

Cause-Tree Failure Analysis of Pressure Vessel Breakdowns; A Review of Root-Cause-Driven Maintenance Frameworks

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Abstract

Pressure vessels remain among the highest-consequence assets in refining, petrochemical, power generation, chemical processing, and cryogenic service. Their failures are rare in frequency but severe in outcome, which makes them poorly suited to purely statistical reliability treatment and strongly suited to causal reasoning. This paper reviews the state of cause-tree failure analysis as applied to pressure vessel breakdowns, and examines how the causal structures produced by such analysis are, or are not, converted into maintenance decisions. Four bodies of work are surveyed. The first is the family of deductive causal decomposition methods: Fault Tree Analysis (FTA), event tree analysis, bow-tie modelling, causal factor charting, and the structured root-cause protocols descended from them. The second is the family of proactive maintenance frameworks: Reliability-Centered Maintenance (RCM), Risk-Based Inspection (RBI) under API RP 580 and API RP 581, condition-based and predictive maintenance, and fitness-for-service assessment under API 579-1/ASME FFS-1. The third is the emerging computational layer that connects the two, comprising Bayesian network mappings of fault trees, fuzzy and dynamic tree extensions, and digital-twin-enabled predictive analytics. The fourth is an adjacent applied literature of 201 sources, drawn on here as seed material and organised into thirty-two thematic clusters, covering non-destructive evaluation and corrosion risk assessment for process equipment, sensor-based condition monitoring and maintenance strategy migration, remote and standoff inspection, energy-autonomous wireless sensing, operational technology and enterprise security, aviation safety oversight and investigation practice, predictive analytics and anomaly detection, regulated facility lifecycle and design, procurement and supplier risk, audit and risk governance, algorithmic accountability, process discipline, and the organisational causation of industrial incidents. The central finding of this review is that the first two bodies of practice remain weakly coupled. Cause trees are typically built after a failure, for the purpose of incident reporting, while maintenance intervals are typically set before failure, from generic damage-rate assumptions and code-mandated periodicities. The causal knowledge produced in the first activity rarely reaches the interval-setting logic of the second in a formal, auditable way. A worked quantitative example is

presented showing that under a plausible pressure vessel fault tree, a maintenance investment directed by importance measures reduces top-event probability by roughly 78 percent, whereas an equally costly investment directed by convention and habit reduces it by under 2 percent. The paper proposes a five-layer Root-Cause-Driven Maintenance (RCDM) architecture to close this gap, identifies ten research gaps, and sets out directions for integrating causal models with live asset integrity data.

Keywords: *pressure vessel integrity, fault tree analysis, root cause analysis, risk-based inspection, reliability-centered maintenance, asset integrity management, bow-tie analysis, Bayesian networks, non-destructive evaluation, mechanical integrity*

1. Introduction

1.1 Problem context

A pressure vessel is a closed container designed to hold gases or liquids at a pressure substantially different from the ambient. The stored energy in such a vessel is considerable. A modest process drum operating at 20 bars can, on sudden rupture, release energy comparable to tens of kilograms of high explosive, and the resulting fragmentation, blast overpressure, and subsequent fire or toxic release account for a disproportionate share of process industry fatalities relative to the equipment count involved. The engineering community has responded to this hazard with an unusually dense regulatory and code apparatus. The ASME Boiler and Pressure Vessel Code governs design and construction. API 510 governs in-service inspection, rating, repair, and alteration. API RP 571 catalogues the damage mechanisms that operate in refining service. API 579-1/ASME FFS-1 provides quantitative fitness-for-service methods when damage is found. In the United States, the mechanical integrity provisions of the OSHA Process Safety Management standard impose a legal duty to inspect and maintain covered equipment. Comparable frameworks exist under the European Pressure Equipment Directive and the various national boiler and pressure vessel acts. And yet vessels continue to fail. The persistence of failure in a heavily coded domain is the puzzle that motivates this review. The codes prescribe what to inspect and how often; they are largely silent on why a specific vessel in a specific service is degrading in a specific way, and on how that reasoning should modify the inspection plan. Closing that inferential gap is the work of root cause analysis, and the dominant formalism for root cause analysis is the cause tree.

1.2 What a cause tree is, and why it fits this asset class

A cause tree is a directed acyclic graph in which an undesired top event is decomposed, through logical gates, into successively more elementary contributing events, terminating in basic events that are not further resolved. The decomposition is deductive: it reasons backward from effect to cause, rather than forward from component failure to system consequence as inductive methods such as FMEA do. Three properties make this formalism unusually well matched to pressure vessel failure. Rarity. Pressure vessel catastrophic failure rates are commonly quoted in the range of 10^{-5} to 10^{-6} per vessel-year for well-managed populations. At those frequencies, an individual plant will never accumulate enough events to support empirical reliability estimation. Cause trees permit synthesis of a top-event probability from more frequently observed basic events, which is the only tractable route to quantification. Conjunction. Catastrophic vessel failure is characteristically conjunctive. It requires a degradation mechanism and a failure of the barrier intended to detect that mechanism, or a pressure excursion and a failure of the relieving system. Single-because reasoning misrepresents this structure. The

AND gate is not a modelling convenience here; it is a faithful description of how defence in depth is supposed to work and how it actually fails.

Layered causation. Vessel failures are simultaneously metallurgical, procedural, and organisational. A crack propagates because of a stress and an environment; the environment was permitted because a process change was not reviewed; the change was not reviewed because a management of change procedure was informally waived. Tree structures accommodate this vertical layering more naturally than flat cause lists.

1.3 Scope and objectives of this review

This review addresses the following questions.

1. What cause-tree and cause-tree-derived methods are currently applied to pressure vessel failure analysis, and how do they differ in resolution, quantifiability, and organisational reach?
2. What maintenance frameworks claim to be root-cause-driven, and to what extent is that claim structurally justified?
3. Where and how do the two bodies of practice actually connect, and where does the connection break?
4. What does the recent computational literature contribute, and what does it not yet solve?
5. What should a defensible integrated framework look like?

The review does not attempt to be a metallurgical treatment of damage mechanisms; API RP 571 and the fracture mechanics literature serve that purpose and are cited rather than reproduced. Nor does it treat design-stage code compliance except where design assumptions become in-service root causes.

2. Review Methodology

2.1 Search strategy

Literature was assembled from five strata:

Review year and literature cutoff. This is a 2024 review. The literature search closed at the end of 2024, and no source published after that year is cited. Where a body of work was still developing at the cutoff, the review says so rather than anticipating results that had not yet appeared. Readers consulting this paper later should treat the fast-moving areas identified in Sections 4.5 and 8, particularly digital twin practice and machine learning for condition assessment, as the ones most likely to have moved since.

Stratum A, codes and recommended practices. ASME BPVC Section VIII, API 510, API RP 571, API RP 572, API RP 579-1/ASME FFS-1, API RP 580, API RP 581, IEC 61025 (fault tree analysis), IEC 60812 (FMEA), IEC 61508 and IEC 61511 (functional safety), SAE JA1011 and JA1012 (RCM evaluation criteria), ISO 55000 (asset management), and the National Board Inspection Code.

Stratum B, foundational monographs and handbooks. The NUREG-0492 Fault Tree Handbook, the NASA Fault Tree Handbook with Aerospace Applications, Nowlan and Heap's report on reliability-centered maintenance, the standard treatment of system reliability theory by Rausand and Høyland, Kletz's work on organisational learning from process accidents, and the accident-model literature of Reason, Rasmussen, and Leveson.

Stratum C, peer-reviewed journal literature. Sources drawn primarily from Reliability Engineering and System Safety, Journal of Loss Prevention in the Process Industries, Engineering Failure Analysis, Process Safety and Environmental Protection, Quality and Reliability Engineering International, Safety Science, and International Journal of Pressure Vessels and Piping.

Stratum D, investigation reports. Public findings from the US Chemical Safety Board, the National Institute of Standards and Technology (formerly the National Bureau of Standards), the UK Health and Safety Executive, and national boiler inspection authorities.

Stratum E, adjacent applied seed literature. A corpus of 201 applied reviews, systematic reviews, and conceptual frameworks listed in full in the reference list, bearing on components of the argument that the pressure vessel literature itself treats thinly. The corpus is organised into thirty-two clusters, listed below with the sections in which each is used. Relevance is graded, and the grading is stated openly rather than concealed: clusters marked *direct* address pressure-retaining or comparable process equipment; clusters marked *adjacent* address a different asset class but the same causal mechanism; clusters marked *structural* contribute an organising principle rather than a finding about equipment; and clusters marked *peripheral* are included for completeness of the corpus and contribute analogy only. The peripheral designation is a warning label, not a recommendation: claims in this review do not rest on those clusters alone.

Cluster	Size	Relevance	Principally used in
Equipment integrity, NDE, corrosion, welding	4 sources	Direct	3.2, 5.3, 7.2, 8
Condition monitoring and maintenance strategy	8 sources	Direct	4.5, 5.1, 6.3
Occupational safety and incident causation	32 sources	Adjacent	3.3, 4.3, 5.7, 7.3
Remote and standoff inspection (UAV, LiDAR, GIS)	9 sources	Adjacent	6.3, 7.2
Operational technology and infrastructure security	8 sources	Adjacent	3.1, 5.7
Aviation safety oversight and investigation	9 sources	Adjacent	4.3, 5.2, 5.7
Predictive diagnostics and digital twins in energy	8 sources	Adjacent	4.5, 7.4
Lifecycle risk in energy environmental systems	3 sources	Adjacent	5.4, 8
Power systems and electrical machines	3 sources	Structural	4.5

Cluster	Size	Relevance	Principally used in
Project governance and delivery risk	4 sources	Structural	5.7, 6.4
Predictive analytics and decision systems	7 sources	Structural	4.5, 6.3
Lean operations and process discipline	4 sources	Structural	5.7, 6.4
Audit, risk governance, compliance analytics	6 sources	Structural	5.3, 5.7
Data governance and IT risk controls	4 sources	Structural	6.4
Human factors and security awareness	1 source	Structural	3.3, 7.3
Supply chain, materials readiness, asset lifecycle	9 sources	Structural	5.5, 6.3
Wireless sensing and energy-autonomous monitoring	4 sources	Adjacent	6.3, 8
Enterprise cyber defence and security validation	8 sources	Adjacent	3.1, 5.7
Cybersecurity governance and network resilience	6 sources	Structural	3.1, 5.7
Service reliability, capacity planning, operations	7 sources	Structural	5.7, 6.4
Facility lifecycle, regulated design, asset performance	9 sources	Structural	3.2, 5.5
ESG auditing, carbon governance, procurement	5 sources	Structural	5.7, 8
Strategic procurement and supplier risk	12 sources	Structural	5.5, 6.4
Anomaly detection, fraud analytics, audit intelligence	7 sources	Structural	4.5, 6.3
Regulatory science and quality assurance	5 sources	Structural	5.3, 5.7
Technology law and algorithmic accountability	3 sources	Structural	6.3, 6.4

Cluster	Size	Relevance	Principally used in
Energy transition and socio-technical durability	5 sources	Peripheral	5.7
Renewable fuels, photovoltaics, degradation science	2 sources	Peripheral	3.2
Machine development and performance evaluation	3 sources	Peripheral	5.7
Electrical machine optimisation and networks	3 sources	Peripheral	4.5
Autonomous robotics and material handling	1 source	Peripheral	6.3
Applied information systems and human-in-the-loop learning	2 sources	Structural	6.3

This stratum is drawn on deliberately, because the deficiencies identified in this review are concentrated precisely where pressure equipment codes are silent and where these adjacent literatures are informative. Section 5.7 is devoted to the synthesis, and Section 2.4 states the limits of what may legitimately be inferred from it.

2.2 Inclusion and exclusion criteria

Included: work presenting a causal decomposition method applied to pressure-retaining equipment; work presenting a maintenance or inspection framework claiming causal grounding; work presenting an integration of the two; investigation reports where the causal chain is documented to a resolvable level of detail; and, within Stratum E, work whose method or finding transfers to the pressure boundary problem even where the studied asset differs.

Excluded: purely material-science studies of a single failure specimen with no framework contribution; RBI vendor literature without methodological disclosure; and predictive maintenance work in which the asset class has no meaningful pressure-boundary analogue, unless the method itself is transferable.

2.3 Analytical framework used for comparison

Methods are compared along six dimensions, which are used consistently through Sections 4 and 5:

- **Directionality:** deductive (effect to cause) versus inductive (cause to effect).
- **Resolution depth:** does the method terminate at component, at procedure, or at management system?
- **Quantifiability:** can the method produce a probability, and under what data assumptions?
- **Temporal treatment:** static, sequence-aware, or fully time-dependent.
- **Uncertainty handling:** point estimate, interval, fuzzy, or Bayesian.
- **Maintenance actionability:** does the output map onto an inspection interval, technique, or task?

2.4 Limitations of the evidence base

Three limitations should condition every conclusion below.

First, publication asymmetry. Successful integrations of causal analysis into maintenance planning are commercially valuable and are therefore under-published relative to their prevalence. Conversely, failure case studies are over-represented because failures are publicly investigated.

Second, data opacity. Basic event probabilities used in published pressure vessel fault trees are frequently drawn from generic databases (OREDA, CCPS, and similar) whose applicability to a specific service is asserted rather than demonstrated. Quantified results across studies are therefore not straightforwardly comparable. Third, retrospective bias. Cause trees built after a known failure tend to be pruned toward the branch that actually occurred. The completeness of the tree, which is the property on which quantification depends, is rarely tested. A fourth limitation applies specifically to Stratum E and should be read as a qualification on every claim that rests on it. Most of those 201 sources are conceptual frameworks and systematic reviews rather than instrumented field studies, and the great majority address construction, power, aviation, healthcare, renewable, financial, or enterprise information systems rather than pressure vessels directly. They are used here for structural insight, meaning what causes what and through which mechanism, and never as sources of numerical parameters for a pressure vessel calculation.

The corpus is deliberately tiered, and the tiering should be read as the primary caveat on this review rather than as a formality. Only two clusters bear on pressure-retaining or closely comparable equipment: the equipment integrity, non-destructive evaluation, and welding work of Atta and colleagues with Monye and colleagues, and the condition monitoring and maintenance strategy work of Sunday, Omoegun, Oyeleke, Yeboah, Adenuga and their co-authors, 12 sources in total. A further group is adjacent, meaning a different asset class exhibiting the same causal mechanism. The largest group is structural, contributing an organising principle. A final group is peripheral, contributing analogy only, and no claim in this review rests on a peripheral cluster alone.

Three consequences follow, and they are stated plainly because a corpus of this size invites a misreading. First, where a claim in Sections 3 to 7 rests solely on an adjacent or structural cluster, it is offered as a hypothesis for testing on pressure equipment rather than as an established finding. Second, breadth of citation is not evidence: a claim supported by forty structural sources is not thereby better supported than one resting on a single direct study of the asset class in question, and in a strict evidential ordering it is weaker. Third, the corpus is not a representative sample of any literature. It is a purposive selection, and the selection was made by the present authors against the argument being advanced, which is a bias no amount of breadth corrects. A reader who wants to test the argument should attack the 12 direct sources and the reasoning in Section 6, not the citation count.

3. Pressure Vessel Failure: Taxonomy of Top Events and Basic Events

Before reviewing tree methods, the event space they must span requires definition. A cause tree is only as good as the top event it names and the basic events it terminates in.

3.1 Defining the top event

Careless top-event definition is the most common defect in applied pressure vessel FTA. "Vessel failure" is not a usable top event: it conflates outcomes with different consequences, different causal paths, and different maintenance responses. Practical work distinguishes at least four:

Top event	Consequence class	Dominant causal signature
Catastrophic rupture	Blast, fragmentation, mass release	Critical flaw plus pressure demand; or gross overpressure
Through-wall leak (stable)	Localised release, fire potential	Progressive thinning, pitting, weld defect growth
Loss of function without loss of containment	Production loss	Internals failure, fouling, distortion
Loss of protective function	Latent, enabling	Relief device, instrumentation, trip system failure

The fourth is frequently omitted, which is an error of consequence. Loss of protective function is not itself a breakdown, but it converts otherwise survivable process excursions into breakdowns. Trees that omit it systematically underestimate risk.

A further consideration has entered this category in the last decade and is not yet reflected in most pressure equipment fault trees. Protective functions on modern vessels are implemented in instrumented systems that sit on networks, which makes their availability partly a cybersecurity question rather than purely a reliability one. The operational technology security literature is explicit that industrial control and supervisory systems in energy networks present attack surfaces distinct from enterprise information technology, and it has developed threat detection architectures, convergence security models, zero trust designs, vulnerability governance schemes, and risk quantification approaches specifically for that environment (Adebayo et al., 2022, 2023; Adegbite et al., 2020, 2022, 2023, 2024a, 2024b; Ahmed et al., 2021). For fault tree purposes the implication is narrow but real: the basic event "high-pressure trip fails on demand" has a contribution from deliberate compromise as well as from random failure, and the two have different distributions, different dependencies, and different mitigations. Common-cause treatment is particularly affected, since a shared control system can defeat nominally independent protective layers simultaneously in a way that random failure modelling will not predict.

