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Original Research Article

Risk-Based Design, Construction Quality, and Lifecycle Integrity of Hydrocarbon Distribution Pipelines in Saudi Arabia: An Integrated Engineering Framework for Vision 2030

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Abstract: Hydrocarbon distribution pipelines connect production, processing, storage and end users, yet their integrity is often governed through disconnected design, construction and operating records. This critical review examines research published from 2020 to 2025 to develop an integrated engineering framework applicable to Saudi Arabian liquid and gas networks. The synthesis evaluates corridor hazards, design margins, corrosion, girth weld acceptance, commissioning evidence, risk assessment, inspection and digital monitoring. It distinguishes established engineering controls from emerging predictive methods and considers the transferability of international evidence to arid, coastal and industrial settings. Findings indicate that effective integrity assurance depends less on deploying individual technologies than on maintaining traceable links among threat assumptions, construction deviations, measured deterioration, consequence exposure and intervention decisions. A lifecycle assurance framework is proposed around risk registers, verifiable quality gates, spatially referenced evidence and periodic model recalibration. Saudi-specific research additionally identifies specification discrepancies and material quality as important delivery vulnerabilities. The review provides decision criteria for asset owners and contractors, while identifying validation gaps concerning local deterioration data, sensor performance and the operational economics of digital systems.

Keywords: Hydrocarbon Pipelines, Saudi Arabia, Risk-Based Design, Construction Quality, Corrosion, Girth Welds, Integrity Management, Vision 2030.

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1. INTRODUCTION

Reliable transportation of crude oil, refined products and natural gas is a prerequisite for industrial continuity, fuel supply and environmental protection. A distribution pipeline is not simply a pressure boundary: it is a geographically extended system whose performance depends on material condition, construction history, surrounding land use, operating excursions and the ability to detect deterioration. Failures can therefore arise even when individual components nominally satisfy their original specifications. Recent integrity research favours risk-informed decisions in which inspection, assessment and intervention evolve with the condition and consequences of each pipeline segment [1, 2].

Saudi Arabia provides a demanding context for this approach. Large distances between energy assets, varied industrial corridors, coastal exposure,

remote crossings and evolving development footprints create heterogeneous threats. These conditions should not be treated as a single national corrosion or failure profile. Rather, temperature, soil conductivity, water availability, mechanical interference, product composition and emergency access require location-specific evidence. Saudi project research identifies specification discrepancies, unsuitable materials and deficient threat monitoring among consequential sources of construction risk [20]. These findings make the handover between delivery and operation a substantive integrity concern, not merely an administrative milestone.

The study aims to establish an evidence-grounded framework linking risk-based design, construction acceptance and lifecycle integrity in Saudi hydrocarbon distribution networks. Its objectives are to identify consequential threat pathways; determine what design and construction records must survive commissioning; evaluate inspection and prediction methods against uncertainty; and define decision gates that convert observations into timely interventions. The principal contribution is the integration of these activities into one auditable chain, rather than another catalogue of inspection technologies. The proposed framework is a critical synthesis, not an independently validated national risk model.

2. Review Scope and Analytical Method

A structured critical review was used because the question concerns relationships across disciplines rather than the pooled effect of a single intervention. Literature dated 2020–2025 was identified through targeted searches using combinations of pipeline integrity, risk-based inspection, hydrocarbon leakage, corrosion prediction, girth weld, construction quality, Saudi Arabia and digital twin. Priority was given to peer-reviewed papers with identifiable digital object identifiers and direct relevance to oil or gas pipelines. Evidence on offshore, transmission and gathering systems was retained only where the engineering mechanism could plausibly inform distribution assets; its limits of transferability are stated where consequential.

Thirty sources were selected for analytical coverage across risk modelling, corrosion, construction, inspection, sensing and Saudi policy context. The review compares their stated methods and conclusions and develops a thematic synthesis organized by lifecycle decisions. Studies reporting numerical model performance were not pooled because datasets, products, exposure conditions and validation designs differ. Numerical outputs are therefore treated as study-specific, not as transferable Saudi performance coefficients. Technical standards inform the recommended engineering practice conceptually, but no unverified claim of mandatory national adoption is made.

