrial problem, explain its system consequences, and state the paper objectives. For pipeline interfaces, the decision model must represent utility failure, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Barrier assessment supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. This aim responds to longstanding calls in the risk-analysis literature for frameworks that make assumptions, evidence quality, and residual uncertainty explicit rather than implicit (Kaplan, 1997; Bier, 1999; Apostolakis, 2004). Comparable lifecycle risk-assessment work on offshore produced

water management shows that loss-of-containment scenarios require the same explicit tracing of assumptions from design basis through to verified outcome (Falegan & Aniebonam, 2022) (Akin-Oluyomi & Akinleye, 2023b; Ogundairo & Ayivi-Donkor, 2023a; Falegan & Aniebonam, 2023) (Ogundairo & Ayivi-Donkor, 2023; Ogundairo & Ayivi-Donkor, 2023). (Amayo et al., 2023b; Okojie & Abioye, 2020)

Introduction is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should define the industrial problem, explain its system consequences, and state the paper objectives. For utilities and control systems, the decision model must represent common-cause protection failure, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Risk evaluation supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. This requirement is consistent with formal risk-assessment theory, which treats common-cause protection failure in utility and control systems as a case requiring explicit probability, consequence, and uncertainty structures rather than informal judgment (Rausand, 2011) (Adebayo & Ahmed, 2023) (Adeyelu, 2021).

Theoretical Framework

The methodological foundations of hazard and operability analysis, reliability modelling, and layer of protection analysis are well documented in the process safety literature. Kletz (1999) and Crawley and Tyler (2015) established the deviation-guideword procedure that underlies HAZOP practice, while the Center for Chemical Process Safety (2008) and Mannan (2012) situate HAZOP within a wider family of hazard-evaluation procedures. Reliability-theory treatments (Rausand, 2014; Rausand & Høyland, 2004; Villemeur, 1992) and the original fault tree handbook (Vesely, Goldberg, Roberts, & Haasl, 1981) supply the logic structures used for fault-tree and event-tree modelling in this framework, and Ericson (2015) and Modarres, Kaminskiy, and Krivtsov (2016) extend this logic to failure-mode and effects analysis and broader reliability-engineering practice (Vesely & Haasl, 1981). Literature reviews of HAZOP practice document substantial variability in team composition, rigor, and documented outcome across studies (Dunjó, Fthenakis, Vílchez, & Arnaldos, 2010; Khan & Abbasi, 1998; Marhavilas, Koulouriotis, & Gemeni, 2011). Methodological critiques further question whether HAZOP and layer of protection analysis reliably capture the judgment of the experts who conduct them, given known sources of cognitive bias in engineering assessment (Baybutt, 2018). Barrier-based safety management rests on the prevention, detection, control, and mitigation classification proposed by Sklet (2006) and on the layer of protection analysis method formalized by the Center for Chemical Process Safety (2001, 2014) and Summers (2003). Bow-tie representations of the same causal structure have been reviewed and found broadly consistent with layer of protection outputs when barrier definitions are held constant (Ruijter & Guldenmund, 2016), which supports the cross-method barrier assessment adopted in this framework.

Risk-evaluation practice has been shaped by longstanding debate over how numerical risk estimates should inform tolerability judgments. Kaplan and Garrick (1981) and Kaplan (1997) frame risk as a structured set of scenario, likelihood, and consequence triplets, while Cox (2008) demonstrates that ordinal risk-matrix scoring can misrank hazards relative to the quantitative risk

it is meant to approximate. Comparative regulatory analysis shows that tolerable-risk thresholds differ materially between jurisdictions (Ale, 2005), and reviews of risk-assessment foundations argue that assumption transparency, not numerical precision alone, should govern confidence in a risk-based decision (Aven, 2016; Aven & Zio, 2014; Apostolakis, 2004; Bier, 1999).

Methodology

Conceptual Review Method is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should describe source selection, cutoff control, thematic coding, and synthesis logic. For feed and transfer systems, the decision model must represent high pressure, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Design action prioritization supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. The source-selection and synthesis approach adopted here is comparable in scope to prior structured reviews of hazard-identification and risk-analysis methods (Khan & Abbasi, 1998; Dunjó, Fthenakis, Vílchez, & Arnaldos, 2010; Marhavilas, Koulouriotis, & Gemeni, 2011) (Ebhojie & Oyeleye, 2023a) (Oyeleye et al., 2022).

Conceptual Review Method is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should describe source selection, cutoff control, thematic coding, and synthesis logic. For separation and treating units, the decision model must represent low flow, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Closeout assurance supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. This shift mirrors the broader transition from reactive to predictive maintenance practice documented for mechanical systems more generally (Sunday, Omoegun, Essien, & Oluokun, 2020) (Sunday & Oluokun, 2019; Sunday & Omoegun, 2022; Tonoyan & Ayivi-Donkor, 2022c) (Tonoyan et al., 2022; Tonoyan et al., 2023; Ogunnowo et al., 2021).

Conceptual Review Method is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should describe source selection, cutoff control, thematic coding, and synthesis logic. For compression systems, the decision model must represent reverse flow, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Design-basis confirmation supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. Established reliability and maintainability engineering practice supports this emphasis on operating mode and model version when evaluating reverse-flow exposure in compression systems

(Ebeling, 1997) (Okonkwo & Okeke, 2023; Efobi & Fasawe, 2022b) (Okonkwo et al., 2023; Patrick et al., 2021).

Findings and Discussion

The Integrated Framework

System Boundary and Functional Requirements sets the stage for the rest of the framework: process deviations, equipment failures, and business-interruption exposure are too often assessed in separate studies that do not share a common boundary or a common set of assumptions, and this step is meant to close that gap. Working through it means mapping the physical, information, utility, organizational, and market interfaces that the analysis has to respect. In storage systems, that requires building loss of containment into the decision model in enough detail to show how it would begin, where detection would reach its limits, which safeguards would respond, how long recovery would take, and what would follow downstream. Hazop deviation review contributes some of that picture, but technical adequacy is never established by one dataset alone; each record also needs its source, date, operating mode, measurement uncertainty, model version, and a named accountable owner. Keeping that trail stops a tidy-looking result from hiding assumptions that would not hold up, and it means operating experience gathered afterward can still revise the decision rather than sitting unused in a separate file. Fuzzy rule-based risk-graph methods developed for safety integrity level determination offer one route for representing loss-of-containment scenarios in storage systems under this kind of boundary definition (Nait-Said, Zidani, & Ouzraoui, 2009) (Ogbete & Ambali, 2023; Atta & Adenuga, 2021) (Ogbete et al., 2023; Aneke et al., 2023).