The enterprise security literature contributes one further idea that transfers unusually cleanly. Breach and attack simulation, adversary simulation design, and continuous security control validation (Dosunmu & Ogundele, 2024b, 2024c, 2024d) rest on the premise that a control's effectiveness is unknown until it is exercised against a realistic challenge, and that periodic assertion of compliance is not a substitute for that exercise. This is conceptually identical to proof testing a relief device, and the transfer runs in the useful direction: the security field has developed continuous validation while pressure equipment practice still relies predominantly on periodic testing at code-mandated intervals. Related work on threat-informed defence engineering, control effectiveness measurement at scale, cyber risk quantification for investment prioritisation, and executive-level defence performance measurement (Dosunmu & Ogundele, 2021, 2022) addresses the same problem this review addresses for maintenance, namely how to direct finite protective effort by measured effectiveness rather than by convention. Incident response, forensics, and orchestration models (Dosunmu & Ogundele, 2024a) describe the mitigative half of the equivalent bow-tie. Governance-level treatments of frameworks, resilience, and identity-centric architecture (Jimoh & Ahmed, 2024; Jimoh et al., 2023a, 2023b; Ogbole et al., 2021; Okoruwa et al., 2020, 2024b) complete the picture, though they operate at a level of abstraction well above the vessel.

3.2 Damage mechanisms as basic-event generators

API RP 571 provides the canonical mechanism catalogue for refining service. For cause-tree construction, the useful organisation is by the driving variable, because the driving variable is what maintenance and operations can influence.

Thinning mechanisms. General and localised corrosion, erosion, erosion-corrosion, and flow-accelerated corrosion. These are characterised by a rate, which makes them the most tractable class: remaining life follows directly from measured thickness, retirement thickness, and rate. Most inspection interval logic in API 510 is built around this class, which is one reason the other classes are less well served. The applied integrity literature reinforces this asymmetry from the detection side. The critical review by Atta and colleagues (2020) of non-destructive-testing-based integrity management and corrosion risk assessment for refinery process equipment sets out how technique selection, coverage, and the corrosion risk picture jointly determine what a programme can actually see, which is the point at which a rate-based interval either works or silently fails. Mitigation at the mechanism level is a distinct lever from detection, and the systematic review by Atta, Asomani, and Adenuga (2018) of green corrosion inhibitors for mild steel protection in acidic and alkaline media illustrates the class of intervention that suppresses the rate itself rather than improving the measurement of it. In cause-tree terms these are different nodes: inhibition lowers the probability of the growth event, whereas improved inspection lowers the probability of the detection-failure event, and the two are not substitutes.

Cracking mechanisms. Stress corrosion cracking in its many environmental variants (chloride, caustic, amine, wet H₂S, polythionic acid), corrosion fatigue, mechanical fatigue, and creep cracking. These do not have a usable rate in the thinning sense. They exhibit initiation periods followed by rapid propagation, which makes interval-based inspection a poor fit and makes detection capability, rather than measurement accuracy, the governing inspection parameter. Cracking preferentially locates at welds, which makes weld-directed inspection method the operative variable. Work by Atta, Tofah, and Adenuga (2021) on advances in non-destructive testing methods for weld integrity evaluation in high-capacity power infrastructure addresses precisely this problem of resolving flaws at the joint rather than in the parent plate.

Fabrication-stage latent defects. A category that cause trees frequently omit entirely, on the assumption that construction quality is settled at handover. It is not. A weld defect accepted at fabrication is a basic event with a probability that persists for the life of the asset and interacts with every subsequent service mechanism. The review of welding inspection standards and quality assurance practices in large-scale power generation projects by Atta and colleagues (2022) is relevant here, because it locates the causal contribution in the inspection and acceptance regime applied during construction rather than in the welding process alone. For pressure vessels, this converts fabrication quality assurance from a procurement matter into an integrity-model parameter. The wider regulated-facility literature in the seed corpus reinforces the point from the project side, covering risk-managed construction strategies for highly regulated facility developments, regulatory-compliant design systems for controlled environments, lifecycle performance evaluation of purpose-built facilities, materials selection and durability strategies, and digital coordination methods for complex delivery (Aminu-Ibrahim & Ogbete, 2023; Aminu-Ibrahim et al., 2018, 2019, 2024; Ogbete et al., 2018, 2019, 2020, 2021, 2023). The transferable claim is that design and construction decisions have measurable in-service consequences that

persist for decades, and that lifecycle performance evaluation is the mechanism by which those consequences become visible. Machine development and performance evaluation practice (Bello et al., 2022a, 2022b, 2024) and degradation science in other material systems, including photovoltaic and thin-film architectures and alternative fuel effects (Atta et al., 2024; Bello et al., 2023), provide adjacent instances of the same design-to-degradation linkage.

Metallurgical and environmental degradation. Temper embrittlement, hydrogen embrittlement, high-temperature hydrogen attack, sigma phase and 885 °F embrittlement, spheroidisation, graphitisation. These change the material's tolerance of a flaw rather than creating a flaw. They are invisible to thickness monitoring, which is precisely why they have featured in several of the most severe recorded failures. The general principle is that environmental exposure can alter the degradation pathway rather than simply accelerating a single rate, which is what defeats a monitoring regime built around measuring one.

Mechanical and thermal loading. Overpressure, vacuum collapse, thermal shock, brittle fracture on low-temperature excursion, vibration-induced fatigue, and mechanical overload from settlement or external event. The distinction between mechanisms that create a flaw and mechanisms that reduce flaw tolerance matters greatly to tree structure. It is the archetypal AND gate in pressure vessel analysis: a crack that would have been survivable in tough material becomes critical in embrittled material. The 1984 amine absorber rupture at a Chicago-area refinery, investigated by what was then the National Bureau of Standards, is a documented instance. Investigators found a pre-existing crack that had propagated through the great majority of the wall thickness, combined with a substantial loss of fracture resistance attributable to hydrogen embrittlement. Neither factor alone would have produced the observed catastrophic rupture, in which the upper portion of the vessel was propelled roughly a kilometre from its foundation. The 2009 NDK Crystal vessel rupture at Belvidere, Illinois shows the same conjunctive signature. Analysis conducted in support of the Chemical Safety Board investigation identified stress corrosion cracking on and near the inner diameter together with a probable reduction in fracture toughness consistent with temper embrittlement, the combination allowing a flaw to reach critical size. Both cases are, structurally, the same fault tree: a growth mechanism AND a toughness-reduction mechanism AND a detection failure. That recurrence is a strong argument for treating cause trees as reusable templates rather than as one-off incident artefacts, a point developed in Section 6.

3.3 Human and organisational basic events

Empirical work on pressure equipment integrity consistently finds that the terminal causes of failure are more often organisational than metallurgical. A representative example is the risk assessment methodology of Golubović and colleagues, published in *Tehnički Vjesnik*, which separates the probability axis of the conventional risk matrix into two distinct contributions, one attributable to material defects and one attributable to human factors, with the material-defect probability estimated using a failure assessment diagram and the human-factor probability estimated from structured survey of the operators and managers responsible for the vessel. The separation is analytically useful because the two probability contributions respond to entirely different interventions: one to inspection and metallurgy, the other to training, staffing, and procedure.

The adjacent safety literature supplies more structure for the second of these than the pressure equipment codes do. The conceptual framework for human error causation in high-risk construction and industrial activities developed by Obriki and Arumosoye (2020) is directly usable for basic-event definition, because it treats error as an outcome of identifiable antecedent conditions rather than as an irreducible residual. That matters for tree construction: an antecedent condition can be a node, whereas an irreducible residual cannot. The companion framework by the same authors (2022) on the recurrence mechanisms of unsafe behaviours in high-hazard worksites addresses a further property that trees handle badly, namely that the same organisational basic event tends to re-occur after correction unless the mechanism sustaining it is interdicted. A corrective action that resets a condition without disturbing its recurrence mechanism produces a temporary, not a permanent, reduction in basic-event probability, and integrity models that assume otherwise will overstate the durability of their own risk reduction.

At the programme level, the organisational learning-based maturity model for continuous safety performance improvement of Arumosoye and Obriki (2021) provides a graded, rather than binary, representation of management system quality. This is a more discriminating instrument than the single plant-wide multiplier used in current risk-based inspection practice, a limitation discussed in Section 5.3. The critical review of occupational safety management systems specifically in oil and gas maintenance projects by Obogo, Arumosoye, and Obriki (2020) is the closest of the seed sources to the operating environment considered here, and the conceptual model for incident prevention in industrial maintenance engineering environments by Obogo, Obriki, and Arumosoye (2021) locates causation inside the maintenance activity itself rather than in the asset, which is where several documented pressure equipment events have in fact originated.

Organisational basic events that recur across the case literature include: inspection scope reduction under cost pressure; failure to reassess damage mechanisms after a feedstock or process change; loss of corrosion engineering expertise through turnover or outsourcing; deferral of recommendations generated by prior inspections; and inadequate management of change for what appear to be minor operating adjustments. The seed corpus assembled for this review contains a substantial body of work on precisely these antecedents, and it is worth setting out what that body covers, because the coverage indicates which organisational basic events are already characterised well enough to be modelled and which are not. Contractor and subcontractor performance, which governs who actually executes inspection and maintenance, is addressed through governance-oriented models of contractor safety performance in multi-contract industrial projects, subcontractor performance governance, and contractor compliance systems (Arumosoye & Obriki, 2020; Obogo et al., 2021c; Obriki & Arumosoye, 2024a). Leadership and culture, which govern whether recommendations are closed or deferred, are addressed through models of safety leadership influence in temporary project organisations, leadership-driven culture transformation, and leadership models for culture development in engineering projects (Arumosoye & Obriki, 2024; Obogo et al., 2019a, 2023). Workforce capability, which governs execution quality, is addressed through training models for operational risk reduction and behavioural programme reviews (Obriki et al., 2022a, 2023b), and complemented outside the safety domain by evidence on the effectiveness of awareness training on actual behaviour (Onche et al., 2024). Hazard recognition capability, which governs whether a developing condition is noticed at all, is addressed through proactive hazard recognition and near-miss reporting systems, hazard identification systems for large-scale operations, and reviews of hazard identification and risk control practice (Obogo et al., 2019c, 2021a). Assurance, which governs whether the programme is checked, is addressed through internal quality, health, safety, and environment audit systems for industrial

engineering operations (Obogo et al., 2020a). Institutionalisation, which governs whether improvements persist across projects and personnel changes, is addressed through models for embedding life-preserving practices across project-based organisations and for integrated safety management across multi-zone works (Obriki & Arumosoye, 2021). Specific high-energy activities that intersect with vessel maintenance, notably lifting and rigging during internals replacement or vessel relocation, are addressed through risk pathway models for lifting operations and crane installation (Arumosoye & Obriki, 2022; Obogo et al., 2020b). Leading indicators, which are the measurable precursors an integrity model would ideally consume, are addressed through work linking management walkthrough frequency and coverage to culture outcomes and linking leading safety signals to sustained performance (Obriki & Arumosoye, 2019).

The value of this coverage for cause-tree construction is that it converts a category previously treated as unquantifiable into a set of named, separately-addressed antecedents. The limitation, stated plainly, is that almost all of it is conceptual rather than measured, and none of it yields a probability that an integrity calculation could consume without further work. That conversion problem is identified as Gap 3 in Section 8. A related and under-used evidence source is the near-miss record. The systematic review of near-miss and hazard observation data utilisation in industrial safety management by Arumosoye and Obriki (2019) is relevant to the quantification problem raised immediately below, because near-miss and observation data are high-frequency signals bearing on low-frequency top events. Where the top event is too rare to estimate directly, the basic events beneath it frequently are not, and the near-miss record is where their frequencies can be observed. These are legitimate basic events. They are also the ones most often truncated out of published fault trees, on the grounds that they cannot be assigned a probability. That objection is weaker than it appears, and Section 4.5 addresses the fuzzy and Bayesian methods developed precisely to handle it.

4. Cause-Tree Methods: Formalism, Variants, and Comparative Assessment

4.1 Fault Tree Analysis

FTA originated at Bell Telephone Laboratories in 1961 in work on the Minuteman launch control system, and was subsequently developed by Boeing and codified for nuclear applications in the NUREG-0492 handbook and for aerospace in the corresponding NASA handbook. It is standardised internationally as IEC 61025. Construction. The analyst defines a top event with explicit boundary conditions (which system, which operating state, which time window), then repeatedly asks what immediate, necessary, and sufficient events produce the event above. Gates are principally OR (any input suffices) and AND (all inputs required), with extensions for voting, priority, and inhibit conditions. Development terminates at basic events, which are events for which either data exist or further decomposition is judged unproductive. Qualitative evaluation. Boolean reduction of the tree yields minimal cut sets, the smallest combinations of basic events whose joint occurrence produces the top event. Cut set order carries direct engineering meaning: a first-order cut set is a single point of failure, and its presence in a pressure vessel tree is normally a design or programme defect rather than an acceptable residual risk.

Quantitative evaluation. With basic event probabilities assigned, top-event probability follows by rare-event approximation, inclusion-exclusion, or binary decision diagram methods for larger trees; the standard derivations are set out by Rausand and Høyland. Importance measures then rank basic events by contribution. Fussell-Vesely importance gives the fraction of top-event probability attributable to cut sets containing a given event; Birnbaum importance gives the sensitivity of top-event probability to that event's probability; risk achievement and reduction worth bound the value

of degrading or perfecting an event. These measures are, for the purposes of this review, the single most important output of FTA, because they are the natural interface to maintenance resource allocation. Section 6 develops this argument quantitatively.

Assessment against the six dimensions. FTA is deductive; resolves to whatever depth the analyst chooses, including organisational depth; is quantifiable given data; is static in its classical form; handles uncertainty only through point estimates unless extended; and is highly actionable through importance measures. Its principal weaknesses are dependence on analyst completeness, the assumption of basic event independence, and the binary state assumption, all of which the extensions in Section 4.5 attack.

4.2 Event trees and bow-tie models

Where a fault tree reasons backward from a top event, an event tree reasons forward from an initiating event through the success and failure of successive barriers to a set of distinct outcomes. For pressure vessels, the initiating event is typically loss of containment and the barriers are isolation, detection, ignition prevention, and emergency response.

The **bow-tie** joins the two at the top event, giving threats and preventive barriers on the left and consequences and mitigative barriers on the right. Its adoption in process safety has been rapid, for reasons that are partly analytical and partly communicative. Analytically, it forces explicit identification of barriers and of the degradation factors that can defeat them, which maps cleanly onto maintenance tasks: every barrier in a bow-tie implies a critical task with an owner and a periodicity. Communicatively, it produces a single diagram legible to operators, engineers, and executives, which fault trees of realistic size are not. The right-hand side of the bow-tie is routinely modelled with less rigour than the left, which is a mistake given how strongly consequence depends on response capability. The conceptual model for emergency response readiness and capability in energy and process facilities developed by Arumosoye and Obriki (2023) is directly applicable to this half of the diagram, because it treats readiness as a set of assessable capability conditions rather than as the existence of a written plan. In event tree terms, those conditions are the branch probabilities. The bow-tie's weakness is resolution. The left-hand side is typically a flattened fault tree with the gate logic suppressed, which means conjunctive structure, the very thing that characterises pressure vessel failure, is often lost. Best practice treats the bow-tie as a communication and barrier-management layer over an underlying fault tree rather than as a replacement for it.

4.3 Simple causal decomposition: five whys, Ishikawa, causal factor charting

Three lower-formality methods are in widespread industrial use and deserve treatment because they are what most plants actually do.

Five whys iteratively ask why, terminating at a cause judged actionable. Its virtues are speed and accessibility. Its defect is severe for this asset class: it produces a single chain, not a tree, and therefore cannot represent conjunction. Applied to a vessel failure with a genuine AND structure, five whys will select one branch and declare it the root cause, producing a corrective action that would not have prevented the event.

Ishikawa (fishbone) diagrams, developed within the Japanese quality movement and popularised through Ishikawa's guides to quality control, organise candidate causes into categories,

conventionally machine, method, material, measurement, environment, and people. The method is a structured brainstorming aid and is genuinely useful for populating the basic event set of a subsequent fault tree. It is not itself a causal model: it asserts association, not logical necessity, and it cannot be quantified.

Causal factor charting builds a time-sequenced chart of events and conditions and is the backbone of several proprietary protocols including MORT-derived approaches, TapRooT, Apollo root cause analysis, and Kepner-Tregoe problem analysis. These add valuable discipline, especially in evidence handling and in pushing analysis past the first plausible stopping point into management system causes. Their limitation for pressure vessel work is that they are incident-driven by design. They produce excellent post-failure narratives and comparatively weak prospective models. The systematic review of incident investigation approaches and prevention-oriented learning in industrial operations by Obriki and Arumosoye (2024) is the most directly relevant seed source for this section, and its framing is important to the argument developed later in this paper. The distinction it draws is between investigation as a reporting activity and investigation as a learning activity, the latter being defined by whether findings alter subsequent practice. That is the same distinction, expressed in safety management terms, that Section 6 expresses in integrity management terms as the coupling problem. An investigation whose output terminates in a report and a corrective action register has produced causal knowledge without producing causal change. Aviation supplies the most developed comparison case for investigation practice, because its regulatory environment has required structured root-cause methodology for longer than the process industries have. The safety oversight literature reviewed here includes an explicit root-cause investigation framework tied to standardised corrective action for a recurring hazard, alongside adaptive safety management system implementation models (Adeyelu, 2019), predictive compliance monitoring built on complaint and report streams (Adeyelu, 2018), risk-tiered oversight schemes (Adeyelu, 2023), certification benchmarking (Adeyelu & Dagodzo, 2022), and maturity models for predicting audit outcomes (Adeyelu & Dagodzo, 2024b). Two features of that body of work transfer directly to pressure equipment. The first is the pairing of investigation with *standardised* corrective action, which addresses the generalisation failure described in Section 6.1: a corrective action defined once and applied across the fleet is the aviation solution to the problem that process plants solve asset by asset, if at all. The second is the treatment of oversight maturity as predictive of outcomes rather than merely descriptive of compliance.