Interpretation followed three tests. First, each claim was linked to a credible failure mechanism or observed evidence. Second, a technology was assessed according to what it measures, what it cannot observe and the decision it can safely support. Third, the proposed practice had to produce a reviewable record connecting assumptions to acceptance or intervention. This logic separates established requirements, such as welding qualification and corrosion protection, from promising but incompletely validated automated inference. The result is an engineering review with explicit boundaries rather than a claim that all pipeline categories share identical operating risks.

3. Saudi Operating Context and Risk Boundaries

Hydrocarbon distribution systems cover different products and pressures, from wet or dry gas to crude oil and refined liquids. A single generic risk score obscures these distinctions. Segment boundaries should therefore reflect changes in fluid inventory, location class, aboveground interfaces, crossing type, isolation capability and inspection accessibility. Operators must also distinguish the transportation function of the asset from any assumptions imported from high-pressure trunk lines or offshore systems [1-14].

Inland aridity does not demonstrate absence of external corrosion. Buried pipelines may encounter saline pockets, irrigation influence, intermittent flooding, industrial drainage and local moisture retention; coastal facilities add different exposure mechanisms. Equally, heat and solar loading affect coating application, construction procedures and operating temperature but do not create a universal corrosion rate. Under-deposit and top-of-line mechanisms depend on fluid chemistry, water condensation and deposits rather than climate labels alone [28, 29]. Credible screening begins with sampling, operating history and coating or cathodic-protection condition, not a national average.

The Vision 2030 relevance lies in preserving dependable infrastructure while strengthening resource efficiency, localization and the value obtained from energy assets. Energy-transition analysis describes a policy setting in which operational efficiency and industrial development must be considered together [30]. Pipeline integrity contributes through prevention of lost product, avoidable outages and repair-related material consumption. These are potential outcomes of better management, not quantified savings demonstrated

by this review. A credible implementation programme should consequently report measured safety, availability and environmental indicators alongside investment in inspection or digitalization.

4. Risk-Based Design as a Sequence of Defensible Decisions

Design integrity starts with explicit hazards rather than a nominal wall thickness. Route selection should compare third-party interference, ground movement, crossings, access for repair and credible release exposure before detailed alignment is frozen. A lower construction cost may be offset by difficult isolation, recurrent flooding or future encroachment. Where rerouting is impracticable, protective measures and surveillance must be specified as design commitments with named owners. The landslide failure analysis by Vasseghi and colleagues illustrates why local geometry and displacement-driven loading can dominate simplistic pressure-only assessments [26].

Pressure containment, fracture control and thermal flexibility require compatible design bases. Pipe grade, diameter, thickness, manufacturing tolerances, toughness, operating envelope and transient loading must be considered together. For welded lines, tensile strength alone cannot establish displacement capacity: strength mismatch, local flaws and residual stress modify the fracture response [24, 25]. Designers should distinguish load-controlled events from displacement-controlled events and document the consequences of changing wall thickness, grade or bend configuration after procurement. The final design basis must record allowances and modelling assumptions, not merely nominal code compliance.

Corrosion control must be designed as a system combining material selection, coating, cathodic protection where appropriate, fluid treatment, drainage and inspectability. A nominal corrosion allowance is not a substitute for credible local deterioration mechanisms. In sour service or when corrosion-resistant cladding is considered, interfaces and weld preparations require specific integrity scrutiny. Reda and colleagues report a clad-pipe failure involving misalignment and grinding that compromised the corrosion-resistant layer, demonstrating why material specification cannot compensate for uncontrolled fabrication practices [27].

Functional design also determines whether future data will be usable. Pig launchers, receiving facilities, valve spacing, access points, test posts, instrumentation and reliable positional references must be considered before construction. An uninspectable segment imposes recurring uncertainty and may require alternative inspection technology or a conservative intervention strategy. The design deliverable should therefore include a preliminary threat register, approved monitoring concept, isolation philosophy and baseline data plan. Figure 1 shows how these decisions pass forward into construction and operation rather than ending at the drawing approval stage.

Design reviews should also test foreseeable change. A pipeline corridor that is remote at commissioning can acquire roads, utilities, industrial facilities and informal access routes during its service life. The consequence model must therefore be revisited when land use changes, even if corrosion inspections remain satisfactory. At major crossings, installation records should preserve cover depth, protective structures, separation distances and the rationale for any special wall or impact protection. If monitoring cannot verify the intended protection, a right-of-way surveillance plan becomes part of the design obligation. This establishes a route from initial hazard identification to later management of third-party activity without assuming that original conditions will remain fixed.