The same System Boundary and Functional Requirements step applies to pipeline interfaces, where utility failure is the deviation the model has to carry: what triggers it, the point at which detection stops being reliable, the safeguards that come into play, the time recovery takes, and the downstream effects that follow. As before, the review has to fix the physical, information, utility, organizational, and market interfaces in scope before any of that can be assessed. Failure-mode analysis is one source of supporting evidence, though never the only one needed to call the design technically sound, so each entry should still carry its source, date, operating mode, uncertainty, model version, and accountable owner. That discipline is what keeps a clean-looking figure from concealing shaky assumptions, and it leaves the decision open to revision as real operating data comes in rather than being filed away and forgotten. External domino-effect prevention frameworks illustrate how utility failure at pipeline interfaces can propagate consequences beyond the immediate boundary being defined (Reniers, Dullaert, Ale, & Soudan, 2005) (Eze & Akinleye, 2022b; Sanni & Attah, 2023c).

For utilities and control systems, this same boundary-setting stage has to represent common-cause protection failure: the conditions that would trigger it, the limits of detection, the safeguards that would respond, the recovery timeline, and the effects it would have downstream. Framing that model still starts with agreeing the physical, information, utility, organizational, and market interfaces the study covers, since deviations, failures, and interruption risk are otherwise assessed in disconnected studies with mismatched assumptions. Fault and event tree modelling supplies part of the case, but not enough on its own to prove the design adequate, so the reviewer still needs to log source, date, operating mode, uncertainty, model version, and ownership for every entry. That record-keeping is what keeps a precise-seeming output honest about its weaker assumptions, and it lets later operating experience change the decision instead of being archived separately. Fuzzy risk-matrix approaches provide one way of representing the ambiguity inherent in common-cause

protection failure across utilities and control systems (Markowski & Mannan, 2008) (Atakpa, 2021; Dagodzo & Ahiaeke Patrick, 2023a) (Dagodzo & Ahiaeke, 2023).

Technology and Process Fundamentals asks a different question at this stage: what governs the equipment, what its functions and constraints are, and how it can fail. For feed and transfer systems, that means the decision model has to represent high pressure in full: how it would arise, the limits on detecting it, the safeguards that would intervene, how long recovery would take, and what happens downstream. Barrier assessment feeds into that picture but cannot settle technical adequacy alone, so records still need to state source, date, operating mode, uncertainty, model version, and an accountable owner. This is what keeps a seemingly exact result from disguising weak assumptions, and it allows operating experience gathered later to update the decision instead of being kept apart from it. Embedding inherent-safety thinking into these technology and process fundamentals is consistent with longstanding guidance on making inherent-safety practice operational in high-pressure feed and transfer systems (Khan & Amyotte, 2003).

The same question, applied to separation and treating units, centers on low flow: what starts it, where detection reaches its limit, which safeguards apply, how recovery unfolds, and what it affects downstream, once the governing mechanisms, equipment functions, constraints, and failure modes for the unit are laid out. Risk evaluation is part of the supporting evidence, though on its own it cannot establish that the design is technically adequate, so the reviewer still records source, date, operating mode, measurement uncertainty, model version, and an accountable owner for each item. That traceability is what stops a clean number from masking weak assumptions, and it keeps the decision open to correction as later operating experience comes in rather than treating the record as final. Indices developed for evaluating inherently safer design options offer a structured basis for comparing low-flow vulnerabilities across separation and treating technology options (Khan, Sadiq, & Amyotte, 2003) (Eyetsemitan & Fadayomi, 2023b) (Eyetsemitan et al., 2023).

In compression systems, working through governing mechanisms, equipment functions, constraints, and failure modes means representing reverse flow as fully as the earlier cases: its triggers, the boundaries of detection, the safeguards in place, recovery time, and downstream consequence. Design action prioritization is one piece of evidence supporting that model, but never sufficient by itself, so source, date, operating mode, uncertainty, model version, and accountable ownership still need to be recorded against each entry. Doing so keeps a precise-looking figure from hiding assumptions that would not stand up, and it means the decision can still be revised once operating experience accumulates instead of sitting untouched in a separate record. Inherent-safety-based incident investigation methodology similarly links reverse-flow vulnerabilities in compression systems back to the underlying process fundamentals that created them (Goraya, Amyotte, & Khan, 2004).

Data and Measurement Requirements turns to the variables, quality rules, reconciliation, uncertainty, and traceability the framework depends on. For feed and transfer systems, high pressure has to be represented with its triggering conditions, detection limits, safeguards, recovery time, and downstream effects all specified. Failure-mode analysis contributes evidence here, but not enough by itself to confirm technical adequacy, which is why every record still needs a source, date, operating mode, measurement uncertainty, model version, and named owner attached to it. That level of traceability keeps an apparently precise result honest about its underlying assumptions, and it means operating experience collected afterward can revise the decision instead of being kept in an unconnected file. Computer-aided fault tree methods support the systematic capture of these data and measurement requirements for high-pressure feed and transfer systems (Ferdous, Khan, Veitch, & Amyotte, 2007) (Ilodigwe & Adesemoye, 2021) (Aneke et al., 2022).

For separation and treating units, the same data and measurement discipline, covering variables, quality rules, reconciliation, uncertainty, and traceability, has to capture low flow: what initiates it, where detection stops being reliable, which safeguards respond, how recovery proceeds, and what downstream effects follow. Fault and event tree modelling adds part of the picture, though it is not sufficient on its own to establish that the model is technically sound, so source, date, operating mode, uncertainty, model version, and accountable ownership still belong in the record. This is what stops a superficially precise output from masking weaker assumptions underneath, and it leaves room for later operating experience to change the decision rather than being logged and set aside. Formal treatments of uncertainty handling in fault and event tree analysis show why source date, operating mode, and measurement uncertainty must be recorded explicitly for low-flow scenarios in separation and treating units (Ferdous, Khan, Sadiq, Amyotte, & Veitch, 2011) (Ogeawuchi et al., 2023).

Compression systems present the same data and measurement problem for reverse flow: defining its triggers, the point where detection is no longer reliable, the safeguards that would act, recovery time, and downstream consequence, all within a framework of clearly defined variables, quality rules, reconciliation, and uncertainty. Barrier assessment supplies some of that evidence, but establishing technical adequacy still depends on more than a single dataset, so each entry needs its source, date, operating mode, uncertainty, model version, and owner recorded. Keeping that record prevents a falsely exact-looking result from hiding weak assumptions, and it allows the decision to be updated as operating experience builds rather than staying fixed in an isolated file. Bayesian dynamic risk assessment methods use exactly this kind of accountable, time-stamped data to update reverse-flow failure probabilities in compression systems as new evidence arrives (Kalantarnia, Khan, & Hawboldt, 2009) (Akomolafe & Agu, 2018) (Ogunnowo et al., 2020).