A defensible reading of the evidence is that the low-formality methods are appropriate for high-frequency, low-consequence maintenance problems, and are structurally inadequate for pressure boundary failure. The mismatch is not one of effort but of representational capacity.

4.4 Systemic methods

Systems-theoretic accident modelling, developed principally by Leveson under the STAMP framework, rejects the chain-of-events premise underlying classical trees and treats accidents as failures of control in a hierarchical safety control structure. Related traditions include Rasmussen's work on migration toward accident boundaries under economic and workload pressure, and Reason's organisational accident model.

Kletz's case-based work on learning from accidents belongs alongside these, and makes a complementary point from the opposite direction: that organisations repeatedly re-experience accidents whose causes were documented after an earlier event, because the record of the earlier

event did not survive in a usable form. That observation is the historical antecedent of the coupling problem set out in Section 6.

For pressure vessels, systemic methods illuminate a specific and important failure pattern that trees handle poorly: slow, undramatic drift in which inspection scopes are progressively trimmed, deferrals become routine, and the integrity programme degrades without any discrete failure event to trigger analysis. No basic event occurs; the control structure simply relaxes. Trees have no natural representation for this. The practical recommendation emerging from the comparative literature is complementary use. Trees for the pressure boundary and its protective systems, where the physics is conjunctive and quantifiable; systemic models for the integrity management programme that maintains those trees.

4.5 Computational extensions

The most active recent research direction is the extension of classical trees to handle uncertainty, dependence, and time. Four strands are relevant.

Fuzzy fault tree analysis. Where basic event probabilities are unavailable, expert judgement is elicited as linguistic terms and represented as fuzzy numbers, propagated through gates by fuzzy arithmetic, and defuzzified to a top-event possibility. This is the standard response to the organisational-basic-event objection raised in Section 3.3, and it is now common in process and subsea applications, often paired with FMEA to generate the event set.

Fault tree to Bayesian network mapping. A fault tree maps onto a Bayesian network by direct correspondence: basic events become root nodes, gates become conditional probability tables, and the top event becomes a leaf. The mapping is information-preserving for classical trees and strictly more expressive beyond them. Three capabilities follow that FTA lacks. First, **dependence** between basic events can be represented explicitly rather than assumed away, which matters for common-cause failures such as a single corrosive upset affecting multiple vessels or a single inspection contractor affecting multiple detection events. Second, **multi-state** representation replaces the binary working/failed assumption, which is valuable for degradation that is intrinsically graded; recent work has developed multi-state fault tree and multi-state Bayesian network frameworks that fuse historical data with expert opinion to construct prior and conditional probabilities under data scarcity. Third, and most valuable operationally, **diagnostic inference** runs the model backward: given observed evidence, such as an inspection finding or an alarm, the posterior probabilities of candidate causes update. This converts a static risk model into a live diagnostic aid.

Dynamic fault trees and dynamic Bayesian networks. Dynamic gates (priority-AND, sequence enforcing, functional dependency, spare) capture order-dependent failure logic. Solved through Markov chains or, more tractably, by conversion to dynamic Bayesian networks extended over time slices, they represent time-dependent reliability without requiring enumeration of minimal cut sets. The approach has been applied to subsea blowout preventer stacks in the presence of common-cause failures, to floating offshore wind structures, to marine machinery, and to nuclear emergency diesel generators, and related work has used fault tree analysis to identify critical components of wind turbines as their contribution evolves over the operating life, which is the time-varying importance measure that Section 6.2 uses in its static form, and a 2024 study in *Quality and Reliability Engineering International* develops a variable-structure dynamic Bayesian

network built from a hierarchical reliability block diagram using the established correspondence between block diagrams, fault trees, and Bayesian networks.

Machine learning and digital twins. A large and rapidly growing literature applies supervised learning, deep learning, and digital twin architectures to predictive maintenance. A systematic review published in *PeerJ Computer Science* in 2024 surveys the intersection of predictive maintenance and digital twins and notes that industrial organisations continue to rely predominantly on reactive or preplanned maintenance, positioning digital twins as a route to accurate condition assessment when combined with machine learning trained on historical data. The caution required here is significant and is stated plainly: these methods are strong at **detection** and comparatively weak at **causal attribution**. A model that flags an anomaly with high accuracy has not thereby identified a mechanism, and a remaining-useful-life estimate contains no information about which barrier to reinforce. Correlational learners and causal models are complements, not substitutes. Two features of the applied seed literature sharpen this point. The first is interpretability. The work of Komi and Adamolekun (2021) on interpretable machine learning for early failure prediction in distributed renewable energy assets is directly on the seam this review is concerned with, because interpretability is what allows a learned prediction to be interrogated for the feature attribution that a causal model can then consume. An uninterpretable prediction can trigger an inspection; only an interpretable one can revise a tree. The second is sensing granularity. The sensor-based fault detection work of Sunday and Omoegun (2022) in HVAC systems and the vibration-based condition monitoring implementation of Omoegun and colleagues (2023) for rotating machinery illustrate what Layer 1 of the architecture proposed in Section 6.3 actually consists of, and both make clear that the informativeness of the detection layer is set by instrument placement and signal selection, which are themselves decisions that should be driven by the causal model rather than by convenience. The wider applied analytics literature reviewed here reinforces both the promise and the limitation. Predictive models are now routinely deployed for demand forecasting, real-time risk dashboards, infrastructure risk monitoring, lifecycle performance management, and financial risk detection (Adelanwa et al., 2023a, 2023b, 2024; Anene & Clement, 2022; Aifuwa et al., 2020; Filani et al., 2022; Okojie et al., 2023a), and in the energy domain specifically for wind power forecasting, distributed energy control architecture, tiered digital twins for resource-constrained sites, battery degradation, and edge-based resilient control (Komi & Adamolekun, 2021, 2022; Komi & Adeniji, 2023, 2024b; Komi, 2021; Adenuga, 2022; Komi & Ganiu, 2022, 2023). What is striking across that corpus is how much of it forecasts a *state* and how little of it attributes a *cause*. The tiered digital twin work (Komi & Adeniji, 2023) and the interpretable failure prediction work (Komi & Adamolekun, 2021) are the exceptions that prove the point, since both treat explanation as a design requirement rather than as a byproduct. Physical modelling of machines and power apparatus, including loss and weight objective function formulations for induction machines and voltage control under distributed generation (Adenuga, 2023; Amayo, 2017; Oshevire et al., 2017), sits at the opposite end of the same spectrum: fully causal, fully explanatory, and not adaptive to observed condition. The engineering problem this review identifies is the absence of a routine method for joining the two ends. A specific and underappreciated difficulty sits at that junction, and it has been studied more carefully outside engineering than within it. Fuzzy fault tree analysis and Bayesian prior construction both depend on expert elicitation, and both ordinarily assume that expert disagreement is noise to be averaged away. The human-in-the-loop machine learning literature treats disagreement as a first-class problem instead, including explicit work on the disagreement

problem in human-in-the-loop federated learning and on human-centred annotation with generative assistance (Ladapo et al., 2022b, 2024b). Applied to integrity modelling, the implication is that systematic disagreement between a corrosion engineer and an operations supervisor about the probability of a procedural basic event is information about the state of the organisation, not measurement error, and averaging it destroys the signal that Section 3.3 identifies as most needed. The most promising architectures in the recent literature are hybrid: learned models perform detection and anomaly localisation, and a causal layer, typically a Bayesian network derived from a fault tree, performs attribution and drives the maintenance decision. This hybrid structure is the core of the framework proposed in Section 6.

4.6 Comparative assessment

Method	Direction	Depth	Quantifiable	Time	Uncertainty	Maintenance actionability
Five whys	Deductive, single chain	Shallow to medium	No	Static	None	Low; single corrective action
Ishikawa	Associative	Medium	No	Static	None	Low; generates candidates
FMEA / FMECA	Inductive	Component	Semi (RPN)	Static	Ordinal only	Medium; task per failure mode
Fault tree (classical)	Deductive	Analyst-set, to organisational	Yes	Static	Point estimate	High; importance measures
Event tree	Inductive	Barrier	Yes	Sequential	Point estimate	Medium; mitigation barriers
Bow-tie	Bidirectional	Barrier	Partial	Static	Point estimate	High; barrier task ownership
Causal factor charting	Deductive	Deep, to management system	No	Sequential	None	Medium; corrective actions
Fuzzy FTA	Deductive	As FTA	Yes, possibilistic	Static	Fuzzy	High
FTA to Bayesian network	Bidirectional	As FTA	Yes	Static or dynamic	Full probabilistic	Very high; supports diagnosis

Method	Direction	Depth	Quantifiable	Time	Uncertainty	Maintenance actionability
Dynamic FTA / DBN	Deductive	As FTA	Yes	Time-dependent	Full probabilistic	Very high
STAMP / systemic	Control-theoretic	Whole sociotechnical system	No	Continuous	None	Medium; programme-level
ML / digital twin	Correlational	Signal	Yes, predictive	Continuous	Model-dependent	High for timing, low for cause

5. Root-Cause-Driven Maintenance Frameworks

5.1 The maintenance strategy spectrum

Maintenance strategies form a spectrum by the trigger for intervention: corrective (failure), time-based preventive (elapsed interval), condition-based (measured indicator), predictive (forecast indicator), and prescriptive (optimised recommended action). Movement rightward increases information requirements and, when the information is good, decreases total cost. The empirical basis for that last claim is more conditional than commonly asserted; work published in *Reliability Engineering and System Safety* has examined the practical factors that determine whether condition-based maintenance actually outperforms time-based maintenance over an asset's life, and finds that the advantage depends materially on those factors rather than following automatically from the strategy choice. This is an important corrective to enthusiasm.

The transition itself has an implementation literature that the pressure equipment field tends to skip. The study by Sunday and colleagues (2020) on transitioning from reactive to predictive maintenance in mechanical systems treats the migration as an organisational and instrumentation programme with sequenced prerequisites, rather than as a technology purchase. That framing is important for pressure vessels, where the prerequisite most often missing is not sensing capability but a defensible causal model specifying what the sensing is supposed to resolve. Preventive programme design remains relevant at the other end of the spectrum, and the work of Yeboah and colleagues (2024) on advanced preventive maintenance programme design in renewable energy systems is a useful reminder that interval-based tasks do not disappear when predictive capability arrives; they are re-scoped to the failure modes for which prediction is not feasible.

The condition monitoring and maintenance strategy cluster assembled for this review (Sunday et al., 2019, 2020; Sunday & Omoegun, 2018, 2019, 2022; Omoegun et al., 2023; Yeboah et al., 2024; Yeboah & Ike, 2020) is worth characterising as a whole, because its internal spread illustrates a point about what a maintenance strategy actually consists of. It contains instrumentation work, in the form of sensor-based fault detection and vibration monitoring (Sunday & Omoegun, 2022; Omoegun et al., 2023); strategy work, in the form of the reactive-to-predictive migration and reliability-centered maintenance applied to a dense computing estate (Sunday et al., 2020); thermal and control engineering, in the form of efficiency and control strategy analysis for conditioned systems (Sunday et al., 2019); systems integration and load management for hybrid installations (Sunday & Omoegun, 2018, 2019); and programme-level

work covering preventive programme design, safety and environmental compliance programmes, and programmatic strategy for large deployments (Yeboah et al., 2024; Yeboah & Ike, 2020). A functioning maintenance strategy requires all five layers, and the common failure in pressure equipment programmes is to procure the first, declare the second, and neglect the remaining three. The compliance programme work in particular addresses the mechanism by which a technical standard becomes an enforced practice, which Section 6.4 identifies as the binding constraint on the architecture proposed here. The intermediate position between condition-based and risk-based practice has its own literature under the label risk-based maintenance, in which inspection and maintenance scheduling is derived from a quantitative risk assessment rather than from condition alone. The formulation of Khan and Haddara and the subsequent review of risk-based maintenance techniques and applications by Arunraj and Maiti are the standard references, and they matter for the present argument because they made the same move for maintenance scheduling that RBI made for inspection planning, namely substituting computed risk for elapsed time. Neither, however, opens the causal model to editing by the analyst, which is the limitation identified for RBI in Section 5.3 and the reason this review treats the fault tree rather than the risk score as the primary artefact. What distinguishes a **root-cause-driven** framework from any of these is not the trigger but the justification: the intervention exists because a specific causal pathway has been identified and the intervention interdicts it. By that criterion, several widely deployed frameworks qualify only partially.

5.2 Reliability-Centered Maintenance

RCM originated in commercial aviation, formalised in the 1978 report by Nowlan and Heap prepared for the United States Department of Defense, and is now standardised through SAE JA1011 (evaluation criteria) and JA1012 (guide). Its logic proceeds through seven questions: system functions, functional failures, failure modes, failure effects, failure consequences, proactive task selection, and default actions where no proactive task is effective.

Two contributions of RCM are foundational and are frequently misattributed elsewhere. The first is the **consequence-based task selection principle**: the decision to perform a task depends on the consequence of the failure, not merely its probability. The second is the empirical finding, from the aviation reliability data underlying the original report, that most failure modes do not exhibit wear-out behaviour, which invalidates fixed-interval overhaul as a general strategy. That finding was radical in 1978 and is still imperfectly absorbed in process industry practice.

RCM's applicability to pressure vessels is real but partial. RCM analyses functions and functional failures, which suits rotating and instrumented equipment well. A pressure vessel has essentially one function, containment, and one functional failure, loss of containment. The interesting variation lies not in the function tree but in the degradation mechanisms, which is exactly the domain RBI addresses. RCM applied naively to a vessel produces a thin analysis. RCM applied to the vessel's *protective systems*, meaning relief devices, trips, and instrumentation, produces a rich one, and this is where its value in pressure equipment programmes principally lies.

The framework continues to be extended to asset classes far from its aviation origin, and those extensions are informative about its portability. Recent RCM methodology work in the marine domain, including an approach for assessing reliability challenges and maintenance needs of unmanned cargo ships published in *Reliability Engineering and System Safety*, illustrates the framework's adaptability where function structures are complex. What transfers in such extensions is the function-and-consequence logic and the discipline of rejecting tasks that do not address an identified failure mode, not any specific task set. It is worth recalling that RCM's regulatory home

remains aviation, and that the aviation safety management and oversight literature reviewed here continues to develop the surrounding assurance apparatus through adaptive safety management system implementation models, certification benchmarking, and maturity models for audit outcome prediction (Adeyelu, 2019; Adeyelu & Dagodzo, 2022, 2024b). RCM in process industry practice has largely been imported without that apparatus, which may explain why its adoption is frequently reported as an analysis exercise that decays rather than as a sustained programme.

5.3 Risk-Based Inspection

RBI is the framework with the strongest claim to being genuinely root-cause-driven for pressure equipment, and it is treated at length here.

API RP 580 establishes principles and minimum general guidelines for risk-based inspection programmes on fixed equipment in refining, petrochemical, chemical process, and oil and gas production facilities, while API RP 581 supplies quantitative calculation procedures for developing inspection plans covering pressure vessels, piping, tankage, pressure relief devices, and heat exchanger tube bundles. Risk is computed as the product of probability of failure and consequence of failure, and inspection is allocated in proportion to computed risk. API RP 581 states four goals for an RBI programme: to identify and measure risk across covered equipment, to convey an accurate understanding of the risks and their drivers, to enable effective risk management, and to reduce the risks of operating the facility.

The causal content of RBI resides in the probability of failure calculation. Probability is built from a generic failure frequency modified by a damage factor, a management systems factor, and equipment-specific adjustments. The **damage factor** is where causation enters: it is computed per damage mechanism, from susceptibility, from measured or estimated damage rate, and critically from **inspection effectiveness**, which encodes how likely the applied inspection technique is to have detected the damage actually present. The **management systems factor** applies a plant-wide multiplier derived from audit of the process safety management system.

Three observations follow. First, RBI's damage factor structure is, formally, a fault tree branch. Susceptibility AND rate AND detection failure is precisely the conjunctive structure identified in Section 3.2 as characteristic of vessel failure. RBI has therefore internalised cause-tree logic, but has done so in a closed parametric form rather than an open, editable model. The analyst selects mechanisms from a catalogue and the calculation proceeds; the analyst does not build the tree.

Second, the treatment of **inspection effectiveness** is RBI's most valuable and most underexploited feature. It makes explicit what conventional interval-based inspection leaves implicit: that the value of an inspection lies in its probability of detection for the specific mechanism present, not in its occurrence. A visual external inspection has near-zero effectiveness against high-temperature hydrogen attack regardless of frequency. This principle, once stated, has consequences that many programmes have not followed through, and the non-destructive evaluation literature reviewed by Atta and colleagues (2020, 2021) is where the technique-specific evidence for following it through actually resides. Third, the **management systems factor** is a blunt instrument. It applies a single plant-wide multiplier to every vessel, which means the organisational causes that Section 3.3 identified as dominant are represented by one number applied uniformly. Two responses to this limitation are available in the literature reviewed here. The methodology of Golubović and colleagues separates human-factor probability from material-defect probability at the level of the individual vessel and its actual operating crew. The graded organisational maturity model of Arumosoye and Obriki (2021) offers a complementary route, replacing a binary or lightly-scored audit outcome with a maturity position that can be differentiated by unit, by contractor, and by

activity type. Either is more discriminating than a single facility-level multiplier. The audit and governance cluster in the seed corpus indicates what the supporting machinery would look like, covering technology-enabled internal audit quality models, risk-based internal control frameworks, data-driven compliance analytics, and quantitative compliance risk assessment (Agu et al., 2023a; Akomolafe & Agu, 2018, 2019a, 2019c; Akomolafe et al., 2023a, 2023b). The relevant transfer is not the financial subject matter but the design principle: these approaches score control effectiveness continuously and at the level of the individual control, rather than periodically and at the level of the enterprise. Applied to the management systems factor, that principle would yield a multiplier that differs between two vessels in the same plant maintained by different contractors under different procedures, which is what the causal evidence in Section 3.3 suggests it should do. Regulatory readiness maturity modelling in the pharmaceutical domain (Eze et al., 2022b) is a further instance of the same design, expressing compliance capability as a graded position rather than a binary state, and audit intelligence work on cognitive bias in decision-making and on auditing algorithmically-driven systems anticipates two failure modes that a differentiated management systems factor would need to guard against, namely assessor bias and unauditable model-derived scores.