Figure 1: Transfer of engineering assumptions and verifiable assurance records across the pipeline lifecycle (conceptual synthesis)

5. Corrosion Mechanisms and Uncertainty-Aware Assessment

Internal corrosion depends on water availability, phase behaviour, acid gases, flow regime, deposits, microbial activity and operating transients. External corrosion depends on the coating, soil environment, electrical interference and effectiveness of protection systems. These mechanisms require separate evidence and cannot be represented safely by one averaged wall-loss assumption. Reviews of under-deposit and top-of-line corrosion show that localized chemistry and condensation pathways can create damage not explained by bulk fluid composition alone [28, 29]. Sampling programmes should therefore consider low points, dead legs, changing throughput and preservation history, with results linked to physical locations.

Predictive models can assist screening when sufficient data exist. Ensemble learning has been investigated for internal corrosion rates [4], while other studies trace progression from empirical correlations towards data-driven modelling [5–7]. Their usefulness depends on measurement provenance, input coverage and whether model validation resembles the intended operating environment. A high statistical fit within simulated or homogeneous data does not certify prediction of rare pits, new chemical treatments or a materially different Saudi distribution network. Field calibration and uncertainty reporting are essential before a model controls repair priority.

Decision making must retain uncertainty in defect size, growth and detection capability. A wall-thickness measurement is not the true minimum thickness unless spatial coverage and measurement error support that conclusion. Similarly, repeating an inspection with a different tool can create apparent growth through registration or sizing differences. The operator should reconcile tool runs, preserve raw measurements and establish confidence bounds before revising remaining-life estimates. Where credible rapid growth or high consequences exist, conservative reassessment may be preferable to an apparently precise point forecast. This is the practical distinction between predictive support and automated engineering authority.

Monitoring programmes should distinguish an observed adverse condition from confirmed damage. For example, an interruption in cathodic protection can increase susceptibility without proving that measurable metal loss has occurred, whereas an isolated ultrasonic reading may reveal loss without identifying its cause. Treating both signals as equivalent leads to misdirected repairs. A structured response distinguishes immediate containment concerns, diagnostic inspection and corrective prevention. Relevant chemistry, flow histories, maintenance interventions and measurement uncertainty must be captured over time. Where product composition or throughput changes, a reassessment trigger should be defined before the change is introduced. The same principle applies to temporary chemical treatments, which may alter corrosion behaviour and affect subsequent model predictions.

6. Construction Quality and Traceable Acceptance

Construction transforms design assumptions into an installed asset and introduces defects that subsequent operating inspections may not distinguish from service deterioration. Material identification, heat-number traceability, storage, handling, bending, fit-up, weld preparation, coating application, burial and reinstatement all influence the resulting integrity baseline. Saudi evidence from pipeline construction highlights how internal welding controls can improve field discipline under demanding site conditions [21]. Wider industry analysis likewise stresses qualification, personnel, materials, methods, environment and consistent data acquisition as interacting determinants of girth-weld quality [22].

A defensible inspection and test plan identifies the acceptance basis, responsible authority, hold points, nonconformance process and independent verification required for each critical activity. Welding procedure qualification must represent the actual joint configuration, materials, consumables, heat input and environmental controls. Production records should identify each weld spatially and include operator qualifications, procedure revision, examination results, repair cycle and final disposition. Radiographic or ultrasonic examination can detect relevant discontinuities, but neither method removes the need to assess flaw acceptance in relation to loading, toughness and service conditions [23–25].

Automated interpretation deserves cautious adoption. Machine-vision studies have reported strong weld-radiograph recognition results within their evaluated datasets [23], yet image quality, class imbalance and field generalization remain material concerns. Algorithms should triage or assist qualified examiners until site-specific validation demonstrates reliable defect detection, sizing and false-alarm behaviour. A construction dataset that records only accepted welds conceals the frequency and location of rework, defeating later assessment of recurring contractor or environmental issues. Retaining repaired and rejected records is therefore essential for both quality improvement and lifecycle analysis.