Model Development and Validation is where assumptions, calibration evidence, sensitivity testing, and acceptance limits are kept separate from each other. For feed and transfer systems, that means representing high pressure with its initiating conditions, detection limits, safeguards, recovery time, and downstream effects all made explicit. Design-basis confirmation is one input to that validation, but it cannot alone demonstrate the design is technically adequate, so source, date, operating mode, uncertainty, model version, and an accountable owner still need to be logged. This traceability is what keeps a precise-seeming figure from concealing weak assumptions, and it lets subsequent operating experience feed back into the decision instead of being recorded separately and left there. Plant-specific dynamic failure assessment using Bayesian theory demonstrates how model development for high-pressure feed and transfer systems can be validated against evolving operating evidence rather than fixed at commissioning (Meel & Seider, 2006).

The same separation of assumptions, calibration evidence, sensitivity testing, and acceptance limits applies to separation and treating units facing low flow, where the model still has to specify what starts it, where detection is limited, which safeguards apply, how long recovery takes, and what happens downstream. Hazop deviation review provides part of that evidence, but not the whole basis for calling the model technically adequate, so records still need source, date, operating mode, measurement uncertainty, model version, and ownership. This keeps an apparently precise output from disguising weak assumptions, and it means operating experience gathered later can revise the decision rather than being confined to a separate record. Reviews of dynamic risk analysis approaches highlight the same validation challenge for low-flow scenarios in separation and treating units, cautioning that static models can understate evolving risk (Villa, Paltrinieri, Khan, & Cozzani, 2016).

For compression systems, model development and validation, again meaning separated assumptions, calibration evidence, sensitivity testing, and acceptance limits, has to represent reverse flow: what would set it off, where detection would run out, which safeguards would engage, how long recovery would take, and what would happen downstream. Failure-mode analysis contributes to that evidence base without being able to settle technical adequacy on its own, so source, date, operating mode, uncertainty, model version, and accountable owner still have to be recorded. That discipline is what stops a tidy-looking result from concealing weak assumptions, and it keeps the decision open to being updated once operating experience accumulates rather than being treated as closed. Case-based application of dynamic risk management to industrial dust-handling accidents shows how model assumptions for reverse-flow conditions in compression systems should be revisited as precursor evidence accumulates (Paltrinieri, Khan, Amyotte, & Cozzani, 2014).

Screening, Risk, and Barrier Evaluation

Screening and Prioritization sets the criteria used to rank sources, assets, technologies, or interventions against each other. Applied to storage systems, this means the model must show how loss of containment would begin, where detection would fail, which safeguards would respond, how recovery would proceed, and what happens downstream. Risk evaluation is one source of evidence for that ranking, though it cannot establish technical adequacy by itself, so each record still needs its source, date, operating mode, measurement uncertainty, model version, and accountable owner. That traceability keeps a precise-looking result from concealing weak assumptions underneath, and it allows later operating experience to update the ranking instead of remaining locked into a separate record. Classification schemes developed to support risk-based decision-making in hazardous processes offer a structured basis for ranking loss-of-containment scenarios in storage systems against other candidate interventions (Yang & Haugen, 2015) (Aliliele & Iwuanyanwu, 2023b) (Aliliele et al., 2023).

The same screening and prioritization logic, still built on criteria for ranking sources, assets, technologies, or interventions, applies to pipeline interfaces facing utility failure, which the model must capture: what sets it off, where detection reaches its ceiling, which safeguards intervene, how long recovery takes, and what follows downstream. Design action prioritization adds evidence to that ranking without being sufficient on its own, so source, date, operating mode, uncertainty, model version, and ownership should still be recorded for each item. This is what prevents an apparently precise score from hiding weak assumptions, and it leaves room for operating experience gathered afterward to revise the ranking rather than treating it as fixed. Analytic hierarchy process applications to maintenance strategy selection provide a comparable multi-criteria basis for prioritizing design actions addressing utility failure at pipeline interfaces (Bevilacqua & Braglia, 2000).

For utilities and control systems, screening and prioritization, again using criteria for ranking sources, assets, technologies, or interventions, has to capture common-cause protection failure, from what would trigger it through the limits of detection, the safeguards involved, the recovery time, and the downstream effects. Closeout assurance is part of the supporting evidence, but not enough on its own to confirm technical adequacy, so records still need source, date, operating mode, measurement uncertainty, model version, and an accountable owner. That traceability keeps a seemingly exact ranking from disguising weak assumptions, and it lets later operating experience revise the decision rather than leaving it in a separate file. Table 1 summarizes the eight decision stages used throughout the framework, together with each stage's primary question, evidence basis,

and expected decision output. Dynamic bow-tie approaches to risk analysis support closeout assurance for common-cause protection failure in utilities and control systems by updating barrier performance as operating evidence accumulates (Khakzad, Khan, & Amyotte, 2012) (Mbonu & Oluoha, 2018) (Mbonu et al., 2018).

Figure 1 presents a likelihood-consequence matrix for combining HAZOP findings with reliability evidence. Table 1 instead specifies the evidence measures used to test safeguard strength and residual-risk decisions.

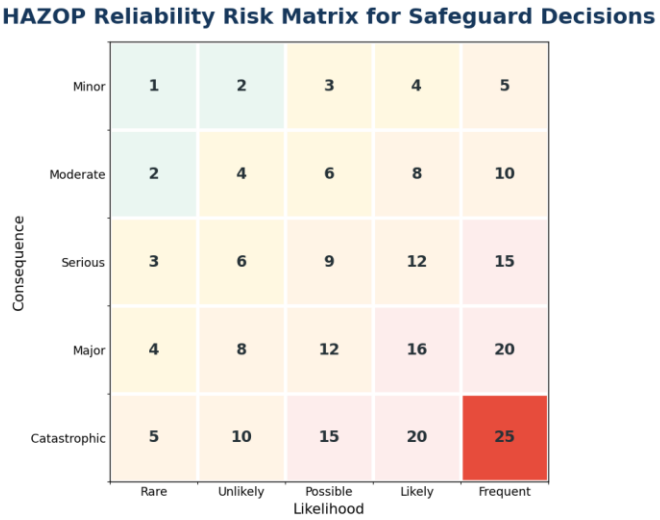

Figure 1. HAZOP reliability risk matrix supporting safeguard and residual-risk decisions.

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Table 1. Evidence Measures for Testing HAZOP and Reliability-Based Design Decisions

Evidence dimension	Measure	Interpretation	Design response
Scenario severity	Credible consequence level	Magnitude of harm if controls fail	Set design priority
Initiating frequency	Events per operating year	Expected occurrence of the initiating cause	Refine prevention
Safeguard independence	Independence test result	Freedom from common dependencies	Redesign weak layers
Instrumented protection	Required and achieved SIL	Risk reduction delivered by SIS	Close the SIL gap
Common-cause exposure	Shared dependency count	Potential for simultaneous safeguard loss	Separate dependencies

Evidence dimension	Measure	Interpretation	Design response
Maintainability	Proof-test and repair burden	Ability to sustain safeguard performance	Improve access and testing
Residual risk	Post-control risk ranking	Remaining exposure after design action	Accept or add controls
Action assurance	Verified closure rate	Evidence of completed and effective actions	Escalate overdue actions

Hazard, Reliability, and Environmental Dimensions links loss scenarios to reliability, safety, emissions, and resource outcomes rather than treating them as separate concerns. In storage systems, that means capturing how loss of containment would start, where detection would reach its limit, which safeguards would respond, how long recovery would take, and what would follow downstream. Closeout assurance contributes part of the evidence for that linkage, but technical adequacy still cannot rest on a single dataset, so source, date, operating mode, measurement uncertainty, model version, and accountable owner belong in every record. This is what keeps an apparently precise conclusion from hiding weak assumptions, and it means operating experience collected later can revise the decision instead of sitting apart from it. Quantitative area risk analysis of domino effects illustrates how a loss-of-containment event in storage systems can escalate into a wider hazard, reliability, and environmental consequence chain (Cozzani, Gubinelli, Antonioni, Spadoni, & Zanelli, 2005).