Applied RBI studies published in 2024 illustrate both the maturity and the constraints of the method. A study in *AIP Conference Proceedings* applied API 581 methodology to a condensate drum in a petrochemical plant, producing a risk ranking and a corresponding inspection plan for that specific vessel, and a study in *Scientific Contributions Oil and Gas* applied API 581 to pressure safety valves and a stripper in an acid gas removal unit, computing probability of failure from demand rate and relief device parameters. These are careful and useful analyses. They are also, characteristically, single-asset applications that produce an inspection plan and stop. The causal insight generated does not visibly propagate to sister vessels in comparable service, which is a recurring theme of Section 7.

5.4 Fitness-for-service and the damage-tolerance layer

API 579-1/ASME FFS-1 provides quantitative assessment procedures for equipment containing known damage: general and local metal loss, pitting, blisters and laminations, weld misalignment and shell distortion, crack-like flaws, creep damage, fire damage, dents and gouges. Assessments are structured in three levels of increasing conservatism-reduction and analytical demand.

Fitness-for-service is not itself a maintenance framework, but it occupies a critical position in the causal chain, because it determines the **consequence of a detected condition**. Without it, detection of a flaw forces a binary choice between immediate repair and unquantified acceptance. With it, the finding enters a defensible run-repair-replace decision with a computed remaining life. In cause-tree terms, fitness-for-service assessment is what converts the discovery of a basic event into an updated top-event probability, and it is therefore the natural quantitative bridge between inspection findings and interval revision. The failure assessment diagram, used within fitness-for-service practice to evaluate the interaction of fracture and plastic collapse, has also been adopted directly as a probability-estimation tool in risk assessment work on pressure vessels.

A parallel concept appears in the energy environmental engineering literature, where lifecycle risk assessment frameworks are applied to produced water management and treatment infrastructure, including decentralised systems serving remote assets and data-driven performance optimisation of treatment plant (Falegan & Aniebonam, 2022, 2023, 2024). The structural similarity is that both convert a detected condition into a lifecycle decision under uncertainty rather than into a pass or fail verdict. The difference is that fitness-for-service rests on fracture mechanics with quantified

conservatism, while the lifecycle risk frameworks rest on qualitative or semi-quantitative scoring. For emerging pressure equipment services where the damage mechanisms are not yet characterised well enough to support a Level 2 or Level 3 fitness-for-service assessment, notably hydrogen and carbon capture duty, the semi-quantitative approach may be the only available route in the interim.

5.5 Mechanical integrity and asset integrity management

The OSHA Process Safety Management standard requires covered facilities to establish written procedures, train maintenance personnel, perform inspections and tests following recognised and generally accepted good engineering practice, correct deficiencies before further use, and apply quality assurance to new and replacement equipment. ISO 55000 supplies a broader asset management system framework, and API 510 supplies the pressure-vessel-specific inspection code including interval rules tied to remaining life.

The interval rule in API 510 is instructive as a case study in the limits of code-based causal reasoning. Internal or on-stream inspection is generally required at the lesser of one half the remaining life or ten years, with provision for extension under specified conditions. This rule is genuinely causal in one respect: it ties the interval to remaining life, which is a function of measured corrosion rate. It is non-causal in another: the halving factor is a uniform safety margin, not a quantity derived from the uncertainty in the rate estimate or the detection capability of the technique applied. Two vessels with identical remaining life but different mechanism types, different inspection coverage, and different consequence exposure receive the same interval. RBI exists precisely to differentiate these cases, and its adoption is best understood as the substitution of a computed, mechanism-specific interval for a uniform code default.

One class of causes sits outside the integrity function altogether and is consistently under-represented in cause trees, namely the logistics of executing the plan. A recommendation cannot be closed if the material is not available, and deferral driven by parts and materials availability is a common and traceable contributor to extended exposure. The conceptual model for asset lifecycle management and inventory visibility of Okonkwo, Mayo, and Okeke (2023) and the related model for materials readiness and maintenance-driven supply chain performance of Okonkwo and colleagues (2021) address this pathway directly. For cause-tree purposes the implication is specific: spares and materials readiness belongs in the tree as an antecedent of deferral, and deferral belongs in the tree as an antecedent of extended exposure to an active mechanism. A second pathway runs through supplier qualification rather than availability. Replacement components, weld consumables, and repair services enter the pressure boundary through a procurement process, and a qualification failure in that process is a latent defect introduced by the maintenance activity itself. The strategic procurement cluster in the seed corpus covers supplier risk assessment frameworks, cross-border supplier relationship management, sustainability and performance metrics, negotiation and cost optimisation, process automation and transparency, and resilience indexing (Akin-Oluyomi et al., 2020, 2023a, 2023d, 2024; Akinleye & Adeyoyin, 2021, 2022a, 2022b; Akinleye et al., 2023; Babatope et al., 2023; Efobi et al., 2022a, 2022b; Okojie & Abioye, 2020). Two of its findings bear directly on integrity: that cost-driven supplier selection and technical qualification are frequently governed by different functions with different incentives, and that supply chain resilience is an assessable property rather than an assumption. The regulatory science cluster (Eze et al., 2022a, 2022b, 2023, 2024a, 2024b) supplies a parallel from pharmaceutical practice, where quality assurance is treated explicitly as a determinant of supply reliability, shortage early-warning models are built, and regulatory readiness is expressed as a maturity position. The structural analogy to pressure equipment is close: in both

cases a technically compliant artefact must be produced by a qualified supplier under an auditable regime, and in both cases failure of the regime is invisible until the artefact is in service.

5.6 Comparative assessment of maintenance frameworks

Framework	Primary trigger	Causal content	Handles conjunction	Organisational causes	Coupling to cause trees
Corrective	Failure	None	No	None	None
Time-based preventive	Elapsed time	Weak, assumes wear-out	No	None	None
API 510 interval rules	Remaining life	Partial, rate-based	No	None	Weak
RCM	Consequence and failure mode	Strong for function, weak for mechanism	Partially	Limited	Moderate
RBI (API 580/581)	Computed risk	Strong, mechanism-specific	Yes, within damage factor	Single plant-wide factor	Strong but implicit
Condition-based	Measured indicator	Depends on indicator selection	No	None	Weak
Predictive / digital twin	Forecast indicator	Correlational, not causal	No	None	Weak
Fitness-for-service	Detected flaw	Strong, physics-based	Yes	None	Strong, at consequence node

The pattern is clear. Causal strength concentrates in RBI and fitness-for-service, both of which are technically deep and organisationally shallow. Organisational causation, which the case literature identifies as dominant, is addressed by none of them in a discriminating way.

5.7 What the adjacent literature contributes, and what it does not

Because this review draws on a large seed corpus of adjacent work, it is worth stating compactly what that corpus adds to a pressure vessel argument and where it stops being informative.

It supplies antecedent structure for organisational basic events. The safety causation cluster (Arumosoye & Obriki, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Obogo et al., 2019a, 2019b, 2019c, 2020a, 2020b, 2020c, 2021a, 2021b, 2021c, 2022, 2023, 2024a, 2024b; Obriki & Arumosoye, 2018, 2019, 2020, 2021, 2022, 2023, 2024a, 2024b; Obriki et al., 2022a, 2022b, 2023a, 2023b) is the largest in the corpus and the most useful, for the reason given in Section 3.3: it decomposes categories that pressure equipment practice treats as single audit scores into separately-addressed antecedents with identified mechanisms.

It supplies precedent for standardised, fleet-wide corrective action. The aviation oversight cluster (Adeyelu, 2018, 2019, 2020, 2021, 2022, 2023; Adeyelu & Dagodzo, 2022, 2024a, 2024b) demonstrates a regulatory model in which investigation findings are converted into standardised corrective actions and audit maturity is treated as predictive. This is the closest available analogue to the population-level propagation that Section 6.3 proposes as Layer 5.

It supplies the detection-side evidence base. The integrity and NDE cluster (Atta et al., 2018, 2020, 2021, 2022) and the remote inspection cluster (Dagodzo, 2018a, 2018b; Dagodzo & Ahiaekwe Patrick, 2020, 2021a, 2021b, 2022, 2023a, 2023b; Dagodzo et al., 2022) together describe what can be resolved, at what cost, over what coverage. The second of these matters more than its adjacency suggests, because coverage extension by standoff methods changes the same parameter that technique improvement changes, namely the probability that a developing condition is observed at all.

It supplies execution constraints. The supply chain and materials readiness cluster (Okonkwo et al., 2021, 2023, 2024b; Ike et al., 2021; Nnabueze et al., 2021; Akin-Oluyomi et al., 2023b, 2023c; Efobi et al., 2023; Okoruwa et al., 2024a), the process discipline cluster (Ambali et al., 2021; Eyetsemitan et al., 2022, 2023a, 2023b), and the project governance cluster (Amayo et al., 2023a, 2023b, 2024a, 2024b) jointly describe why a technically correct plan is not executed: materials unavailable, procedure absent or unfollowed, governance diffuse across contracting parties. Standard operating procedure design as a strategic asset (Eyetsemitan et al., 2022), structured validation of deployed changes (Eyetsemitan et al., 2023b), and change management in operational transitions (Eyetsemitan et al., 2023a) are the mechanisms by which a revised inspection plan becomes actual practice rather than an updated document.

It supplies assurance and governance analogues. The audit and risk governance cluster (Agu et al., 2023a; Akomolafe & Agu, 2018, 2019a, 2019c; Akomolafe et al., 2023a, 2023b) describes technology-enabled internal audit quality, risk-based internal control models, and compliance analytics. These are the closest available models for what a differentiated replacement for the RBI management systems factor would look like in operation, a point developed in Section 5.3.

It supplies a continuous-validation model for protective functions. The enterprise security clusters (Dosunmu & Ogundele, 2019, 2020, 2021, 2022, 2024a, 2024b, 2024c, 2024d; Jimoh & Ahmed, 2024; Jimoh et al., 2023a, 2023b; Ogbole et al., 2021; Okoruwa et al., 2020, 2024b) treat control effectiveness as something to be exercised continuously rather than asserted periodically, an idea developed further in Section 3.1 and directly applicable to relief and trip systems.

It supplies operational discipline for running the integrity function itself. The service reliability and operations cluster (Ladapo et al., 2022a, 2023a, 2023b, 2024a; Edivri & Oteri, 2022, 2024; Oteri & Edivri, 2024) covers service assurance frameworks for systems supporting large user populations, predictive capacity planning across multi-stakeholder programmes, performance optimisation for high-demand programmes, and key-performance-indicator-driven decision frameworks. An integrity programme is an operations function with a backlog, a capacity constraint, and a service level, and it is rarely managed as one.

It supplies decision-gate and maturity structures for non-traditional risk. The ESG and carbon governance cluster (Abioye et al., 2023; Ike et al., 2022, 2024a, 2024b; Okojie et al., 2023b) contains a structure worth borrowing regardless of one's view of its subject matter: carbon-driven decision gates embedded in project lifecycle governance, and a maturity model for organisational carbon management capability. A decision gate is a point at which a project cannot proceed without a specific assessment being complete, which is precisely the mechanism absent from most integrity workflows, where a deferred recommendation simply persists. The cluster also covers automated compliance reporting for energy projects, quantitative risk architecture for public-private partnerships, digital twin-driven environmental compliance in oil and gas procurement, lean practice in supply operations, and integration of assessment metrics into infrastructure auditing (Abioye et al., 2023; Ike et al., 2022, 2024a, 2024b; Okojie et al., 2023b). The transferable content is the gating and maturity machinery, not the environmental subject matter.

It supplies accountability structure for model-driven decisions. The technology law cluster (Annan, 2022, 2023, 2024) addresses algorithmic accountability, automated decision-making compliance, and the tension between explainability and proprietary protection. When a Bayesian network sets an inspection interval, the question of who is accountable for that interval, and what record must exist to defend it, becomes a live regulatory question rather than an abstract one. Section 6.4 treats this as an implementation requirement.

It does not supply damage mechanism data, detection probabilities, or failure frequencies for pressure vessels. No part of the corpus can be used to populate a fault tree with numbers. This is not a defect of the sources; it is a consequence of their being about different assets or about frameworks rather than measurements.

It does not establish that the mechanisms transfer. That an antecedent structure holds for construction safety or aviation oversight is a reason to hypothesise that it holds for pressure equipment integrity, not a demonstration. The empirical work to test the transfer has not been done, and Gap 6 in Section 8 is framed accordingly.

It thins markedly toward the periphery. The clusters designated peripheral in Section 2.1, covering socio-technical durability in energy transition (Komi, 2023, 2024; Komi & Adamolekun, 2024; Komi & Adeniji, 2020, 2024a), renewable fuels and photovoltaic degradation (Atta et al., 2024; Bello et al., 2023), machine development practice (Bello et al., 2022a, 2022b, 2024), electrical machine optimisation (Amayo & Popoola, 2017a, 2017b; Amayo et al., 2015), and robotics (Akanbi & Sunday, 2024), contribute analogy and little else. They are retained because the analogies are real. The most useful is the multi-objective optimisation formulation in the electrical machine work (Amayo & Popoola, 2017a, 2017b; Amayo et al., 2015), which is structurally the same problem as allocating a fixed maintenance budget across competing basic events. A second, less obvious, comes from the energy transition cluster, which models infrastructure durability as a function of stakeholder trust and models the consequences of forecasts that are accurate but inequitably distributed (Komi, 2023, 2024). The pressure equipment analogue is that an integrity programme surviving a budget cycle depends on whether the operating organisation believes its outputs, and that a technically correct risk ranking which concentrates all inspection on one unit will be resisted by that unit whatever its statistical merit. Workforce transition and capability displacement modelling in the same cluster (Komi & Adamolekun, 2024;

Komi & Adeniji, 2020, 2024a) bears on the loss-of-expertise basic event identified in Section 3.3, which is among the more consequential and least modelled organisational contributors. But an argument that needed them would be an argument in trouble, and none of the conclusions in Section 9 depends on them.

6. Coupling Cause Trees to Maintenance Decisions

6.1 The coupling problem stated

The frameworks reviewed in Section 5 set intervals. The methods reviewed in Section 4 explain failures. In most operating organisations these are separate activities, conducted by separate functions, on separate timescales, with separate documentation. Root cause analysis is triggered by an incident and produces a corrective action register. Inspection planning is triggered by a calendar and produces a work schedule. The corrective action register and the inspection plan are, in the common case, not the same document and do not update each other.

The consequence is a specific and diagnosable pathology: causal knowledge does not generalise across the asset population. A cause tree built for the failure of vessel V-201 identifies a mechanism, a detection gap, and a procedural contributor. Vessels V-202 through V-240, in comparable service with comparable detection gaps, receive no revision, because nothing in the workflow connects the finding to their inspection plans. This is the integrity-management form of the distinction drawn by Obriki and Arumosoye (2024) between investigation as reporting and investigation as prevention-oriented learning, and the failure mode is the same in both framings: knowledge is produced, recorded, and not applied.

6.2 A worked quantification of why the coupling matters

The following example is constructed to be representative rather than to describe a specific asset. It demonstrates that the direction of maintenance investment, when set by causal structure rather than convention, dominates the magnitude of that investment.

Top event T: Catastrophic loss of containment of vessel V-201 within one operating year.

Tree structure:

$T = G1 \text{ OR } G2$

$G1$ (degradation-driven rupture) = $B1 \text{ AND } B2$

$B1$ Wall damage progresses beyond critical dimension in the interval

$B2$ Applied inspection fails to detect the damage present

$G2$ (overpressure-driven rupture) = $G3 \text{ AND } G4$

$G3$ (pressure excursion initiator) = $B3 \text{ OR } B4 \text{ OR } B5 \text{ OR } B6$

$B3$ Control valve fails open on inlet

$B4$ Outlet inadvertently blocked

$B5$ External fire exposure

$B6$ Runaway exothermic reaction

$G4$ (protective system failure) = $B7 \text{ AND } B8$

$B7$ Pressure relief device fails on demand

$B8$ High-pressure trip fails on demand

Basic event probabilities (per year, or probability of failure on demand where applicable):

Event	Description	Probability
B1	Damage progresses beyond critical	5.0×10^{-2}
B2	Inspection non-detection	1.0×10^{-1}
B3	Control valve fails open	1.0×10^{-1}
B4	Blocked outlet	5.0×10^{-2}
B5	External fire	1.0×10^{-2}
B6	Runaway reaction	5.0×10^{-3}
B7	Relief device PFD	2.0×10^{-2}
B8	High-pressure trip PFD	3.0×10^{-2}

Minimal cut sets and contributions:

Cut set	Order	Probability	Share of total
{B1, B2}	2	5.00×10^{-3}	98.06 %
{B3, B7, B8}	3	6.00×10^{-5}	1.18 %
{B4, B7, B8}	3	3.00×10^{-5}	0.59 %
{B5, B7, B8}	3	6.00×10^{-6}	0.12 %
{B6, B7, B8}	3	3.00×10^{-6}	0.06 %

Top event probability: $P(T) \approx 5.099 \times 10^{-3}$ per year.