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Coating inspection, holiday detection, lowering-in controls, backfill suitability and separation from foreign infrastructure should be documented to the same level of traceability. Post-weld coating repairs are especially vulnerable to divided responsibilities. A photograph without chainage, weld identifier, test method and acceptance result is weak evidence. Conversely, a coherent digital dossier can identify each deviation, the engineering concession, compensating protection and any required operating surveillance. The acceptance gate must reject undocumented substitutions and unresolved deviations even when the physical pipeline is ready for pressure testing.

Quality surveillance is more effective when acceptance criteria are linked to physical consequences. A minor surface blemish and a planar weld flaw are not equivalent simply because both appear in a nonconformance log. Their significance depends on size, location, orientation, material properties and loading. Disposition should distinguish rework needed to meet the approved specification from an engineered concession requiring further assessment. Statistical tracking can reveal whether a recurring defect follows a welding shift, equipment setup, supplier batch or environmental exposure. However, defect counts should be normalized against examined production and assessed alongside detection sensitivity. Otherwise, a contractor using more rigorous examination may appear worse than one whose defects remain undiscovered.

7. Commissioning as the Integrity Baseline

Commissioning is the point at which construction evidence is tested against the intended operating envelope. Pressure tests, cleaning, gauging, drying or dewatering, instrumentation calibration and valve functionality each answer a different integrity question. A successful pressure test does not demonstrate that external coating is undamaged, internal moisture is controlled or every weld record has been reconciled. Acceptance should consequently combine physical test results with a verified as-built alignment, segment inventory, inspection accessibility statement and closed nonconformance register.

Preservation and start-up histories matter because dormant lines and wet services can change exposure before normal operation begins. The clad-pipeline failure reported by Reda and colleagues demonstrates the importance of weld detail and preservation chronology when evaluating apparently premature service failure [27]. For distribution systems, isolation set-points, flow-measurement accuracy and alarm logic must also be tested in conditions representative of foreseeable demand changes. The initial integrity dossier should establish what has been measured, what remains uncertain and which assumptions require early operational confirmation. Without this baseline, later assessments risk treating missing construction information as evidence of sound condition.

Commissioning acceptance also needs a credible route to operational readiness. The test boundary and temporary configuration should match recorded drawings, while blinds, temporary spools and test instruments should be reconciled against the permanent arrangement. Valve positions, shutdown permissives and communication pathways require witnessed checks because a pressure-tight line may still be difficult to isolate during a release. For lines commissioned in stages, the dossier should identify which segments have completed each requirement and which remain subject to restrictions.

8. Integrated Risk Modelling and Intervention Logic

Risk assessment should distinguish likelihood of failure from its consequences and from the confidence attached to either estimate. A segment may have low estimated failure probability yet demand priority because a release could threaten a densely occupied crossing. Another may deteriorate quickly but have accessible isolation and limited exposure. Risk-based integrity reviews frame this as an allocation problem: prioritize inspections and mitigation according to changing threat and consequence profiles, not fixed intervals alone [1, 2]. Simple categories can support initial screening, but decisions affecting major hazards require explicit assumptions and competent review.

Bow-tie analysis links initiating threats to the loss-of-containment event and its outcomes through preventive and mitigative barriers. Bayesian methods can update interacting pathways when evidence changes, although their apparent precision is sensitive to elicited probabilities, dependence assumptions and scarce incident data [8, 9]. An integrated corrosion-incident model combining neural networks with Bayesian analysis illustrates the potential to relate predictive signals to event risk [3]. Such methods should supplement rather than replace transparent fault descriptions and documented safety barriers. Operators must be able to explain why a new inspection result changes a particular maintenance decision.

The proposed risk register has a permanent segment identifier, product, exposure context, credible threats, barrier status, inspection evidence, uncertainty range and decision owner. Each review should preserve both the pre-intervention and residual-risk view. A recommended repair becomes

actionable only after checking operational constraints, isolation requirements, technical feasibility and verification criteria. Bayesian decision modelling can help explore alternatives under resource limits [8], but final acceptance must remain tied to engineering judgement and authority. The framework uses a mandatory escalation path when consequence severity or evidence gaps render numerical ranking unreliable.