Applied to pipeline interfaces, the same connection between loss scenarios and reliability, safety, emissions, and resource outcomes requires capturing utility failure's triggers, the limits of detection, the relevant safeguards, the recovery time, and the downstream effects. Design-basis confirmation supplies part of that evidence without being conclusive on its own, so each record still needs source, date, operating mode, uncertainty, model version, and an accountable owner. That discipline stops a precise-seeming figure from masking weak assumptions, and it allows the decision to be updated as later operating experience arrives rather than staying confined to a separate record. Offshore safety-indicator research linking utility failure at pipeline interfaces to broader consequence outcomes supports this connection between loss scenarios and reliability, safety, and resource performance (Skogdalen, Utne, & Vinnem, 2011) (Ilodigwe & Adesemoye, 2019b; Yeboah & Oloto, 2023).

For utilities and control systems, connecting loss scenarios to reliability, safety, emissions, and resource outcomes means specifying what would trigger common-cause protection failure, where detection would fall short, which safeguards would engage, how long recovery would take, and what would happen downstream. Hazop deviation review is one input to that connection, though not sufficient by itself to establish technical adequacy, so source, date, operating mode, measurement uncertainty, model version, and ownership still need recording. Keeping that record is what stops an apparently exact result from concealing weak assumptions, and it lets subsequent operating experience feed back into the decision rather than being set aside in its own file. Quantitative risk analysis of deepwater drilling operations similarly shows how common-cause protection failure in utilities and control systems can be traced through to environmental and safety outcomes (Skogdalen & Vinnem, 2012).

Operating-Envelope Integration turns design and model assumptions into daily limits and a defined excursion response. For storage systems, this means stating clearly how loss of containment would begin, where detection would be limited, which safeguards would respond, how long recovery would take, and what would follow downstream. Fault and event tree modelling contributes to that evidence base without settling technical adequacy alone, so source, date, operating mode, measurement uncertainty, model version, and an accountable owner still need to be recorded. That traceability prevents a precise-looking limit from hiding weak assumptions, and it allows later operating experience to revise the envelope rather than leaving it fixed in a separate record. Accident modelling applied to an LNG processing facility shows how daily operating limits for storage systems should be set with reference to credible loss-of-containment excursions rather than nominal design values alone (Rathnayaka, Khan, & Amyotte, 2012).

The same translation of design and model assumptions into daily limits and excursion response applies to pipeline interfaces facing utility failure, which the model must capture in terms of what triggers it, where detection falls short, which safeguards respond, how long recovery takes, and what follows downstream. Barrier assessment adds to that evidence but cannot confirm technical adequacy on its own, so each record still needs source, date, operating mode, uncertainty, model version, and accountable ownership. This is what keeps a seemingly exact limit from disguising weak assumptions, and it means operating experience gathered afterward can update the envelope instead of being kept in an unconnected record. The SHIPP predictive accident modelling methodology offers a comparable structure for translating design assumptions about utility failure at pipeline interfaces into daily operating limits and excursion response (Rathnayaka, Khan, & Amyotte, 2011).

For utilities and control systems, converting design and model assumptions into daily limits and excursion response means specifying common-cause protection failure's triggers, the limits of detection, the safeguards involved, the recovery time, and the downstream consequences. Risk evaluation contributes part of that evidence without being sufficient alone to establish technical adequacy, so source, date, operating mode, uncertainty, model version, and ownership should still be logged. That traceability keeps an apparently precise limit from concealing weak assumptions, and it lets later operating experience revise the envelope rather than treating it as permanently fixed. Risk-based plant design that explicitly incorporates inherent safety supports this translation of common-cause protection assumptions in utilities and control systems into operable daily limits (Rathnayaka, Khan, & Amyotte, 2014).

Barrier and Safeguard Assurance evaluates prevention, detection, control, isolation, mitigation, and emergency layers together rather than one at a time. In feed and transfer systems, that means fully specifying how high pressure would arise, where detection would reach its limit, which

safeguards would respond, how long recovery would take, and what would follow downstream. Design action prioritization supplies part of the supporting evidence, though not enough alone to establish technical adequacy, so records still need source, date, operating mode, measurement uncertainty, model version, and an accountable owner. This traceability keeps a precise-seeming assurance case from hiding weak assumptions, and it allows later operating experience to update the decision instead of remaining in a separate record. The expanding role of inherently safer design in process safety practice reinforces why prevention and mitigation layers for high-pressure feed and transfer systems should be assessed together rather than in isolation (Amyotte & Khan, 2021).

Applied to separation and treating units, the same evaluation of prevention, detection, control, isolation, mitigation, and emergency layers has to represent low flow: what would set it off, where detection would run short, which safeguards would engage, the expected recovery time, and the downstream effects. Closeout assurance is one part of that evidence, but technical adequacy still cannot rest on a single dataset, so source, date, operating mode, uncertainty, model version, and ownership belong in each record. That discipline stops an apparently exact assurance case from concealing weak assumptions, and it means operating experience collected later can revise the decision rather than sitting apart from it. An inherently safer design protocol developed for process hazard analysis offers a structured way of evaluating detection, control, and mitigation layers for low-flow conditions in separation and treating units (Brown, Hastie, Khan, & Amyotte, 2021).

For compression systems, evaluating prevention, detection, control, isolation, mitigation, and emergency layers means capturing reverse flow's triggers, the point where detection is limited, the relevant safeguards, the recovery time, and the downstream effects. Design-basis confirmation contributes part of that evidence without confirming technical adequacy on its own, so each record still needs source, date, operating mode, measurement uncertainty, model version, and accountable owner. Keeping that trail prevents a precise-looking assurance case from disguising weak assumptions, and it allows the decision to be updated as later operating experience accumulates rather than staying closed. Fuzzy logic applications to piping risk assessment support this layered evaluation of prevention, detection, and mitigation performance for reverse-flow conditions in compression systems (Markowski & Mannan, 2009) (Aliliele & Iwuanyanwu, 2023a) (Aliliele et al., 2023; Mbonu et al., 2021).