Fussell-Vesely importance:

Event	FV importance
B1	0.981
B2	0.981
B7	0.019
B8	0.019
B3	0.012
B4	0.006
B5	0.001
B6	0.0006

Two competing maintenance investments.

Investment A, causally directed. Improve inspection effectiveness against the governing mechanism, reducing B2 from 1.0×10^{-1} to 2.0×10^{-2} . In practice this means replacing spot ultrasonic thickness readings with automated corrosion mapping and adding phased array coverage at the weld seams where the mechanism actually operates. Revised $P(T) \approx 1.099 \times 10^{-3}$ per year, a **78.4 percent reduction**.

Investment B, conventionally directed. Increase relief device testing frequency, reducing B7 from 2.0×10^{-2} to 5.0×10^{-3} . Revised $P(T) \approx 5.025 \times 10^{-3}$ per year, a **1.5 percent reduction**.

Both are defensible-sounding maintenance improvements. Both consume comparable resources. One is fifty times more effective than the other, and nothing but the cause tree distinguishes them. Investment B is not wasteful in isolation, and relief device integrity remains a legitimate obligation, but as a *risk reduction measure for this vessel* it is close to inert, because the protective system sits behind an AND gate whose companion events are already unlikely, while the detection barrier sits in a two-element cut set that carries almost all the probability mass.

This is the argument of the paper in one calculation. Maintenance effort applied without reference to causal structure is not merely suboptimal; its effectiveness is essentially arbitrary.

6.3 A proposed five-layer Root-Cause-Driven Maintenance architecture

The following architecture is synthesised from the reviewed literature. It is proposed as an organising structure rather than presented as a validated method.

Layer 1, Detection. Continuous and periodic data acquisition: online corrosion and erosion probes, wall thickness monitoring sensors, acoustic emission, process historian data on pressure, temperature, and composition excursions, and scheduled inspection findings. Machine learning anomaly detection operates here, and here alone, because this is where correlational methods are strong. The design questions at this layer are placement and signal selection rather than algorithm choice, as the sensor-based fault detection and vibration monitoring work discussed in Section 4.5 makes clear. Two further inputs belong here and are usually treated as belonging to a different department. The first is the safety observation and near-miss stream, which the framework of Obriki and Arumosoye (2023) for proactive hazard identification using digital safety data streams and the review of continuous hazard monitoring systems by Obriki, Arumosoye, and Obogo (2023) treat as a continuous rather than episodic signal. The second is remote and standoff inspection coverage, which extends the observable surface at low marginal cost. The remote inspection cluster in the seed corpus covers unmanned-aerial-vehicle-based pipeline and corridor monitoring, transmission line inspection methods, integrated frameworks combining unmanned aircraft with LiDAR and geographic information systems, geospatial encroachment detection, integration of drone operations into enterprise asset systems, deep learning classification applied to corridor imagery, and the regulatory frameworks governing deployment (Dagodzo, 2018a, 2018b; Dagodzo & Ahiaeké Patrick, 2020, 2021a, 2021b, 2022, 2023a, 2023b; Dagodzo et al., 2022). For pressure equipment the relevance is coverage rather than resolution: external surfaces, insulation condition, supports, and adjacent piping are inspectable at a frequency that manual access cannot economically match, and corrosion under insulation in particular is a mechanism whose detection probability is presently constrained by access cost rather than by technique capability. Geographic information system integration for utility asset management (Dagodzo & Ahiaeké Patrick, 2021a) is the mechanism by which such observations are attached to a specific asset record rather than accumulating as unlinked imagery. Robotic access is a third route to the same parameter, and work on integrated path planning and slotting optimisation for autonomous mobile robots (Akanbi &

Sunday, 2024) indicates a maturity level that is now transferable to inspection duty in constrained plant environments.

A constraint on this layer that the pressure equipment literature rarely confronts is power. Permanently installed thickness, temperature, and acoustic sensors on a vessel are frequently in locations where cabling is impractical and battery replacement is an entry into a hazardous area, which means monitoring density is limited by energy supply rather than by sensor cost. The energy-harvesting and intermittent-computing cluster in the seed corpus addresses exactly this: systematic assessment of how far radio frequency energy harvesting can support energy-autonomous operation, simulation of performance and reliability in large-scale intermittently powered networks, reliable broadcast protocols for batteryless intermittent sensor networks, predictive power management using lightweight machine learning under uncertain harvest conditions, and the energy, reliability, and latency trade-offs that govern what such a network can actually deliver (Asiedu & Quainoo, 2023a, 2023b, 2024; Quainoo et al., 2024). The finding that matters for integrity monitoring is that intermittency changes the character of the data rather than merely reducing its volume: a sensor that reports opportunistically produces an irregular series with gaps correlated to environmental conditions, and a detection layer built on it must be designed for that structure rather than assuming uniform sampling. Work on wireless link performance, impedance mismatch, coexistence behaviour, and throughput degradation (Quainoo et al., 2024) bears on whether a given plant environment can support the network at all, which is a feasibility question that should precede any monitoring specification.

Anomaly detection methodology is itself importable from fields with far larger labelled datasets than integrity engineering will ever have. The anomaly detection and fraud analytics cluster (Abetoh & Atakpa, 2024; Atakpa, 2021; Atakpa & Abetoh, 2022; Atakpa & Abolaji, 2022; Atakpa & Fobellah, 2023; Atakpa et al., 2024; Eboh & Aliliele, 2023) covers time-series anomaly modelling, machine learning advances in detection for high-volume transactional systems, and privacy-preserving analytics architectures for regulated industries. The transferable content is methodological, principally the handling of extreme class imbalance, which is the defining statistical property of both fraud detection and catastrophic equipment failure. Output: flagged deviations with timestamps and locations.

Layer 2, Attribution. A Bayesian network derived from the vessel's fault tree receives the flagged deviations as evidence and returns posterior probabilities over candidate damage mechanisms and contributing events. This is the diagnostic inference capability described in Section 4.5 and it is the layer most often missing in current practice. Output: ranked causal hypotheses with confidence.

Layer 3, Consequence evaluation. Confirmed findings enter fitness-for-service assessment under API 579-1/ASME FFS-1, producing a remaining life and a run-repair-replace determination. The result updates the probability of the relevant basic events in Layer 2 rather than being recorded separately. Output: revised basic event probabilities and remaining life.

Layer 4, Decision. Importance measures recomputed on the updated tree drive resource allocation: which barrier to reinforce, which technique to change, which interval to shorten or lengthen. Consequence weighting follows RCM's consequence-based selection principle, and risk ranking follows API RP 580 and 581. Materials and spares readiness enter as an execution constraint at this layer rather than as an afterthought, for the reasons set out in Section 5.5. Output: a revised inspection and maintenance plan with each task traceable to the cut set it interdicts.

Layer 5, Generalisation and verification. The revised causal model is propagated across the asset population by service and mechanism similarity, so that a finding on one vessel updates the plans of all comparably exposed vessels. Effectiveness is verified by tracking whether subsequent findings confirm or contradict the posterior distributions produced at Layer 2, which supplies the feedback needed to calibrate the model. Verification should extend to whether corrective actions actually persist, since the recurrence analysis of Obriki and Arumosoye (2022) indicates that organisational basic events revert unless their sustaining mechanism is addressed. Output: population-wide plan revision and model calibration data.

The architecture's distinguishing feature is that **the causal model is a persistent, versioned asset**, maintained continuously and updated by every inspection, rather than a document produced after each failure and archived. This inverts the current relationship between root cause analysis and maintenance planning.

6.4 Requirements for implementation

Realistic implementation requires five things that most organisations do not currently have: a maintained fault tree per vessel class rather than per incident; a data architecture in which inspection findings are recorded against tree nodes rather than as free text; a competent owner of the causal model, which is a role that does not exist in most integrity organisations; a discipline of recording non-findings, since an inspection that found nothing is evidence that updates the model; and governance that requires plan revision when the model changes.

Three of these five have well-developed analogues in the data governance and process discipline literature, which is worth noting because it means the implementation problem is not unprecedented. Recording findings against model nodes rather than as free text is a data classification and traceability problem, treated in the seed corpus through frameworks for enterprise data sensitivity classification and regulatory traceability, data lakehouse governance, and continuous auditing systems (Mbonu et al., 2018, 2019, 2020a, 2022). The more mundane half of the same problem is the conversion of a paper or spreadsheet workflow into a system that captures structured records as a byproduct of normal work, and the applied information systems cluster provides worked instances of exactly that conversion, in which human judgement is retained inside an otherwise automated workflow. These are unglamorous references for a pressure vessel paper and are cited for one reason: the failure mode they address, in which a process continues to function while its record becomes unusable for analysis, is the failure mode that makes most existing inspection histories unfit for the modelling proposed here. Requiring plan revision when the model changes is a controls problem, treated through work on technology-enabled control frameworks and audit automation (Akomolafe & Agu, 2018; Mbonu et al., 2022). Making revised plans actually change field practice is a procedure and change-adoption problem, treated through standard operating procedure design, structured validation of deployed changes, and lean change adoption (Ambali et al., 2021; Eyetsemitan et al., 2022, 2023a, 2023b).

A sixth requirement emerges from the governance literature and is easy to overlook until an incident makes it urgent. If an inspection interval is set or extended by a model, the organisation must be able to explain, to a regulator and potentially to a court, why that interval was defensible at the time it was set. The technology law cluster (Annan, 2022, 2023, 2024) frames this as algorithmic accountability and as the compliance obligation attaching to automated decision-making, and notes the practical tension between explainability and the protection of proprietary methods. For integrity work the resolution is straightforward in principle and neglected in practice:

the model, its inputs, its version, and the reasoning it produced must be retained as records with the same discipline currently applied to thickness measurements.

The fifth requirement is the hardest and the most important. Without it, the architecture produces insight that nothing obliges anyone to act on, which is the current situation with additional software.

7. Discussion

7.1 The recurring structural signature

Across the case evidence surveyed in Section 3, a consistent structure appears: a growth mechanism, a toughness or tolerance reduction, and a detection failure, in conjunction. The 1984 amine absorber rupture and the 2009 NDK Crystal rupture, separated by twenty-five years, different industries, different materials, and different service conditions, share this structure precisely. The implication is that pressure vessel cause trees are more transferable than the incident-specific way they are usually produced would suggest. A library of validated tree templates by service class, with plant-specific probabilities substituted, would convert root cause analysis from a bespoke post-incident activity into a maintained engineering standard. Nothing in the reviewed literature suggests such a library exists in the public domain, and its absence is a significant and tractable gap.

7.2 The detection barrier is the dominant lever, and it is under-modelled

The quantification in Section 6.2 puts almost the entire top-event probability into a cut set containing inspection non-detection. That result is not an artefact of the chosen numbers; it follows from the general structure, in which detection is the last barrier before the degradation path completes and has no redundant partner. Yet probability of detection is the most weakly characterised parameter in most pressure vessel risk models. RBI represents it through discrete inspection effectiveness categories, which is a substantial advance over ignoring it, but the categories are coarse and their assignment is largely judgement-based. The non-destructive evaluation literature contains detailed probability-of-detection information as a function of flaw size, technique, access, and inspector performance, and the reviews by Atta and colleagues (2020) on non-destructive-testing-based integrity management for refinery process equipment and (2021) on weld integrity evaluation methods are representative of the technique-level evidence that exists on the inspection side of this boundary. That evidence is not routinely imported into integrity risk models. Bridging the gap between the non-destructive evaluation reliability literature and the RBI damage factor calculation would improve the quality of pressure vessel risk estimates more than any other single change.

7.3 The organisational layer remains the weakest link

Every framework reviewed treats organisational causation as a modifier applied to a technical calculation, rather than as causation in its own right. RBI's management systems factor is a single plant-wide multiplier. RCM's consequence questions do not interrogate the organisation that will perform the tasks. Fitness-for-service is purely physical.

The methods that do address organisational causation with any depth are either non-quantitative or not integrated into interval-setting. Three of the seed sources illustrate what integration would require. Human error causation must be decomposed into antecedent conditions before it can occupy a tree node at all, which is the contribution of Obriki and Arumosoye (2020). Corrective actions must be assessed for durability rather than closure, which is the contribution of the same

authors' recurrence analysis (2022). And management system quality must be graded and differentiated rather than scored once for a whole facility, which is the contribution of the maturity model of Arumosoye and Obriki (2021). None of these is quantitative in the form an RBI calculation currently consumes, and converting them into that form is arguably the central unsolved problem of the field. It will not be solved by better metallurgy or better sensors.

The scale of the seed corpus assembled here makes a secondary observation possible, and it is not a flattering one for the field. Some 32 distinct sources in this review address occupational safety causation, hazard identification, leadership, contractor governance, training, and organisational learning (Arumosoye & Obriki, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Obogo et al., 2019a, 2019b, 2019c, 2020a, 2020b, 2020c, 2021a, 2021b, 2021c, 2022, 2023, 2024a, 2024b; Obriki & Arumosoye, 2018, 2019, 2020, 2021, 2022, 2023, 2024a, 2024b; Obriki et al., 2022a, 2022b, 2023a, 2023b), and effectively none of them terminates in a parameter that an integrity risk model could accept. The organisational safety literature and the equipment integrity literature have developed in parallel for decades with almost no interface between them. That is a gap in the connective tissue rather than in either body of work, and it will be closed by translation studies rather than by further framework development on either side.

7.4 On the promise and the limits of the computational turn

The 2024 literature on digital twins and predictive maintenance is substantial and technically impressive. It is also, for the purposes of this review, incomplete in a specific way. A high-accuracy remaining-useful-life prediction tells the maintainer *when*. It does not tell them *why*, and therefore it does not tell them *what to change*. Two vessels with identical predicted remaining life may require entirely different interventions if the underlying mechanisms differ, and a purely correlational model cannot distinguish them.

The systematic reviews of predictive maintenance and digital twins published in 2024 correctly identify the potential of these methods for condition assessment, and equally correctly note that industrial practice remains dominated by reactive and preplanned approaches. The gap between the two is often attributed to data availability and organisational readiness. This review suggests an additional and less discussed reason: the outputs of predictive models do not natively connect to the causal reasoning that maintenance decisions actually require. Hybrid architectures of the kind proposed in Section 6.3 address this directly by assigning detection to the learned model and attribution to the causal model, and interpretability is the property that makes the handoff possible, as the early failure prediction work of Komi and Adamolekun (2021) indicates.

A parallel development is worth noting on the safety side, where analytics is being applied to leading indicators rather than to equipment condition. Proactive hazard identification built on digital safety data streams and continuous hazard monitoring systems (Obriki & Arumosoye, 2023; Obriki et al., 2023) are oriented toward elevated risk states rather than component failures. For an integrated architecture these are Layer 1 inputs of a different kind: they bear on the organisational basic events that Section 7.3 identifies as the least well modelled, and they are among the few sources that produce forward-looking signals about them.

7.5 Threats to validity of this review

The conclusions above rest on a literature with the limitations identified in Section 2.4. In particular, the claim that causal knowledge fails to generalise across asset populations is inferred from the structure of published single-asset studies and from investigation reports, rather than from direct observation of maintenance organisations. It is plausible and consistent with the evidence,

but it is not directly measured, and a survey-based study of actual practice would be a valuable contribution. Separately, the seed sources in Stratum E are used for structural insight rather than for parameter values, and several address adjacent asset classes; conclusions drawn from them are therefore qualitative and should be tested on pressure equipment directly.

8. Research Gaps and Future Directions

Gap 1. Validated tree templates by service class. No public library of validated pressure vessel fault tree templates exists. Constructing one, organised by service (amine, sour water, hydrogen, caustic, cryogenic, steam) with documented basic event structures, would be a high-value and largely achievable contribution.

Gap 2. Probability of detection integrated with risk models. Formal incorporation of non-destructive evaluation probability-of-detection data into RBI damage factor calculation, replacing categorical inspection effectiveness ratings with continuous, technique-specific and flaw-size-specific detection probabilities. The technique-level reviews of integrity management and weld inspection cited in Section 7.2 indicate that the source evidence exists; what is missing is the translation layer into risk calculation.

Gap 3. Vessel-level organisational causation. Development of quantitative, vessel-specific representations of human and organisational contribution that go beyond a plant-wide multiplier, building on approaches that separate human-factor probability from material-defect probability at the individual asset level and on graded organisational maturity models.

Gap 4. Live causal models. Persistent Bayesian network models of vessel integrity that update continuously from monitoring data and inspection findings, including systematic treatment of non-findings as evidence, with published validation against subsequent observed conditions.

Gap 5. Population-level causal propagation. Formal methods for determining which assets should receive plan revision when a causal finding is made on one, based on quantified service and mechanism similarity rather than engineering judgement alone.

Gap 6. Empirical validation of the coupling claim. Direct study of maintenance organisations measuring whether and how root cause analysis findings alter inspection plans, and with what lag, which would test the central diagnosis of this review.

Gap 7. Causal-correlational hybrid architectures. Development and field validation of architectures in which learned detection models feed causal attribution models, with attention to the interface between the two, which is where the engineering difficulty concentrates and where model interpretability becomes a functional requirement rather than a preference.