Table 1 converts the synthesized mechanisms into decision-oriented evidence requirements. Its purpose is not to prescribe universal risk scores; it specifies the records without which a classification is difficult to defend. In this arrangement, an apparent low-risk outcome cannot conceal missing weld history, unverified corrosion protection or a model applied outside its calibration domain. The governing principle is that uncertainty changes the decision, rather than disappearing inside a weighted index.

Consequence assessment should be based on credible physical pathways rather than proximity alone. Liquid releases may reach drainage channels or sensitive assets before response crews arrive; gas releases create different dispersion and ignition concerns. Inventories between effective isolation points, elevation profile, release orientation, response access and detection latency may substantially influence outcomes. Uncertainty is particularly important where isolation valves are present but their actual closure performance has not been demonstrated. Scenario assumptions should be tested through emergency exercises and updated when population, facilities or operating pressure changes. This turns consequence modelling into an ongoing coordination mechanism between pipeline engineering, operations, emergency response and surrounding infrastructure stakeholders.

Table 1: Threat-specific evidence and decision consequences synthesized from the reviewed literature

Threat / failure pathway	Minimum traceable evidence	Main uncertainty	Risk-directed action
Internal corrosion	Fluid chemistry, water/deposit history, localized metal-loss measurements	Growth variability; sampling coverage	Treat fluid source; verify damage; set reassessment trigger
External corrosion	Coating condition, potential surveys, soil results, position-matched anomalies	Intermittent wetting; protection effectiveness	Repair coating; check protection; target excavation
Weld / construction defect	Qualified procedure, weld ID, NDT record, repairs and engineering concessions	Detection threshold; strength mismatch	Fracture assessment; repair or approved concession
Mechanical interference	Crossing inventory, depth, encroachment surveys, incident records	Future land use; unrecorded activity	Protect right of way; surveil; revise consequence model
Leak / isolation failure	Alarm tests, leak simulations, valve closure and response exercise records	False negatives; detection and response latency	Layer monitoring; improve isolation and response

9. Inspection, Leak Detection and Interpretation

In-line inspection provides distributed information about metal loss, geometry and selected crack-like features, subject to the tool's physics, velocity range, accessibility and detection threshold. Magnetic flux leakage, ultrasonics and complementary methods are not interchangeable: they respond differently to wall thickness, defect orientation, coating and service configuration. Reviews of instrumentation and data management emphasize the joint importance of suitable tools, reliable feature matching and historical records [10, 11]. The inspection strategy should define the target threat before selecting a tool, then compare observed indications with qualified assessment and repair criteria.

Leak detection addresses a distinct temporal problem: reducing the duration and consequences of an active release. Computational methods based on mass balance, transient pressure and acoustic waves compete with external sensors and inspection patrols. Reviews identify substantial performance differences under noise, transients and multiphase operating conditions [12–15]. Infrared imagery and trained recognition systems show promise for difficult visual scenes [16], self-supervised learning has also been tested using field data from gas gathering systems [17]. None of these findings supports a universal leak-size threshold or detection time for every Saudi distribution line.

A layered architecture is therefore preferable. Continuous operational monitoring can identify suspicious changes, independent field

confirmation can establish location and severity, and isolation systems can reduce release duration. Alarm testing should include normal changes of demand, instrument outages, communication loss, start-up and shutdown rather than only artificially clean leak simulations. Performance measures should report detection sensitivity, nuisance alarms, localization uncertainty and actual response time. Where consequence exposure is high, the operator must explicitly define how uncertainty affects shutdown decisions; avoiding nuisance alarms cannot become an unexamined reason to tolerate delayed action.

10. Digital Twins and Information Governance

Digital twins have been proposed to integrate measured pipeline condition with evolving models, including damage estimation and uncertainty propagation [18]. Models of inspection equipment also demonstrate how tool behaviour and operating conditions can affect interpretation [19]. These are valuable capabilities, but a digital twin is not inherently a certified representation of an operating asset. It must specify its physical boundaries, update frequency, data-quality checks, calibration history, intended decisions and failure modes. When a sensor fails or new operating conditions fall outside training data, the system should expose that limitation instead of silently producing a confident condition score.