Economic and Resource Evaluation connects capital, operating cost, downtime, recovery, emissions, and uncertainty rather than pricing them separately. For storage systems, that means making explicit how loss of containment would begin, where detection would be limited, which safeguards would respond, how long recovery would take, and what would follow downstream. Hazop deviation review supplies part of the evidence for that costing, though not enough alone to establish technical adequacy, so source, date, operating mode, uncertainty, model version, and an accountable owner still need to be recorded. This is what keeps a seemingly precise cost figure from hiding weak assumptions, and it lets later operating experience revise the evaluation instead of leaving it fixed in a separate record. Broader theoretical accounts of how safety science models organizational and technical interaction caution against treating the capital, operating cost, and emissions consequences of a storage-system loss-of-containment event as separable from its safety dimension (Le Coze, 2013) (Arumosoye & Obriki, 2021) (Arumosoye & Obriki, 2021; Obogo et al., 2021).

The same connection between capital, operating cost, downtime, recovery, emissions, and uncertainty applies to pipeline interfaces facing utility failure, represented in terms of what would trigger it, where detection would fall short, which safeguards would respond, the expected

recovery time, and the downstream effects. Failure-mode analysis adds part of that evidence without settling technical adequacy alone, so source, date, operating mode, measurement uncertainty, model version, and ownership still belong in the record. That traceability stops an apparently precise cost estimate from concealing weak assumptions, and it means operating experience gathered afterward can update the evaluation rather than being filed away separately. Classic accounts of normal accidents in tightly coupled, complex systems similarly warn that utility failure at pipeline interfaces can generate downtime, recovery, and emissions costs that are not proportional to the size of the initiating deviation (Perrow, 1999).

For utilities and control systems, connecting capital, operating cost, downtime, recovery, emissions, and uncertainty means accounting for what would trigger common-cause protection failure, the limits of detection, the safeguards involved, the recovery time, and the downstream consequences. Fault and event tree modelling contribute part of that evidence, though it cannot establish technical adequacy by itself, so source, date, operating mode, uncertainty, model version, and accountable owner should still be logged. This keeps a precise-looking cost figure from disguising weak assumptions, and it allows later operating experience to revise the evaluation rather than treating it as closed. Organizational analyses of major technological decisions show that economic pressure can erode the safety margin built into common-cause protection assumptions for utilities and control systems if resource evaluation is not kept visible to decision-makers (Vaughan, 1996).

Application Across Asset Classes

Design-basis confirmation begins with a decision statement for feed and transfer systems. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For integrated HAZOP and reliability analysis, this stage should connect process deviations, equipment failures, barrier performance, and design decisions within one traceable scenario model. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to high pressure, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of design-basis confirmation should use independent evidence from compression systems wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include loss of containment and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts integrated HAZOP and reliability analysis from a one-time study into a controlled operating capability. It also supplies comparable evidence for

future investment and risk decisions. This verification logic mirrors established asset-management and risk-based inspection practice, in which acceptance criteria are tied to observed condition and performance rather than to the existence of a report (International Organization for Standardization, 2014; American Petroleum Institute, 2016a) (Eze & Akinleye, 2023; Omoegun & Oluokun, 2023; Basnet & Anene, 2023).

HAZOP deviation analysis begins with a decision statement for separation and treating units. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For integrated HAZOP and reliability analysis, this stage should connect process deviations, equipment failures, barrier performance, and design decisions within one traceable scenario model. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to low flow, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of HAZOP deviation analysis should use independent evidence from storage systems wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include utility failure and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts integrated HAZOP and reliability analysis from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions. The deviation-guideword logic applied here follows the structured hazard and operability methodology developed by Kletz (1999) and formalized in subsequent practice guidance (Crawley & Tyler, 2015; Center for Chemical Process Safety, 2008), while literature reviews of HAZOP applications document persistent variability in scope, rigor, and outcome across studies (Dunjó, Fthenakis, Vílchez, & Arnaldos, 2010; Baybutt, 2018) (Adelanwa & Anene, 2023a; Aliliele & Iwuanyanwu, 2023c) (Aliliele et al., 2023).

Failure-mode and effects analysis begins with a decision statement for compression systems. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For integrated HAZOP and reliability analysis, this stage should connect process deviations, equipment failures, barrier performance, and design decisions within one traceable scenario model. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to reverse flow, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a

favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of failure-mode and effects analysis should use independent evidence from pipeline interfaces wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include common-cause safeguard failure and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts integrated HAZOP and reliability analysis from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions. Hazard-analysis technique guidance situates failure-mode and effects analysis alongside HAZOP and fault-tree methods as complementary tools for identifying failure mechanisms and their propagation paths (Ericson, 2015; Modarres, Kaminskiy, & Krivtsov, 2016).

Fault-tree and event-tree modeling begins with a decision statement for storage systems. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For integrated HAZOP and reliability analysis, this stage should connect process deviations, equipment failures, barrier performance, and design decisions within one traceable scenario model. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to loss of containment, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of fault-tree and event-tree modeling should use independent evidence from utilities and control systems wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include high pressure and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts integrated HAZOP and reliability analysis from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions. Fault-tree and event-tree construction in this framework follows the logic-gate conventions established in the original fault tree handbook (Vesely,

Goldberg, Roberts, & Haasl, 1981) and extended through reliability-theory treatments of system modelling (Rausand & Høyland, 2004), including Bayesian-network representations that address the static-logic limitations of classical fault trees (Khakzad, Khan, & Amyotte, 2011, 2013) (Obriki & Arumosoye, 2018) (Obriki & Arumosoye, 2018; Obriki & Arumosoye, 2020; Arumosoye & Obriki, 2022).

Barrier performance assessment begins with a decision statement for pipeline interfaces. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For integrated HAZOP and reliability analysis, this stage should connect process deviations, equipment failures, barrier performance, and design decisions within one traceable scenario model. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to utility failure, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of barrier performance assessment should use independent evidence from feed and transfer systems wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include low flow and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts integrated HAZOP and reliability analysis from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions. Barrier classification here follows the prevention, detection, control, and mitigation taxonomy proposed by Sklet (2006), operationalized through layer of protection analysis (Center for Chemical Process Safety, 2001, 2014; Summers, 2003) and cross-checked against bow-tie representations of the same causal pathways (Ruijter & Guldenmund, 2016). For pipeline interfaces specifically, barrier adequacy is benchmarked against sector safety-management expectations (American Petroleum Institute, 2015) and functional-safety requirements for instrumented protection (International Electrotechnical Commission, 2010, 2016) (Filani & Wedraogo, 2022; Adelanwa & Anene, 2023b; Arumosoye & Obriki, 2023) (Obogo et al., 2020; Arumosoye & Obriki, 2023; Obriki et al., 2022).