Gap 8. Energy-constrained continuous monitoring. Specification methods for permanently installed vessel monitoring under realistic energy budgets, treating intermittent and irregular sampling as a designed property of the detection layer rather than as data quality degradation, and quantifying what detection probability such networks actually deliver in plant radio environments.

Gap 9. Continuous validation of protective functions. Transfer of continuous control validation practice from security engineering to pressure relief and trip systems, replacing periodic proof testing with exercised effectiveness measurement where the process permits it, and quantifying the resulting change in probability of failure on demand.

Gap 10. Evidentiary defensibility of model-set intervals. Record-keeping, versioning, and explanation standards sufficient to defend a model-derived inspection interval to a regulator, developed before rather than after the first contested case.

Emerging areas requiring attention. Hydrogen service, where embrittlement mechanisms and high-cycle pressure fluctuation in storage and refuelling infrastructure create a damage environment for which the existing damage factor literature is thin, and where the infrastructure build-out now under way will create a large population of pressure-retaining assets faster than the corresponding integrity evidence base can be assembled. Carbon capture service, where dense phase CO₂ with water and trace contaminants presents corrosion behaviour that is imperfectly characterised. Life extension of ageing assets operating well beyond original design life, where the assumptions underlying generic failure frequencies may no longer hold. Additively manufactured and novel-alloy pressure components, for which the inspection and damage-mechanism knowledge base is immature.

9. Conclusion

Cause-tree failure analysis and root-cause-driven maintenance are each mature bodies of practice. Fault tree analysis has more than six decades of formal development and a rich set of extensions handling uncertainty, dependence, and time. Risk-Based Inspection under API RP 580 and 581 has internalised mechanism-specific causal reasoning into a quantitative inspection planning procedure and represents the most causally grounded maintenance framework in current pressure equipment practice. Fitness-for-service assessment under API 579-1/ASME FFS-1 supplies the physics that converts a detected condition into a defensible decision.

The weakness is not in any of these components. It is at the joints between them.

Three conclusions follow from this review.

First, pressure vessel failure is characteristically conjunctive, requiring a growth mechanism together with a tolerance reduction together with a detection failure. Analytical methods that cannot represent conjunction, which includes the five-whys and fishbone approaches used in the majority of routine industrial investigations, are structurally inadequate for this asset class regardless of how carefully they are applied.

Second, the detection barrier dominates the risk. The quantitative example in Section 6.2 places roughly 98 percent of top-event probability in a cut set containing inspection non-detection, and importance-directed investment in detection capability outperformed conventionally-directed investment by a factor of approximately fifty. Probability of detection is simultaneously the most influential and the most weakly characterised parameter in pressure vessel risk models. This is the field's most consequential and most addressable deficiency.

Third, the coupling between causal analysis and maintenance planning is the binding constraint, not the sophistication of either activity. Causal knowledge produced after an incident does not reliably propagate to the inspection plans of comparably exposed assets. The five-layer architecture proposed in Section 6.3 is one route to closing that loop, and its essential move is to treat the causal model as a persistent, continuously updated engineering asset rather than as an incident report. A fourth observation follows from the breadth of the corpus reviewed rather than

from any single source in it. This review drew on 201 adjacent applied sources spanning safety causation, inspection technology, energy-autonomous sensing, control system and enterprise security, aviation oversight, regulated facility design, procurement and supplier qualification, analytics, audit and governance, algorithmic accountability, and asset logistics. Across that breadth, the recurring pattern is that each field has developed a sophisticated account of its own contribution to failure and almost no interface to the others. The breadth is offered as diagnosis rather than as authority: it demonstrates the fragmentation, and it should not be mistaken for evidential weight, for the reasons set out in Section 2.4. The pressure vessel is where those accounts intersect physically, and it is the absence of an interface between them, rather than a deficiency within any one of them, that this review identifies as the field's characteristic weakness. The computational tools now available, particularly Bayesian network representations that support diagnostic inference and dynamic extensions that handle time-dependent degradation, are sufficient to build such systems. The remaining obstacles are organisational: ownership of the causal model, data discipline in recording findings and non-findings against model nodes, and governance requiring plan revision when the model changes. Those obstacles are more tractable than the technical ones the field has already overcome.

References

Codes, standards, and recommended practices

- American Petroleum Institute. API 510: Pressure Vessel Inspection Code: In-Service Inspection, Rating, Repair, and Alteration. Washington, DC: API.
- American Petroleum Institute. API RP 571: Damage Mechanisms Affecting Fixed Equipment in the Refining Industry. Washington, DC: API.
- American Petroleum Institute. API RP 572: Inspection Practices for Pressure Vessels. Washington, DC: API.
- American Petroleum Institute. API RP 579-1/ASME FFS-1: Fitness-For-Service. Washington, DC: API.
- American Petroleum Institute. API RP 580: Risk-Based Inspection. Washington, DC: API.
- American Petroleum Institute. API RP 581: Risk-Based Inspection Methodology. Washington, DC: API.
- American Society of Mechanical Engineers. ASME Boiler and Pressure Vessel Code, Section VIII, Divisions 1 and 2. New York: ASME.
- International Electrotechnical Commission. IEC 61025: Fault Tree Analysis (FTA). Geneva: IEC.
- International Electrotechnical Commission. IEC 60812: Failure Modes and Effects Analysis (FMEA and FMECA). Geneva: IEC.
- International Electrotechnical Commission. IEC 61511: Functional Safety: Safety Instrumented Systems for the Process Industry Sector. Geneva: IEC.
- International Organization for Standardization. ISO 55000: Asset Management: Overview, Principles and Terminology. Geneva: ISO.
- National Board of Boiler and Pressure Vessel Inspectors. National Board Inspection Code (NBIC), ANSI/NB-23. Columbus, OH: National Board.
- SAE International. SAE JA1011: Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes. Warrendale, PA: SAE.
- SAE International. SAE JA1012: A Guide to the Reliability-Centered Maintenance (RCM) Standard. Warrendale, PA: SAE.
- Occupational Safety and Health Administration. Process Safety Management of Highly Hazardous Chemicals, 29 CFR 1910.119. Washington, DC: US Department of Labor.
- Foundational handbooks and monographs
- Vesely, W. E., Goldberg, F. F., Roberts, N. H., and Haasl, D. F. Fault Tree Handbook, NUREG-0492. Washington, DC: US Nuclear Regulatory Commission, 1981.
- Vesely, W. E., Dugan, J., Fragola, J., Minarick, J., and Railsback, J. Fault Tree Handbook with Aerospace Applications. Washington, DC: NASA Office of Safety and Mission Assurance, 2002.
- Nowlan, F. S., and Heap, H. F. Reliability-Centered Maintenance. Report AD-A066579. Washington, DC: US Department of Defense, 1978.
- Rausand, M., and Høyland, A. System Reliability Theory: Models, Statistical Methods, and Applications, 2nd ed. Hoboken, NJ: John Wiley and Sons, 2004.
- Ishikawa, K. Guide to Quality Control. Tokyo: Asian Productivity Organization, 1986.
- Kletz, T. A. Learning from Accidents, 3rd ed. Oxford: Butterworth-Heinemann, 2001.
- Reason, J. Human Error. Cambridge: Cambridge University Press, 1990.
- Leveson, N. G. Engineering a Safer World: Systems Thinking Applied to Safety. Cambridge, MA: MIT Press, 2011.

- Leveson, N. G. "A new accident model for engineering safer systems." *Safety Science* 42, no. 4 (2004): 237–270.
- Rasmussen, J. "Risk management in a dynamic society: a modelling problem." *Safety Science* 27, no. 2–3 (1997): 183–213.
- Journal literature and applied studies
- Golubović, T., Sedmak, A., Spasojević Brkić, V., Kirin, S., and Rakonjac, I. "Novel risk based assessment of pressure vessels integrity." *Tehnički Vjesnik* 25, no. 3 (2018): 803–807. <https://doi.org/10.17559/TV-20170829144636>
- Khairuldin, M. K. H., Rosli, N., Abd Razak, U. I., and Muhammad, N. "Application of risk-based inspection using API 581 methodology to a pressure vessel in petrochemical plant." *AIP Conference Proceedings* 2895, no. 1 (2024): 020011. <https://doi.org/10.1063/5.0192087>
- "Risk-based inspection analysis of API 581 pressure safety valve and stripper acid gas removal unit." *Scientific Contributions Oil and Gas* 47, no. 3 (December 2024): 313–325. <https://doi.org/10.29017/SCOG.47.3.1645>
- Luo, X., Li, Y., Bai, X., Tang, R., and Jin, H. "A novel approach based on fault tree analysis and Bayesian network for multi-state reliability analysis of complex equipment systems." *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability* (2024). <https://doi.org/10.1177/1748006X231171449>
- Cheng, et al. "Reliability analysis for manufacturing system of drive shaft based on dynamic Bayesian network." *Quality and Reliability Engineering International* 40 (2024): 4482–4497. <https://doi.org/10.1002/qre.3644>
- Liu, Z., Liu, Y., Cai, B., Zhang, D., and Zheng, C. "Dynamic Bayesian network modeling of reliability of subsea blowout preventer stack in presence of common cause failures." *Journal of Loss Prevention in the Process Industries* 38 (2015): 58–66.
- Kang, J., Sun, L., and Guedes Soares, C. "Fault tree analysis of floating offshore wind turbines." *Renewable Energy* 133 (2019): 1455–1467.
- Márquez, F. P. G., Pérez, J. M. P., Marugán, A. P., and Papaelias, M. "Identification of critical components of wind turbines using FTA over the time." *Renewable Energy* 87 (2016): 869–883.
- de Jonge, B., Teunter, R., and Tinga, T. "The influence of practical factors on the benefits of condition-based maintenance over time-based maintenance." *Reliability Engineering and System Safety* 158 (2017): 21–30.
- Eriksen, S., Utne, I. B., and Lützen, M. "An RCM approach for assessing reliability challenges and maintenance needs of unmanned cargo ships." *Reliability Engineering and System Safety* 210 (2021): 107550.
- Mamdikar, M. R., Kumar, V., and Singh, P. "Dynamic reliability analysis framework using fault tree and dynamic Bayesian network: a case study of NPP." *Nuclear Engineering and Technology* 54 (2022): 1213–1220.
- Abd Wahab, N. H., Hasikin, K., Wee Lai, K., Xia, K., Bei, L., Huang, K., and Wu, X. "Systematic review of predictive maintenance and digital twin technologies: challenges, opportunities, and best practices." *PeerJ Computer Science* 10 (2024): e1943. <https://doi.org/10.7717/peerj-cs.1943>
- Daya, A. A., and Lazakis, I. "Systems reliability and data driven analysis for marine machinery maintenance planning and decision making." *Machines* 12, no. 5 (2024): 294.

- Khan, F. I., and Haddara, M. M. "Risk-based maintenance (RBM): a quantitative approach for maintenance/inspection scheduling and planning." *Journal of Loss Prevention in the Process Industries* 16, no. 6 (2003): 561–573.
- Arunraj, N. S., and Maiti, J. "Risk-based maintenance: techniques and applications." *Journal of Hazardous Materials* 142, no. 3 (2007): 653–661.
- Investigation reports and technical studies
- National Bureau of Standards. Analysis of the Catastrophic Rupture of a Pressure Vessel, NBSIR 86-3049. Investigation of the 23 July 1984 amine absorber tower rupture at a Chicago-area petroleum refinery. Gaithersburg, MD: NBS, 1986.
- National Institute of Standards and Technology. "NIST analysis helps the U.S. Chemical Safety Board pinpoint root cause of pressure vessel failure." Material Measurement Laboratory review supporting the CSB investigation of the 2009 NDK Crystal vessel rupture, Belvidere, Illinois.
- US Chemical Safety and Hazard Investigation Board. Final investigation report: NDK Crystal Inc. pressure vessel rupture. Washington, DC: CSB.
- Seed literature: equipment integrity, non-destructive evaluation, corrosion, and welding
- Atta, S., Tofah, P., Kankam, M. A., & Adenuga, O. M. (2020). A critical review of NDT-based integrity management and corrosion risk assessment strategies for refinery process equipment. *International Journal of Engineering and Modern Technology*, 6(2), 19-46. <https://doi.org/10.56201/ijemt.vol.6.no2.2020.pg19.46>
- Atta, S., Tofah, P., & Adenuga, O. M. (2021). Advances in non-destructive testing methods for weld integrity evaluation in high-capacity power infrastructure. *International Journal of Engineering and Modern Technology*, 7(1), 20-47. <https://doi.org/10.56201/ijemt.vol.7.no1.2021.pg20.47>
- Atta, S., Adjaklo, E., Asomani, E., & Adenuga, O. M. (2022). Advances in welding inspection standards and quality assurance practices in large-scale power generation projects. *International Journal of Engineering and Modern Technology*, 8(5), 101-124. <https://doi.org/10.56201/ijemt.v8.no5.2022.pg101.124>
- Atta, S., Asomani, E., & Adenuga, O. M. (2018). A systematic review of green corrosion inhibitors from agricultural extracts for mild steel protection in acidic and alkaline media. *International Journal of Engineering and Modern Technology*, 4(1), 64-97. <https://doi.org/10.56201/ijemt.vol.4.no1.2018.pg64.97>
- Seed literature: condition monitoring, maintenance strategy, and energy systems engineering
- Sunday, E. A., Omoegun, G. O., Essien, M. A., & Oluokun, O. A. (2020). Transitioning from reactive to predictive maintenance in mechanical systems. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 6(6), 425-447.
- Sunday, E. A., & Omoegun, G. O. (2022). Smart fault detection in HVAC systems using sensor-based monitoring. *International Journal of Scientific Research in Science, Engineering and Technology*, 7(4), 380-403.
- Omoegun, G. O., Sunday, E. A., Essien, M. A., & Oluokun, O. A. (2023). Vibration-based condition monitoring of rotating machinery using LabVIEW. *International Journal of Scientific Research in Civil Engineering*, 7(6), 82-108.
- Sunday, E. A., Omoegun, G. O., Essien, M. A., & Oluokun, O. A. (2019). Thermodynamic efficiency and control strategies in residential air conditioning systems. *International Journal of Scientific Research in Civil Engineering*, 3(3), 52-76.

- Sunday, E. A., & Omoegun, G. O. (2018). Integrating solar power solutions in small-scale manufacturing industries in Nigeria. *International Journal of Scientific Research in Science, Engineering and Technology*, 4(8), 832-853.
- Sunday, E. A., & Omoegun, G. O. (2019). Optimizing electrical load distribution for hybrid solar installations in developing economies. *International Journal of Scientific Research in Mechanical and Materials Engineering*, 3(6), 27-47.
- Yeboah, B. K., Enow, O. F., Ike, P. N., & Nnabueze, S. B. (2024). Program design for advanced preventive maintenance in renewable energy systems. *Shodhshauryam, International Scientific Refereed Research Journal*, 7(2), 138-156. <https://doi.org/10.32628/SHISRRJ2472156>
- Yeboah, B. K., & Ike, P. N. (2020). Programmatic strategy for renewable energy integration: Lessons from large-scale solar projects. *International Journal of Multidisciplinary Research and Growth Evaluation*, 1(3), 306-315. <https://doi.org/10.54660/IJMRGE.2020.1.3.306-315>
- Seed literature: occupational safety, incident causation, and organisational reliability
- Arumosoye, O. M., & Obriki, O. D. (2018). Development of an integrated heat stress risk conceptual model for industrial operations in extreme environments. *Iconic Research and Engineering Journals*, 1(12), 141-160. <https://doi.org/10.64388/IREV1112-1714415>
- Arumosoye, O. M., & Obriki, O. D. (2019). Systematic review of near-miss and hazard observation data utilization in industrial safety management. *Iconic Research and Engineering Journals*, 3(2), 981-999. <https://doi.org/10.64388/IREV312-1714417>
- Arumosoye, O. M., & Obriki, O. D. (2020). A governance-oriented conceptual model for contractor safety performance in multi-contract industrial projects. *International Journal of Multidisciplinary Research and Growth Evaluation*, 1(5), 728-740. <https://doi.org/10.54660/IJMRGE.2020.1.5.728-740>
- Arumosoye, O. M., & Obriki, O. D. (2021). Organizational learning-based conceptual maturity model for continuous safety performance improvement. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(1), 970-980. <https://doi.org/10.54660/IJMRGE.2021.2.1.970-980>
- Arumosoye, O. M., & Obriki, O. D. (2022). Conceptual risk pathway model for lifting and rigging operations in heavy industrial construction. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(5), 346-369. <https://doi.org/10.32628/GISRRJ2256237>
- Arumosoye, O. M., & Obriki, O. D. (2023). Conceptual model for emergency response readiness and capability in energy and process facilities. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 9(3), 897-917. <https://doi.org/10.32628/CSEIT25112791>
- Arumosoye, O. M., & Obriki, O. D. (2024). Conceptual model of safety leadership influence in large temporary project organizations. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 3034-3047. <https://doi.org/10.62225/2583049X.2024.4.6.5895>
- Obogo, S. F., Arumosoye, O. M., & Obriki, O. D. (2020a). Advances in internal QHSE audit systems for industrial engineering operations. *Iconic Research and Engineering Journals*, 4(4), 399-417. <https://doi.org/10.64388/IREV414-1715499>
- Obogo, S. F., Arumosoye, O. M., & Obriki, O. D. (2020b). Conceptual risk management model for heavy lifting and crane installation engineering operations. *Shodhshauryam*,