The most useful digital architecture begins with an authoritative asset register. Every weld, anomaly, crossing, coating repair, test point and intervention must connect to a stable spatial identifier and controlled revision history. Engineering drawings alone rarely capture subsequent field changes; conversely, a dashboard without signed inspection findings cannot resolve ownership or auditability. Data pipelines should distinguish raw sensor observations, processed features, analyst interpretation and formally approved decisions. This separation supports traceability, change control and independent review of disputed measurements.

Decision automation should be proportional to evidence maturity. A validated anomaly detector may trigger inspection requests, but repair acceptance, pressure restrictions and retirement decisions should follow controlled engineering review. Access permissions, cybersecurity, backup and version control are also integrity controls because corrupted or unavailable data can compromise hazard decisions. The framework in Figure 2 separates evidence acquisition from assessment authority while providing a feedback loop to design assumptions. Digital capability creates value when it reduces uncertainty and intervention delay, not when it simply increases the number of displayed variables.

Interoperability has a less visible but equally important consequence. Different contractors may use inconsistent stationing, coordinate systems, weld identifiers and defect taxonomies, making comparisons across the lifecycle unreliable. A common information specification should define naming, positional tolerances, units, timestamps, source systems, approval signatures and rules for superseded records. Original measurements must remain accessible when later algorithms produce revised classifications. The asset owner should also establish retention and export requirements before acquiring proprietary monitoring platforms. A carefully curated modest dataset can be more useful for integrity decisions than a much larger collection lacking provenance or spatial accuracy.

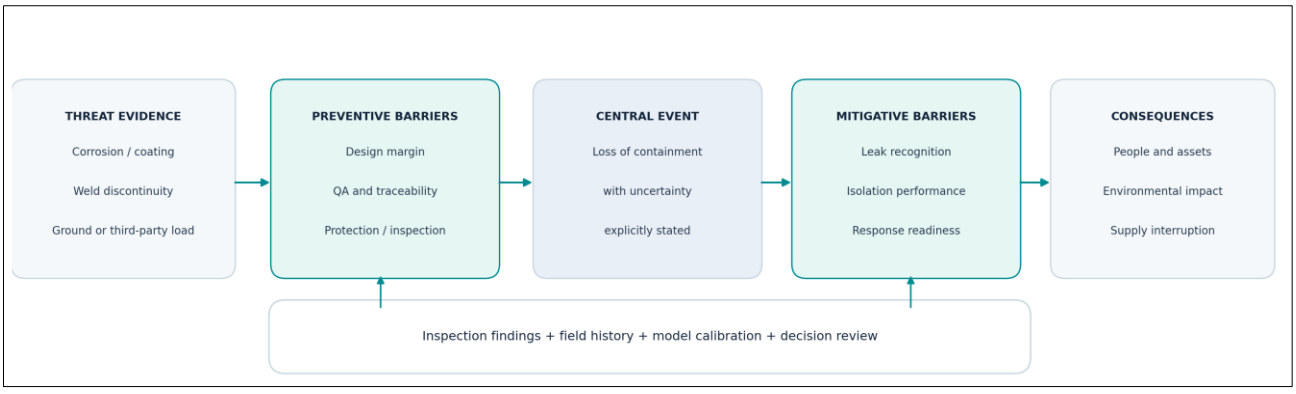


Figure 2: Coupled threat, barrier and consequence logic with evidence-driven updating (conceptual synthesis)

11. Governance, Implementation and Assurance Metrics

A practical rollout can begin with a representative mix of buried liquid, gas, coastal and industrial segments. The owner should first reconcile the asset register and classify material consequences, then identify high-consequence uncertainty that can be resolved through targeted document recovery or

inspection. Existing engineering standards, contractual specifications and approval routes must be mapped to named gates. Where records remain absent, the action should be explicit: inspect, conservatively reassess, impose an operational restriction or justify continued service through competent technical authority.

Roles must not fragment across designers, construction contractors and operating teams. Design engineers own documented assumptions; contractors own verifiable installation evidence; integrity teams own threat reassessment; operations owns real-time conditions and response; and independent assurance checks whether deviations and hazards have been adequately closed. In Saudi projects, specification alignment and supplier verification deserve particular attention given the delivery risks identified empirically [20]. Table 2 details handover outputs and evidence-based decisions that can be applied without assuming identical operating codes for every pipeline category.