Risk evaluation and tolerability review begins with a decision statement for utilities and control systems. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For integrated HAZOP and reliability analysis, this stage should connect process deviations, equipment failures, barrier performance, and design decisions within one traceable scenario model. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to common-cause safeguard failure, because a

locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority (Arumosoye & Obriki, 2020) (Arumosoye & Obriki, 2020).

Validation of risk evaluation and tolerability review should use independent evidence from separation and treating units wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include reverse flow and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts integrated HAZOP and reliability analysis from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions. Risk-tolerability judgments at this stage draw on documented critiques of ordinal risk-matrix scoring (Cox, 2008) and on foundational treatments of what quantitative and qualitative risk measures can and cannot support for decision-making (Kaplan, 1997; Bier, 1999; Apostolakis, 2004), while comparative regulatory analysis clarifies how tolerability thresholds differ across jurisdictions (Ale, 2005; Aven, 2016; Aven & Zio, 2014) (Okonkwo & Okeke, 2021; Aifuwa & Olatunde-Thorpe, 2020) (Okonkwo et al., 2021; Okonkwo et al., 2021; Okonkwo et al., 2020).

Design-action prioritization begins with a decision statement for feed and transfer systems. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For integrated HAZOP and reliability analysis, this stage should connect process deviations, equipment failures, barrier performance, and design decisions within one traceable scenario model. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to high pressure, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of design-action prioritization should use independent evidence from compression systems wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include loss of containment and the loss of one important safeguard or dependency.

Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts integrated HAZOP and reliability analysis from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions. Prioritization criteria applied here extend risk-based inspection and maintenance logic (American Petroleum Institute, 2016a; Khan, Sadiq, & Haddara, 2004) to non-inspection design actions, including structural and lifting-system interventions identified through complementary hazard-pathway modelling.

Closeout and residual-risk assurance begins with a decision statement for separation and treating units. The team must specify what evidence will support the decision, which operating modes are included, and which assumptions require later confirmation. For integrated HAZOP and reliability analysis, this stage should connect process deviations, equipment failures, barrier performance, and design decisions within one traceable scenario model. The analysis should represent normal operation, startup, shutdown, turndown, maintenance, and credible upset conditions. Particular attention should be given to low flow, because a locally acceptable condition may create a wider process, safety, environmental, or commercial consequence. Input records should identify source, timestamp, units, uncertainty, configuration, and accountable owner. A decision threshold should be approved before the final ranking is viewed. This reduces hindsight bias and prevents a favorable economic result from overriding mandatory safety or legal constraints. The resulting record should state the selected option, rejected alternatives, evidence gaps, interim controls, and residual-risk authority.

Validation of closeout and residual-risk assurance should use independent evidence from storage systems wherever feasible. Acceptance should depend on observable performance rather than completion of a report or work order. Suitable measures include availability, detection coverage, response time, product compliance, avoided loss, energy intensity, maintenance burden, and verified risk reduction. The team should test sensitivity to uncertain supply, composition, equipment condition, utility availability, market conditions, and model error. A credible adverse case should include utility failure and the loss of one important safeguard or dependency. Differences between predicted and observed performance should trigger model review, not informal adjustment of the acceptance limit. Management of change should capture revised drawings, procedures, training, spares, software versions, alarm settings, and inspection requirements. This verification loop converts integrated HAZOP and reliability analysis from a one-time study into a controlled operating capability. It also supplies comparable evidence for future investment and risk decisions. Closeout evidence requirements mirror published process-safety metrics guidance (Center for Chemical Process Safety, 2010; American Petroleum Institute, 2016b) and quantitative-risk-analysis documentation practice for pipeline and facility risk registers (Center for Chemical Process Safety, 2000; Zhang, Qin, & Wang, 2019) (Obogo & Ozobu, 2021) (Obogo et al., 2021; Obogo et al., 2023).

Implementation Roadmap

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving feed and transfer systems. Record assumptions about high pressure, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety,

environmental management, commercial planning, and emergency response. A functional HAZOP methodology built around explicit goal and function models supports this phased application to high-consequence scenarios in feed and transfer systems (Rossing, Lind, Jensen, & Jørgensen, 2010). Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving separation and treating units. Record assumptions about low flow, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Documented critiques of conventional HAZOP practice reinforce the need for explicit sensitivity analysis and closure evidence when the phase is first applied to low-flow scenarios in separation and treating units (Baybutt, 2015).Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving compression systems. Record assumptions about reverse flow, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Human-error research on the organizational and cognitive origins of unsafe acts supports assigning explicit ownership for reverse-flow scenarios in compression systems rather than treating error as an isolated operator failure (Reason, 1990) (Anene & Clement, 2022; Obogo & Obriki, 2020c; Obogo & Obriki, 2020b) (Obriki et al., 2023; Obogo et al., 2022; Obriki et al., 2022).

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving storage systems. Record assumptions about loss of containment, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Adaptive safety management system models developed for high-consequence operating environments provide a comparable structure for phasing implementation around loss-of-containment scenarios in storage systems (Adeyelu, 2019) (Eyetsemitan & Fadayomi, 2022) (Eyetsemitan et al., 2022; Akpe et al., 2022). Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving pipeline interfaces. Record assumptions about utility failure, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response. Process safety models that integrate human factors into offshore pipeline commissioning operations support this emphasis on reviewing utility-failure interfaces with operations, maintenance, and emergency response together (Oduro, 2023). Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving utilities and control systems. Record assumptions about common-cause protection failure, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response.

Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving feed and transfer systems. Record assumptions about high pressure, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response.
Establish scope, accountable roles, minimum evidence, approval criteria, and a documented output. Apply the phase first to high-consequence scenarios involving separation and treating units. Record assumptions about low flow, test the decision with sensitivity analysis, and assign closure evidence. Advance to the next phase only when unresolved uncertainty has an explicit treatment and owner. Review interfaces with operations, maintenance, inspection, process safety, environmental management, commercial planning, and emergency response.