- International Scientific Refereed Research Journal*, 3(4), 122-144.
<https://doi.org/10.32628/SHISRRJ214441>
- Obogo, S. F., Arumosoye, O. M., & Obriki, O. D. (2020c). Critical review of occupational safety management systems in oil and gas maintenance projects. *Shodhshauryam, International Scientific Refereed Research Journal*, 3(4), 145-166.
<https://doi.org/10.32628/SHISRRJ214442>
- Obogo, S. F., Arumosoye, O. M., & Obriki, O. D. (2021a). Advances in proactive hazard recognition and near miss reporting systems. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(6), 835-846.
<https://doi.org/10.54660/IJMRGE.2021.2.6.835-846>
- Obogo, S. F., Arumosoye, O. M., & Obriki, O. D. (2024a). Review of sustainable environmental practices in occupational safety management systems. *International Journal of Scientific Research in Civil Engineering*, 8(3), 164-196. <https://doi.org/10.32628/IJSRCE248420>
- Obogo, S. F., Nwafor, M. I., & Ozobu, C. O. (2023). Conceptual leadership model for safety culture development in construction and engineering projects. *International Journal of Scientific Research in Civil Engineering*, 7(6), 121-153.
<https://doi.org/10.32628/IJSRCE237554>
- Obogo, S. F., Obriki, O. D., & Arumosoye, O. M. (2021b). Conceptual model for incident prevention in industrial maintenance engineering environments. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(6), 847-858.
<https://doi.org/10.54660/IJMRGE.2021.2.6.847-858>
- Obogo, S. F., Obriki, O. D., & Arumosoye, O. M. (2022). Conceptual safety governance model for large commercial facility operations. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(6), 383-410. <https://doi.org/10.32628/GISRRJ225639>
- Obogo, S. F., Ozobu, C. O., & Nwafor, M. I. (2024b). Conceptual environmental safety compliance framework for construction and infrastructure projects. *International Journal of Scientific Research in Civil Engineering*, 8(3), 132-163.
<https://doi.org/10.32628/IJSRCE248419>
- Obogo, S. F., Ozobu, C. O., & Uduokhai, D. O. (2019a). Advances in leadership driven safety culture transformation in large construction workforces. *Iconic Research and Engineering Journals*, 3(5), 507-523. <https://doi.org/10.64388/IREV3I5-1715497>
- Obogo, S. F., Ozobu, C. O., & Uduokhai, D. O. (2019b). Development of a construction safety risk governance model for multi contractor high rise projects. *Iconic Research and Engineering Journals*, 2(9), 502-522. <https://doi.org/10.64388/IREV2I9-1715495>
- Obogo, S. F., Uduokhai, D. O., & Ozobu, C. O. (2019c). Systematic review of hazard identification and risk control practices in urban construction projects. *Iconic Research and Engineering Journals*, 2(12), 666-681. <https://doi.org/10.64388/IREV2I12-1715496>
- Obogo, S. F., Uduokhai, D. O., & Ozobu, C. O. (2021c). Review of contractor safety compliance systems in infrastructure engineering projects. *International Journal of Scientific Research in Civil Engineering*, 5(4), 76-100. <https://doi.org/10.32628/IJSRCE215412>
- Obriki, O. D., & Arumosoye, O. M. (2018). Conceptual modeling of data-driven occupational safety risk control in large-scale energy infrastructure projects. *Iconic Research and Engineering Journals*, 1(7), 169-189. <https://doi.org/10.64388/IREV1I7-1714414>
- Obriki, O. D., & Arumosoye, O. M. (2019). A conceptual framework linking management safety walkthrough frequency and coverage to safety culture outcomes in mega projects. *Iconic*

- Research and Engineering Journals*, 2(8), 355-374. <https://doi.org/10.64388/IREV218-1714416>
- Obriki, O. D., & Arumosoye, O. M. (2020). Conceptual framework for human error causation in high-risk construction and industrial activities. *International Journal of Multidisciplinary Research and Growth Evaluation*, 1(5), 715-727. <https://doi.org/10.54660/IJMRGE.2020.1.5.715-727>
- Obriki, O. D., & Arumosoye, O. M. (2021). Conceptual model for institutionalizing life-preserving safety practices across project-based organizations. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(1), 961-969. <https://doi.org/10.54660/IJMRGE.2021.2.1.961-969>
- Obriki, O. D., & Arumosoye, O. M. (2022). Conceptual framework explaining recurrence mechanisms of unsafe behaviors in high-hazard worksites. *Shodhshauryam, International Scientific Refereed Research Journal*, 5(3), 380-402. <https://doi.org/10.32628/SHISRRJ225489>
- Obriki, O. D., & Arumosoye, O. M. (2023). Conceptual framework for proactive hazard identification using digital safety data streams. *Gyanshauryam, International Scientific Refereed Research Journal*, 6(3), 457-481. <https://doi.org/10.32628/GISRRJ236336>
- Obriki, O. D., & Arumosoye, O. M. (2024a). Conceptual governance framework for subcontractor safety performance management. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 3020-3033. <https://doi.org/10.62225/2583049X.2024.4.6.5894>
- Obriki, O. D., & Arumosoye, O. M. (2024b). Systematic review of incident investigation approaches and prevention-oriented learning in industrial operations. *Shodhshauryam, International Scientific Refereed Research Journal*, 7(4), 239-263. <https://doi.org/10.32628/SHISRRJ247163>
- Obriki, O. D., Arumosoye, O. M., & Obogo, S. F. (2023a). Advances in continuous hazard monitoring systems for workplace safety. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2742-2759. <https://doi.org/10.62225/2583049X.2023.3.6.6075>
- Obriki, O. D., Obogo, S. F., & Arumosoye, O. M. (2022a). Advances in workforce safety training models for operational risk reduction. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(6), 349-382. <https://doi.org/10.32628/GISRRJ225638>
- Obriki, O. D., Obogo, S. F., & Arumosoye, O. M. (2022b). Review of emergency preparedness and evacuation systems in high density commercial buildings. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(6), 411-438. <https://doi.org/10.32628/GISRRJ225640>
- Obriki, O. D., Obogo, S. F., & Arumosoye, O. M. (2023b). Review of behavioral safety programs for risk reduction in large workforces. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2760-2775. <https://doi.org/10.62225/2583049X.2023.3.6.6076>
- Seed literature: remote and standoff inspection using UAV, LiDAR, and GIS**
- Dagodzo, D. (2018a). A conceptual framework for UAV integration into national power grid inspection programs. *Iconic Research and Engineering Journals*, 2(5), 391-412. <https://doi.org/10.64388/IREV215-1716082>
- Dagodzo, D. (2018b). A review of UAV applications in electrical transmission line inspection: Methods, technologies, and challenges. *Iconic Research and Engineering Journals*, 2(6), 234-254. <https://doi.org/10.64388/IREV216-1716083>

- Dagodzo, D., & Ahiaeke Patrick, M. C. (2020). UAV-based pipeline and corridor monitoring: A review of current practices and emerging technologies. *Iconic Research and Engineering Journals*, 3(10), 574-597. <https://doi.org/10.64388/IREV3110-1716084>
- Dagodzo, D., & Ahiaeke Patrick, M. C. (2021a). A review of GIS applications in utility asset management and infrastructure planning. *Iconic Research and Engineering Journals*, 5(3), 468-492. <https://doi.org/10.64388/IREV5I3-1716085>
- Dagodzo, D., & Ahiaeke Patrick, M. C. (2021b). An integrated framework for UAV, LiDAR, and GIS in infrastructure corridor management. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 7(5), 497-524. <https://doi.org/10.32628/CSEIT217566>
- Dagodzo, D., & Ahiaeke Patrick, M. C. (2022). A review of right-of-way encroachment detection methods using geospatial technologies. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8(1), 638-667. <https://doi.org/10.32628/CSEIT2281226>
- Dagodzo, D., & Ahiaeke Patrick, M. C. (2023a). A framework for integrating drone operations into enterprise GIS systems for utility companies. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 9(4), 924-957. <https://doi.org/10.32628/CSEIT23564536>
- Dagodzo, D., & Ahiaeke Patrick, M. C. (2023b). A review of UAV regulatory frameworks in developing economies: Progress, gaps, and recommendations. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 9(4), 958-994. <https://doi.org/10.32628/CSEIT23564537>
- Dagodzo, D., Ahiaeke Patrick, M. C., & Aliliele, C. (2022). AI and deep learning for vegetation classification in power corridor management: A review. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8(1), 668-698. <https://doi.org/10.32628/CSEIT2281227>

Seed literature: operational technology and critical infrastructure security

- Adebayo, A., Adegbite, M. P., & Ahmed, M. O. (2022). Adversarial machine learning in critical infrastructure: A conceptual framework for threat modeling AI enabled OT systems. *World Journal of Innovation and Modern Technology*, 6(1), 184-234. <https://doi.org/10.56201/wjim.v6.no1.2022.pg184.234>
- Adebayo, A., Adegbite, M. P., & Ahmed, M. O. (2023). AI augmented threat detection in industrial control systems: A systematic review of machine learning approaches for ICS anomaly detection. *International Journal of Engineering and Modern Technology*, 9(3), 287-340. <https://doi.org/10.56201/ijcsmt.v9.no3.2023.pg287.340>
- Adegbite, M. P., Adebayo, A., & Ahmed, M. O. (2020). Securing operational technology networks in electric utilities: A systematic review of NERC CIP compliance and architectural threat mitigation. *International Journal of Engineering and Modern Technology*, 6(3), 103-146. <https://doi.org/10.56201/ijemt.vol.6.no3.2020.pg103.146>
- Adegbite, M. P., Adebayo, A., & Ahmed, M. O. (2022). A security architecture model for IT and OT convergence in regulated energy networks: Design principles and governance alignment. *International Journal of Computer Science and Mathematical Theory*, 8(2), 81-132. <https://doi.org/10.56201/ijcsmt.v8.no2.2022.pg81.132>
- Adegbite, M. P., Adebayo, A., & Ahmed, M. O. (2023). ICS and SCADA threat detection architectures in energy sector networks: A systematic review of SIEM, NDR, and anomaly

- detection approaches. *World Journal of Innovation and Modern Technology*, 7(2), 121-182. <https://doi.org/10.56201/wjimt.v7.no2.2023.pg121.182>
- Adegbite, M. P., Adebayo, A., & Ahmed, M. O. (2024a). A vulnerability governance architecture for power and utilities corporations: From exposure mapping to remediation verification. *World Journal of Innovation and Modern Technology*, 8(6), 185-246. <https://doi.org/10.56201/wjimt.v8.no6.2024.pg185.246>
- Adegbite, M. P., Adebayo, A., & Ahmed, M. O. (2024b). An AI driven security operations architecture for utility sector SOCs: Integrating threat intelligence, behavioral analytics, and automated response. *International Journal of Engineering and Modern Technology*, 10(11), 197-256. <https://doi.org/10.56201/ijemt.v10.no11.2024.pg197.256>
- Ahmed, M. O., Adegbite, M. P., & Adebayo, A. (2021). Zero trust architecture for operational technology in North American critical infrastructure: A framework for implementation and resilience optimization. *International Journal of Engineering and Modern Technology*, 7(1), 66-113. <https://doi.org/10.56201/ijemt.vol.7.no1.2021.pg66.113>
- Seed literature: aviation safety oversight, investigation, and regulatory compliance**
- Adeyelu, O. O. (2022). A regulatory evidence framework for assessing unauthorized structure violations within protected airport obstacle limitation surfaces. *International Journal of Scientific Research in Civil Engineering*, 6(6), 248-283. <https://doi.org/10.32628/IJSRCE229673>
- Adeyelu, O. O., & Dagodzo, D. (2024a). Advances in artificial intelligence and data-driven wildlife hazard monitoring and incident reduction at international airports in West Africa. *International Journal of Scientific Research in Science and Technology*, 11(5), 872-910. <https://doi.org/10.32628/IJSRST52310285>
- Adeyelu, O. O. (2018). A predictive compliance monitoring framework for detecting systemic safety risks through aviation consumer complaint data. *Iconic Research and Engineering Journals*, 1(8), 250-276. <https://doi.org/10.64388/IREV118-1718478>
- Adeyelu, O. O. (2019). An adaptive safety management system implementation model for aerodromes in developing economy contexts. *Iconic Research and Engineering Journals*, 3(4), 628-654. <https://doi.org/10.64388/IREV314-1718479>
- Adeyelu, O. O. (2020). An artificial intelligence-driven conceptual model for wildlife strike risk quantification and aircraft airworthiness impact assessment at high-traffic African airports. *Iconic Research and Engineering Journals*, 4(1), 339-368. <https://doi.org/10.64388/IREV411-1718482>
- Adeyelu, O. O. (2021). A framework for managing encroachments and unauthorized structures around airport boundaries: Regulatory evidence, enforcement, and corrective action protocols for Nigerian civil aviation. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(6), 954-972. <https://doi.org/10.54660/IJMRGE.2021.2.6.954-972>
- Adeyelu, O. O. (2023). A risk-tiered oversight model for unmanned aircraft operations in shared controlled airspace over Nigerian airports. *International Journal of Scientific Research in Civil Engineering*, 7(4), 147-184. <https://doi.org/10.32628/IJSRCE237419>
- Adeyelu, O. O., & Dagodzo, D. (2022). A comparative benchmarking model for aerodrome certification compliance across developing economy civil aviation authorities. *International Journal of Multidisciplinary Research and Growth Evaluation*, 3(6), 1016-1035. <https://doi.org/10.54660/IJMRGE.2022.3.6.1016-1035>

Adeyelu, O. O., & Dagodzo, D. (2024b). A maturity model for predicting airport safety audit outcomes in resource-constrained regulatory environments. *International Journal of Scientific Research in Civil Engineering*, 8(4), 132-170. <https://doi.org/10.32628/IJSRCE248423>

Seed literature: predictive diagnostics, forecasting, and digital twin applications in energy

Komi, N. M., & Adamolekun, A. (2021). Interpretable machine learning for early failure prediction in distributed renewable energy assets. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(6), 1015-1038. <https://doi.org/10.54660/IJMRGE.2021.2.6.1015-1038>

Komi, N. M., & Adeniji, I. O. (2023). A tiered digital twin that brings predictive diagnostics to resource-constrained renewable energy sites. *International Journal of Engineering and Modern Technology*, 9(3), 287-347. <https://doi.org/10.56201/ijemt.v9.no3.2023.pg287.347>

Komi, N. M., & Adamolekun, A. (2022). Hierarchical, decentralized, or hybrid? A systematic review of control architectures for distributed energy resources. *International Journal of Engineering and Modern Technology*, 8(5), 141-195. <https://doi.org/10.56201/ijemt.v8.no5.2022.pg141.195>

Komi, N. M. (2021). Hybrid deep learning for wind power forecasting: From grid stability to market equity for small generators. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(6), 989-1014. <https://doi.org/10.54660/IJMRGE.2021.2.6.989-1014>

Adenuga, O. M. (2022). Smart grid architectures and energy distribution for high renewable penetration: A comprehensive review of technologies, operations, and deployment pathways. *International Journal of Engineering and Modern Technology*, 8(5), 125-155. <https://doi.org/10.56201/ijemt.v8.no5.2022.pg125.155>

Komi, N. M., & Adeniji, I. O. (2024b). Why energy projects survive or fail: Modeling the causal link between community trust and infrastructure durability. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 3263-3296. <https://doi.org/10.62225/2583049X.2024.4.6.6459>

Komi, N. M., & Ganiu, O. S. (2022). Grid-connected battery storage in hot and weak-grid regions: Advances, degradation challenges, and lifecycle equity. *International Journal of Multidisciplinary Research and Growth Evaluation*, 3(6), 1072-1095. <https://doi.org/10.54660/IJMRGE.2022.3.6.1072-1095>

Komi, N. M., & Ganiu, O. S. (2023). Edge intelligence for resilient microgrid control: Advances, energy sovereignty, and open challenges. *Gyanshauryam, International Scientific Refereed Research Journal*, 6(3), 525-586. <https://doi.org/10.32628/GISRRJ236339>

Seed literature: lifecycle risk assessment in energy environmental systems

Falegan, O. C., & Aniebonam, S. O. (2022). Conceptual framework for lifecycle risk assessment in offshore produced water management. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(5), 322-345.

Falegan, O. C., & Aniebonam, S. O. (2023). Integrated physicochemical and bio-based treatment strategies for produced water in arid environments: A review. *Gyanshauryam, International Scientific Refereed Research Journal*, 6(1), 425-443.

Falegan, O. C., & Aniebonam, S. O. (2024). Decentralized produced water treatment systems for remote energy assets: A conceptual design framework. *International Journal of Scientific*

Research in Computer Science, Engineering and Information Technology, 10(3), 1133-1151.

Seed literature: power systems and electrical machines

Adenuga, O. M. (2023). Power electronics and energy efficiency in modern power systems: A comprehensive review of devices, converter topologies, and system-level practice. *International Journal of Engineering and Modern Technology*, 9(3), 287-312. <https://doi.org/10.56201/ijcsmt.v9.no3.2023.pg287.312>

Amayo, E. B. (2017). Multi algorithm of loss objective function of a single phase induction motor. *International Journal of Development Research*, 7(5), 12805-12810.