Meaningful metrics include the proportion of critical welds with complete traceability, overdue high-consequence anomalies, cathodic-protection exceptions, validated leak-detection coverage, time from finding to disposition and unresolved design deviations. Availability and loss-of-containment events remain important lagging outcomes, but they are insufficient alone for low-frequency hazards. Trend reporting should differentiate improvements in actual conditions from increased detection caused by better inspection. Independent periodic review should sample underlying records and test whether stated risk reductions correspond to functioning barriers and completed work.

Implementation success should be judged through staged assurance rather than a single software launch. A pilot should begin with a measurable decision problem, such as reducing unresolved high-consequence weld anomalies or improving leak-alarm localization. Baseline performance and measurement uncertainty should be recorded before introducing new tools. Independent review can then determine whether improvements reflect genuine risk reduction, changed operating conditions or only revised reporting definitions. If a digital alert cannot be associated with a responsible decision and a completed field action, its operational value remains unproven. This sequencing allows investment priorities to follow demonstrated engineering benefit while retaining the flexibility to revise the method when evidence contradicts initial expectations.

Table 2: Evidence-based acceptance gates and delegated decision responsibilities for lifecycle assurance

Lifecycle gate	Evidence required before release	Engineering acceptance question	Accountable function
Design approval	Threat register, design basis, corridor and inspection philosophy	Are credible threats and future inspection addressed?	Design authority
Procurement	Material certificates, supplier controls, approved substitutions	Is the specified material independently traceable?	Quality / materials
Construction	Weld map, examinations, coating tests, nonconformance closure	Are deviations accepted using defensible criteria?	Contractor QA + owner
Commissioning	As-built alignment, pressure tests, operational alarm and valve tests	Is the actual asset ready for its declared envelope?	Commissioning lead
Operation	Inspection trend, barrier status, risk register, intervention decisions	Is continued service justified by current evidence?	Integrity + operations
Revalidation	Reinspection, repair verification and lessons incorporated	Did treatment demonstrably reduce the identified risk?	Technical authority

12. Research Gaps and Validation Priorities

The first gap is transferability. Much published evidence concerns offshore lines, high-pressure transmission or carefully instrumented trials; Saudi distribution assets may have different fluids, geometry, inspection constraints and consequence profiles. Future studies should report soil and operating conditions, coating systems, defect populations and instrumentation uncertainty rather than relying on country labels. Comparative pilots across inland and coastal segments could determine which degradation predictors remain stable outside their development datasets.

The second gap concerns causal evidence. Corrosion prediction papers often optimize error metrics, whereas owners need defensible probabilities of reaching engineering limits before the next intervention [4–7]. Research should connect uncertainty-calibrated predictions to repair decisions and demonstrate how false negatives, delayed discovery and inspection costs change total risk. Similarly, machine-assisted weld examination needs external validation on production radiographs with transparent reference standards, not only training and test partitions drawn from one project [23].

A third gap is organizational integration. Studies rarely measure whether improved construction traceability actually changes later inspection selection or unplanned maintenance. Longitudinal research could link initial quality records with successive integrity assessments to quantify the value of early data capture. Digital pilots should publish data latency, missingness, recalibration frequency and human override behaviour, thereby evaluating practical reliability rather than interface sophistication [18, 19]. A fourth priority is to assess outcomes beyond asset uptime, including avoided release impacts and material efficiency, using transparent baselines consistent with wider Saudi energy-policy objectives [30].

13. CONCLUSIONS

This review identifies lifecycle discontinuity as a central, manageable integrity weakness: design hazards may not survive procurement, construction deviations may be lost at commissioning, and operating data may not be reconciled with the installed asset. The proposed framework connects threat-based design, qualified construction acceptance, an auditable commissioning baseline, uncertainty-aware risk assessment and targeted monitoring through stable segment identifiers and explicit decision authority.

For Saudi hydrocarbon distribution pipelines, the engineering implication is to standardize the quality of evidence while allowing risk controls to vary with product, location and exposure. Predictive analytics and digital models can improve prioritization, but only when validated against local data and coupled with transparent inspection and intervention rules. The framework is a synthesis requiring field validation, not evidence of already achieved national safety gains. Its contribution is a practical basis for testing whether investment in engineering assurance produces measurable integrity and resilience outcomes under Vision 2030.

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