Governance and Performance Measurement

Implementation Governance assigns ownership, decision rights, change control, competence, and assurance so that responsibility does not stay diffuse. For feed and transfer systems, the decision model has to capture how high pressure would arise, where detection would be limited, which safeguards would respond, how long recovery would take, and what would follow downstream. Barrier assessment is one source of evidence for that governance structure, but it cannot establish technical adequacy on its own, so source, date, operating mode, measurement uncertainty, model version, and an accountable owner should still be recorded. That traceability keeps a precise-seeming decision from hiding weak assumptions, and it lets later operating experience revise the arrangement instead of leaving it fixed in a separate record.
The same governance task, assigning ownership, decision rights, change control, competence, and assurance, applies to separation and treating units facing low flow, which the model must capture: what triggers it, where detection falls short, which safeguards respond, the recovery time involved, and the downstream effects. Risk evaluation contributes part of that evidence without confirming technical adequacy alone, so each record still needs source, date, operating mode, uncertainty, model version, and ownership. This discipline stops an apparently exact governance decision from concealing weak assumptions, and it allows operating experience gathered later to update the arrangement rather than sitting apart from it.
For compression systems, implementation governance again means assigning ownership, decision rights, change control, competence, and assurance, this time around reverse flow, represented by what would set it off, where detection would reach its limit, which safeguards would engage, the recovery time, and the downstream effects. Design action prioritization supplies part of the supporting evidence, though not enough alone to establish technical adequacy, so source, date, operating mode, measurement uncertainty, model version, and accountable owner still need recording. Keeping that trail is what prevents a precise-looking decision from disguising weak assumptions, and it means later operating experience can revise it instead of leaving it closed.
Performance Indicators and Learning defines leading and lagging measures along with the thresholds that trigger their update. In storage systems, that means tracking how loss of containment would begin, where detection would be limited, which safeguards would respond, the expected recovery time, and the downstream effects. Closeout assurance contributes part of the evidence behind those indicators, but technical adequacy still cannot rest on one dataset, so source, date, operating mode, measurement uncertainty, model version, and an accountable owner belong in each record. This traceability keeps an apparently precise indicator from hiding weak

assumptions, and it lets later operating experience revise the measure rather than leaving it isolated in its own record (Atakpa & Abetoh, 2022).

Applied to pipeline interfaces, defining leading and lagging measures and their update thresholds means tracking utility failure's triggers, the limits of detection, the relevant safeguards, the recovery time, and the downstream effects. Design-basis confirmation adds part of that evidence without settling technical adequacy alone, so each record still needs source, date, operating mode, uncertainty, model version, and ownership. That discipline stops a seemingly exact indicator from concealing weak assumptions, and it allows operating experience collected afterward to update the measure instead of being kept separately.

For utilities and control systems, the same leading and lagging measures, with their update thresholds, have to capture what would trigger common-cause protection failure, where detection would fall short, which safeguards would respond, the recovery time, and the downstream effects. Hazop deviation review supplies part of the underlying evidence, though not enough by itself to confirm technical adequacy, so source, date, operating mode, measurement uncertainty, model version, and accountable owner should still be logged. This is what keeps a precise-looking indicator from disguising weak assumptions, and it lets later operating experience revise the measure rather than treating it as fixed.

Literature Synthesis

Embedding inherently safer design principles earlier in the decision sequence (Kletz & Amyotte, 2010) and treating organizational memory of past incidents as a formal input rather than an informal one (Kletz, 1993) are consistent extensions of the framework proposed here.

HAZOP findings become stronger when teams connect deviations to human factors, failure mechanisms, and barrier performance. This approach is consistent with systems-level accounts of how risk migrates across levels of a sociotechnical system under production pressure (Rasmussen, 1997) and with resilience-oriented accounts of how normal variability in everyday performance produces both successful and unsuccessful outcomes (Hollnagel, 2014). Public inquiries into major process accidents illustrate the same pattern at facility scale: investigators repeatedly trace root causes to hazard evaluations, reliability estimates, and protective-layer decisions that were recorded in separate, poorly cross-referenced documents (Cullen, 1990; Hopkins, 2000; Paté-Cornell, 1993), and offshore risk-analysis research links weak integration of human and organizational factors into quantitative risk models to underestimated accident likelihood (Skogdalen & Vinnem, 2011) (Michael & Ogunsola, 2023a; Akomolafe & Bello, 2023b).

Later studies add recurrence, training, emergency response, and digital monitoring. These conceptual advances parallel a broader risk-informed decision-making paradigm in the wider safety literature (Amendola, 2002) and a regulatory environment that increasingly mandates similar cross-functional integration at the facility level (Occupational Safety and Health Administration, 1992; European Union, 2012) (Michael & Ogunsola, 2023b) (Obriki & Arumosoye, 2023).

Research Propositions

Research Propositions converts the framework's relationships into statements that can actually be tested. For feed and transfer systems, that means specifying how high pressure would arise, where detection would be limited, which safeguards would respond, the expected recovery time, and the downstream effects. Failure-mode analysis contributes part of the evidence behind such a proposition, but technical adequacy is never settled by a single dataset, so source, date, operating

mode, measurement uncertainty, model version, and an accountable owner still need to be recorded. That traceability keeps an apparently precise result from hiding weak assumptions, and it allows later operating experience to revise the proposition instead of leaving it in a separate record (Aminu-Ibrahim & Ogbete, 2023) (Aminu-Ibrahim & Ogbete, 2023).

The same conversion of framework relationships into testable statements applies to separation and treating units facing low flow, represented by what triggers it, where detection falls short, which safeguards respond, the recovery time, and the downstream effects. Fault and event tree modelling supplies part of that evidence without confirming technical adequacy alone, so each record still needs source, date, operating mode, uncertainty, model version, and ownership. This discipline stops a seemingly exact proposition from concealing weak assumptions, and it means operating experience gathered later can revise it rather than leaving it closed.

For compression systems, turning framework relationships into testable statements means capturing what would set reverse flow off, where detection would run short, which safeguards would engage, the recovery time, and the downstream effects. Barrier assessment adds part of the supporting evidence, though not enough alone to establish technical adequacy, so source, date, operating mode, measurement uncertainty, model version, and accountable owner should still be logged. Keeping that trail prevents a precise-looking proposition from disguising weak assumptions, and it allows later operating experience to revise it instead of treating it as final.

- **P1:** Greater maturity in design-basis confirmation improves the traceability and effectiveness of integrated HAZOP and reliability analysis decisions when data quality and organizational context are controlled.
- **P2:** Greater maturity in HAZOP deviation review improves the traceability and effectiveness of integrated HAZOP and reliability analysis decisions when data quality and organizational context are controlled.
- **P3:** Greater maturity in failure-mode analysis improves the traceability and effectiveness of integrated HAZOP and reliability analysis decisions when data quality and organizational context are controlled.
- **P4:** Greater maturity in fault and event tree modelling improves the traceability and effectiveness of integrated HAZOP and reliability analysis decisions when data quality and organizational context are controlled.
- **P5**: Greater maturity in barrier assessment improves the traceability and effectiveness of integrated HAZOP and reliability analysis decisions when data quality and organizational context are controlled.
- **P6:** Greater maturity in risk evaluation improves the traceability and effectiveness of integrated HAZOP and reliability analysis decisions when data quality and organizational context are controlled.

Limitations and Future Research

Limitations and Future Research states the evidence, transferability, model, and implementation limits that apply to the framework. For storage systems, this means tracing how loss of containment would begin, where detection would be limited, which safeguards would respond, the expected recovery time, and the downstream effects. Risk evaluation contributes part of the evidence behind that assessment, but technical adequacy is never established by one dataset alone, so source, date, operating mode, measurement uncertainty, model version, and an accountable owner still belong in the record. This traceability keeps an apparently precise conclusion from hiding weak assumptions, and it lets later operating experience revise the assessment rather than leaving it isolated in its own record (Mbonu & Uzoka, 2021a) (Mbonu et al., 2021; Agboola et al., 2022).

Applied to pipeline interfaces, stating evidence, transferability, model, and implementation limits means tracing utility failure's triggers, the limits of detection, the relevant safeguards, the recovery time, and the downstream effects. Design action prioritization supplies part of that evidence without settling technical adequacy alone, so each record still needs source, date, operating mode, uncertainty, model version, and ownership. This is what stops a seemingly exact conclusion from concealing weak assumptions, and it allows operating experience gathered afterward to revise the assessment instead of leaving it in a separate record.

For utilities and control systems, the same limitations, covering evidence, transferability, model, and implementation limits, apply to common-cause protection failure, represented by what would trigger it, where detection would fall short, which safeguards would respond, the recovery time, and the downstream effects. Closeout assurance contributes part of the evidence behind that assessment, though not enough by itself to confirm technical adequacy, so source, date, operating mode, measurement uncertainty, model version, and accountable owner should still be recorded. This traceability keeps a precise-looking conclusion from hiding weak assumptions, and it lets later operating experience revise the assessment rather than treating it as final. Likelihood modelling of major accidents using accident precursors and approximate reasoning illustrates a further model limitation relevant to common-cause protection failure in utilities and control systems, since precursor data are rarely complete enough to fully specify rare-event likelihood (Khakzad, Khan, & Amyotte, 2015) (Mbonu & Uzoka, 2022a) (Mbonu et al., 2022).

Safety studies reinforce the need to convert HAZOP findings into owned actions with measurable closure criteria (Bevilacqua et al., 2018; Liang et al., 2012; Fang et al., 2019; Conley, 2005; Asiedu et al., 2023; Restrepo et al., 2009; Center for Chemical Process Safety., 2018; Center for Chemical Process Safety., 1992; Mbonu et al., 2022; Dada et al., 2021; Arumosoye et al., 2019; Li et al., 2018; Moskowitz et al., 2016; Necci et al., 2015; Popli et al., 2012; Figueroa et al., 2008).

Reliability evidence supports linking failure modes, safeguards, inspection tasks, and maintenance intervals within the same decision record (Landucci et al., 2017; Teng et al., 2012; Yazdi et al., 2017; Bransby, 1999; Woldesellasse et al., 2023; Khan et al., 2003; Center for Chemical Process Safety., 2018; Adeyelu, 2023; Obriki et al., 2022; Dagodzo et al., 2021; Li et al., 2019; Yu et al., 2018; Paltrinieri et al., 2016; Witkowski et al., 2014; Bian et al., 2011; Jardine et al., 2006).

Control-system research highlights the importance of alarm performance, functional safety, and escalation under degraded operation (Li et al., 2016; Mannan, 2012; Zarei et al., 2017; Michelsen, 1998; Khan et al., 2015; Center for Chemical Process Safety., 2001; Center for Chemical Process Safety., 2009; Komi et al., 2023; Ogunnowo et al., 2022; Mbonu et al., 2020; Listou Ellefsen et al., 2019; Kukadiya et al., 2017; Severson et al., 2016; Upreti et al., 2013; Meyer et al., 2011; Remeljej et al., 2006).

Infrastructure-risk studies support consequence-based prioritization alongside uncertainty and evidence-quality ratings (Zarei et al., 2016; Komi et al., 2021; Jin et al., 2015; Nivolianitou et al., 1998; Kidam et al., 2013; Center for Chemical Process Safety., 2000; Center for Chemical Process Safety., 2008; Okojie et al., 2023; Ominyi et al., 2022; Agbabiaka et al., 2019; Obogo et al., 2019; Zavala-Araiza et al., 2017; Allen et al., 2015; Cao, 2012; Stack, 2009).

Maintenance literature reinforces periodic revalidation after process changes, equipment degradation, or new operating experience (Khakzad, 2015; Komi et al., 2021; Kariuki et al., 2006; Asiedu et al., 2023; Cai et al., 2012; Center for Chemical Process Safety., 1992; Center for Chemical Process Safety., 2007; Komi et al., 2022; Ben Seghier et al., 2021; Aminu-Ibrahim et al., 2019; Adeyelu, 2018; Massaiu et al., 2016; Li et al., 2015; Fabiano et al., 2012; Center for Chemical Process Safety., 2008). Additional safety literature supports continuous hazard identification, reliability review, maintenance readiness, and governed action closure (Adaramola et al., 2018; Obriki et al., 2023; Obriki et al., 2023; Obriki et al., 2023; Dagodzo et al., 2021a; Ogunwole et al., 2021). The same evidence base also supports traceable performance review and lifecycle learning (Okonkwo et al., 2021; Gideon et al., 2019).

Ewim's safety, energy-system, and pollution-risk studies reinforce evidence-led hazard analysis and consequence assessment (Ibrahim et al., 2013; Nnaji et al., 2019; Adesina et al., 2022; Ewim et al., 2023).

Conclusion

Conclusions is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should summarize the contribution and practical implications. For feed and transfer systems, the decision model must represent high pressure, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Design-basis confirmation supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record.

Conclusions is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should summarize the contribution and practical implications. For separation and treating units, the decision model must represent low flow, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Hazop deviation review supplies part of the evidence, but no single dataset establishes technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record.

Conclusions is central to integrated HAZOP and reliability analysis because design teams often identify process deviations, equipment failures, and business interruption through separate studies with inconsistent boundaries and assumptions. The analysis should summarize the contribution and practical implications. For compression systems, the decision model must represent reverse flow, including initiating conditions, detection limits, safeguards, recovery time, and downstream effects. Failure-mode analysis supplies part of the evidence, but no single dataset establishes

technical adequacy. The reviewer should record source date, operating mode, measurement uncertainty, model version, and accountable owner. This traceability prevents an apparently precise result from concealing weak assumptions. It also allows later operating experience to update the decision rather than remaining in a separate record. The paper's specific contribution is a common scenario model that translates HAZOP findings into reliability structures, risk priorities, and verified design actions. Future work should test the propositions with operating data and report both successful and unsuccessful applications. This contribution responds directly to the fragmentation documented in HAZOP and risk-analysis literature reviews, in which hazard identification, reliability quantification, and risk-based decision-making are typically reported as separate exercises rather than as one traceable workflow (Agu & Bello, 2023b).

Recent refinery and maintenance studies reinforce the need to connect HAZOP findings with functional safety, alarm management, control-system integration, and workforce practices (Onyeke et al., 2022a; Onyeke et al., 2022b; Onyeke et al., 2023a; Onyeke et al., 2023b; Obogo et al., 2019).

Declarations

Ethics approval and consent to participate: This design-method study used documentary evidence and involved no human participants or animals.

Consent for publication: Not applicable.

Availability of data and materials: The supporting evidence is available through the works cited in the reference list; no new dataset was assembled.

Competing interests: The author declares no competing interests.

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