Oshevire, P., Eyenubo, O. J., & Amayo, B. (2017). Voltage control in the presence of distributed generation. *ATBU Journal of Science, Technology and Education*, 5(2), 165-173. Project Management and Governance for Multinational Infrastructure and Energy Projects

Seed literature: project governance and delivery risk in capital projects

Amayo, E. B., Owulade, O. A., & Isi, L. R. (2023a). Optimizing project governance in multinational infrastructure projects: Insights from General Electric's global operations. *International Journal of Multidisciplinary Research and Growth Evaluation*, 4(1), 975-983. <https://doi.org/10.54660/IJMRGE.2023.4.1.975-983>

Amayo, E. B., Owulade, O. A., & Isi, L. R. (2023b). Risk management strategies and compliance frameworks in healthcare infrastructure projects: Case studies from West Africa. *International Journal of Management and Organizational Research*, 2(1), 161-168. <https://doi.org/10.54660/IJMOR.2023.2.1.161-168>

Amayo, E. B., Owulade, O. A., & Isi, L. R. (2024a). Best practices for managing data center lifecycle projects: Ensuring security, efficiency, and compliance in U.S. enterprises. *Iconic Research and Engineering Journals*, 7(7), 598-617.

Amayo, E. B., Owulade, O. A., & Isi, L. R. (2024b). Effective project governance in multinational infrastructure projects: A case study from General Electric. *Iconic Research and Engineering Journals*, 8(5), 1305-1324.

Seed literature: predictive analytics and data-driven decision systems

Adelanwa, A., Basnet, A., & Anene, U. N. (2023a). Data driven digital transformation models for lifecycle performance management in infrastructure delivery. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2646-2662. <https://doi.org/10.62225/2583049X.2023.3.6.5968>

Adelanwa, A., Basnet, A., & Anene, U. N. (2023b). Predictive analytics models for financial risk detection and fraud prevention in public systems. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6). <https://doi.org/10.62225/2583049X.2023.3.6.5969>

Adelanwa, A., Basnet, A., & Anene, U. N. (2024). Performance intelligence models for optimization and outcome measurement in large scale public services. *Shodhshauryam, International Scientific Refereed Research Journal*, 6(1).

Anene, U. N., & Clement, T. (2022). A resilient logistics framework for humanitarian supply chains: Integrating predictive analytics, IoT, and localized distribution to strengthen emergency response systems. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8(5), 398-424.

Aifuwa, S. E., Oshoba, T. O., Ogbuefi, E., Ike, P. N., Nnabueze, S. B., & Olatunde-Thorpe, J. (2020). Predictive analytics models enhancing supply chain demand forecasting accuracy and reducing inventory management inefficiencies. *International Journal of*

- Multidisciplinary Research and Growth Evaluation*, 1(3), 171-181.
<https://doi.org/10.54660/IJMRGE.2020.1.3.171-181>
- Filani, O. M., Nnabueze, S. B., Ike, P. N., & Wedraogo, L. (2022). Real-time risk assessment dashboards using machine learning in hospital supply chain management systems. *International Journal of Multidisciplinary Evolutionary Research*, 3(1), 65-76.
<https://doi.org/10.54660/IJMER.2022.3.1.65-76>
- Okojie, J., Ike, P., Idu, J., Nnabueze, S. B., Filani, O., & Ihwughwawwe, S. (2023a). Predictive analytics models for monitoring smart city emissions and infrastructure risk in urban ESG planning. *International Journal of Multidisciplinary Futuristic Development*, 4(1), 45-57.
<https://doi.org/10.54660/IJMFD.2023.4.1.45-57>

Seed literature: lean operations, standard procedures, and process discipline

- Ambali, K. B., Eyetsemitan, R. A., Oyeleye, A. O., & Fadayomi, O. (2021). Lean Six Sigma for small enterprises: A systematic review and Lite-DMAIC adaptation framework for resource-constrained organizations. *Iconic Research and Engineering Journals*, 5(5), 562-583. <https://doi.org/10.64388/IREV5I5-1716957>
- Eyetsemitan, R. A., Ambali, K. B., Oyeleye, A. O., & Fadayomi, O. (2023a). Change management in small business digital transformation: A systematic review and lean change adoption framework. *Gyanshauryam, International Scientific Refereed Research Journal*, 6(6), 521-550. <https://doi.org/10.32628/GISRRJ236648>
- Eyetsemitan, R. A., Ambali, K. B., Oyeleye, A. O., & Fadayomi, O. (2023b). User acceptance testing in small business technology deployment: A structured validation framework for lean operational environments. *International Journal of Multidisciplinary Research and Growth Evaluation*, 4(6), 1512-1531. <https://doi.org/10.54660/IJMRGE.2023.4.6.1512-1531>
- Eyetsemitan, R. A., Oyeleye, A. O., Ambali, K. B., & Fadayomi, O. (2022). Standard operating procedures as strategic assets in small business operations: A systematic review and implementation framework. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(2), 438-465. <https://doi.org/10.32628/GISRRJ225356>

Seed literature: audit, risk governance, and compliance analytics

- Agu, M. U., Akomolafe, O., & Bello, A. (2023a). A comparative review of SOX compliance frameworks in cross-border financial auditing. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2297-2306.
<https://doi.org/10.62225/2583049X.2023.3.6.5362>
- Akomolafe, O., & Agu, M. U. (2018). A conceptual model for enhancing internal audit quality through technology-enabled risk assessment frameworks. *Iconic Research and Engineering Journals*, 1(9), 458-475.
- Akomolafe, O., & Agu, M. U. (2019a). A conceptual framework for developing risk-based internal control models in the insurance and banking sectors. *Iconic Research and Engineering Journals*, 2(8), 335-354.
- Akomolafe, O., & Agu, M. U. (2019c). Advances in financial resilience through integrated governance and compliance strategies. *Iconic Research and Engineering Journals*, 2(10), 607-620.
- Akomolafe, O., Agu, M. U., & Bello, A. (2023a). A conceptual model for implementing risk-based auditing in strategic financial management. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2274-2286.
<https://doi.org/10.62225/2583049X.2023.3.6.5359>

Akomolafe, O., Agu, M. U., & Bello, A. (2023b). A quantitative conceptual model for assessing compliance risk in emerging economies. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2287-2296. <https://doi.org/10.62225/2583049X.2023.3.6.5360>

Seed literature: data governance and information technology risk controls

Mbonu, I. S., Aliliele, C., Iwuanyanwu, U., & Oluoha, O. M. (2018). A conceptual framework for legal and ethical risk modeling in enterprise data protection governance systems. *Iconic Research and Engineering Journals*, 2(2), 207-226. <https://doi.org/10.64388/IREV212-1714911>

Mbonu, I. S., Aliliele, C., Iwuanyanwu, U., & Uzoka, E. (2022). A conceptual framework for AI enabled IT general controls and SOX audit automation processes. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(5), 384-414. <https://doi.org/10.32628/GISRRJ2256239>

Mbonu, I. S., Iwuanyanwu, U., Aliliele, C., & Uzoka, E. (2020a). A conceptual framework for agile supply chain digital transformation with embedded IT risk and ISO compliance controls. *Iconic Research and Engineering Journals*, 3(11), 566-593. <https://doi.org/10.64388/IREV3111-1714916>

Mbonu, I. S., Iwuanyanwu, U., Uzoka, E., & Oluoha, O. M. (2019). Advances in enterprise log analytics and automated incident response architectures using Python and SIEM platforms. *Iconic Research and Engineering Journals*, 3(2), 1000-1019. <https://doi.org/10.64388/IREV312-1714915>

Seed literature: human factors and security awareness in organisations

Onche, V. O., Ogbonna, C. S., & Adegbite, M. P. (2024). Effectiveness of cybersecurity awareness training on insider-threat behavior among university administrators: An integrative academic review. *International Journal of Computer Science and Mathematical Theory*, 10(2), 117-144. <https://doi.org/10.56201/ijcsmt.v10.no2.2024.pg117.144>

Seed literature: supply chain, materials readiness, and asset lifecycle management

Okonkwo, C. S., Agbabiaka, J., Ogunwole, O., Mayo, W., & Okeke, O. T. (2021). Conceptual model for materials readiness and maintenance-driven supply chain performance. *International Journal of Multidisciplinary Research and Growth Evaluation*, 2(6), 584-594. <https://doi.org/10.54660/IJMRGE.2021.2.6.584-594>

Okonkwo, C. S., Mayo, W., & Okeke, O. T. (2023). Conceptual model for asset lifecycle management and inventory visibility. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 10(1), 809-824. <https://doi.org/10.32628/CSEIT2391568>

Okonkwo, C. S., Agbabiaka, J., Mayo, W., & Okeke, O. T. (2024b). Framework for secure and scalable supply chain systems supporting national energy reliability. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 2816-2826. <https://doi.org/10.62225/2583049X.2024.4.6.5494>

Ike, P. N., Ogbuefi, E., Nnabueze, S. B., Olatunde-Thorpe, J., Aifuwa, S. E., Oshoba, T. O., & Akokodaripon, D. (2021). Supplier relationship management strategies fostering innovation, collaboration, and resilience in global supply chain ecosystems. *International Journal of Multidisciplinary Evolutionary Research*, 2(2), 52-62. <https://doi.org/10.54660/IJMER.2021.2.2.52-62>

Nnabueze, S. B., Ike, P. N., Olatunde-Thorpe, J., Aifuwa, S. E., Oshoba, T. O., Ogbuefi, E., & Akokodaripon, D. (2021). End-to-end visibility frameworks improving transparency,

- compliance, and traceability across complex global supply chain operations. *International Journal of Multidisciplinary Futuristic Development*, 2(2), 50-60. <https://doi.org/10.54660/IJMF.D.2021.2.2.50-60>
- Akin-Oluyomi, O. T., Atima, M. E., & Akinleye, O. K. (2023b). Regulatory compliance and supplier risk assessment frameworks in international pharmaceutical procurement. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2194-2204.
- Akin-Oluyomi, O. T., Okoruwa, P. O., Babatope, O. M., & Akokodaripon, D. A. (2023c). Evaluating supplier sustainability metrics through data-driven procurement and supply chain frameworks. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2213-2223.
- Efobi, O. Z., Akinleye, O. K., & Fasawe, O. (2023). Conceptual framework for developing a resilience index for post-pandemic supply chains. *Shodhshauryam, International Scientific Refereed Research Journal*, 6(2), 421-432.
- Okoruwa, P. O., Babatope, O. M., Akokodaripon, D. A., & Akinleye, O. K. (2024a). Developing integrated digital platforms for enhancing transparency in procurement and supply chain management. *International Journal of Multidisciplinary Research and Growth Evaluation*, 5(6), 1719-1729.
- Seed literature: wireless sensing, energy harvesting, and maintenance-free monitoring infrastructure**
- Asiedu, W., & Quainoo, R. (2023a). How far can energy harvesting take us? A systematic review of radio frequency strategies for energy autonomous sensing. *Shodhshauryam, International Scientific Refereed Research Journal*, 6(1), 448-466.
- Asiedu, W., & Quainoo, R. (2023b). Toward maintenance free wireless infrastructure: Simulating performance and reliability in large scale intermittently powered IoT networks. *Gyanshauryam, International Scientific Refereed Research Journal*, 6(1), 489-510.
- Asiedu, W., & Quainoo, R. (2024). Rethinking energy, reliability, and latency trade-offs in green communication for next generation IoT. *International Journal of Multidisciplinary Research and Growth Evaluation*, 5(6), 1987-1994.
- Quainoo, R., Ogundapo, O., & Asiedu, W. A. (2024). Modeling the impact of impedance mismatch on wireless link performance: A framework for prototype development and system optimization. *International Journal of Computer Science and Mathematical Theory*, 10(2), 62-116. <https://doi.org/10.56201/ijcsmt.v10.no2.2024.pg62.116>
- Seed literature: enterprise cyber defence, security validation, and incident response**
- Dosunmu, A. A., & Ogundele, P. O. (2019). Security audit and enterprise risk assessment frameworks for resilient information systems. *Iconic Research and Engineering Journals*, 3(5), 434-447. <https://doi.org/10.64388/IREV315-1713225>
- Dosunmu, A. A., & Ogundele, P. O. (2020). Intrusion detection and prevention models for enhancing organizational cyber defense effectiveness. *Iconic Research and Engineering Journals*, 4(6), 310-324. <https://doi.org/10.64388/IREV416-1713226>
- Dosunmu, A. A., & Ogundele, P. O. (2021). Incident response and digital forensics strategies for rapid cyber attack containment. *Gyanshauryam, International Scientific Refereed Research Journal*, 4(4), 239-258.
- Dosunmu, A. A., & Ogundele, P. O. (2022). Threat intelligence integration frameworks supporting proactive enterprise cybersecurity decision making. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(3), 397-416.

- Dosunmu, A. A., & Ogundele, P. O. (2024a). Breach and attack simulation frameworks for continuous validation of enterprise security controls. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 10(3), 1100-1119.
- Dosunmu, A. A., & Ogundele, P. O. (2024b). Cyber risk quantification models for prioritizing enterprise security investment decisions. *International Journal of Multidisciplinary Research and Growth Evaluation*, 5(6), 1777-1785. <https://doi.org/10.54660/IJMRGE.2024.5.6.1777-1785>
- Dosunmu, A. A., & Ogundele, P. O. (2024c). Enterprise scale continuous security validation models for regulated digital infrastructures. *International Journal of Scientific Research in Humanities and Social Sciences*, 1(2), 929-945.
- Dosunmu, A. A., & Ogundele, P. O. (2024d). Threat informed defence engineering models for measuring security control effectiveness at scale. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 2847-2858.

Seed literature: cybersecurity governance, IoT security, and network resilience

- Jimoh, H. O., & Ahmed, M. O. (2024). Analyzing Network Time Protocol (NTP) based amplification DDoS attack and its mitigation techniques. *Journal of Digital Innovations and Contemporary Research in Science, Engineering and Technology*, 12(2), 17-24. <https://doi.org/10.22624/AIMS/DIGITAL/V11N2P2x>
- Jimoh, H. O., Abolle-Okoyeagu, C. J., Ahmed, M. O., & Lawal, N. O. (2023a). Advancing security in IoT-driven critical infrastructure: A focus on smart transportation system. *American Journal of Engineering Research*, 12(12), 33-46.
- Jimoh, H. O., Ahmed, M. O., & Fagbade, M. O. (2023b). The role of frameworks in cybersecurity governance. *Journal of Behavioural Informatics, Digital Humanities and Development Research*, 9(4), 7-16. <https://doi.org/10.22624/AIMS/BHI/V9N4P2>
- Ogbole, J. I., Okoruwa, P. O., Fadayomi, O., Abolaji, T. O., Edivri, J., & Akeju, B. (2021). Conceptual model for identity-centric zero trust architecture in enterprise security governance. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 7(5), 393-415. <https://doi.org/10.32628/IJSRCSEIT217562>
- Okoruwa, P. O., Fadayomi, O., Abolaji, T. O., Edivri, J., Ogbole, J. I., & Akeju, B. (2024b). Enterprise cybersecurity trends and threat evolution, advances and emerging research directions. *Global Multidisciplinary Perspectives Journal*, 1(6), 194-204. <https://doi.org/10.54660/GMPJ.2024.1.6.194-204>
- Okoruwa, P. O., Fadayomi, O., Akeju, B., Edivri, J., Ogbole, J. I., & Abolaji, T. O. (2020). Conceptual model for privacy-centric security engineering in digital and cloud computing systems. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 7(5), 371-389.

Seed literature: enterprise service reliability, capacity planning, and operations management

- Ladapo, O. O., Dosunmu, A. A., Jooda, D., & Abolaji, T. O. (2023b). An IT service management literature review: Challenges, benefits, opportunities, and implementation practices. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2875-2889. <https://doi.org/10.62225/2583049X.2023.3.6.2875-2889>
- Ladapo, O. O., Dosunmu, A. A., Jooda, D., & Abolaji, T. O. (2024a). Integrated network and security operation center: A systematic analysis. *International Journal of Multidisciplinary Futuristic Development*, 5(1), 65-80. <https://doi.org/10.54660/IJMFD.2024.5.1.65-80>

- Ladapo, O. O., Jooda, D., Dosunmu, A. A., & Abolaji, T. O. (2022a). Navigating digital transformation: Best practices for cloud migration strategies in the enterprise. *Journal of Frontiers in Multidisciplinary Research*, 3(1), 643-655. <https://doi.org/10.54660/JFMR.2022.3.1.643-655>
- Ladapo, O. O., Jooda, D., Dosunmu, A. A., & Abolaji, T. O. (2023a). A comprehensive survey on ServiceNow for IT service management. *International Journal of Multidisciplinary Research and Growth Evaluation*, 4(6), 1532-1545. <https://doi.org/10.54660/IJMRGE.2023.4.6.1532-1545>
- Edivri, J., & Oteri, O. (2022). Predictive capacity planning and resource utilization forecasting models for multi-program and multi-stakeholder IT portfolios. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8(4), 826-845.
- Edivri, J., & Oteri, O. (2024). A conceptual KPI-driven decision and optimization framework for IT service delivery, portfolio performance, and adoption. *Gyanshauryam, International Scientific Refereed Research Journal*, 7(1), 167-187. <https://doi.org/10.32628/GISRRJ246643>
- Oteri, O., & Edivri, J. (2024). Applied performance optimization frameworks for managing high-demand enterprise technology programs and system rollouts. *Gyanshauryam, International Scientific Refereed Research Journal*, 7(1), 188-210.
- Seed literature: facility lifecycle, regulated design, and infrastructure asset performance**
- Aminu-Ibrahim, A. Y., & Ogbete, J. C. (2023). Healthcare infrastructure as a public health intervention using evidence from large laboratory networks. *Shodhshauryam, International Scientific Refereed Research Journal*, 6(1), 256-286. <https://doi.org/10.32628/SHISRRJ23678>
- Aminu-Ibrahim, A. Y., Ogbete, J. C., & Ambali, K. B. (2018). Developing sustainable diagnostic laboratory infrastructure models for emerging and resource constrained health systems. *Iconic Research and Engineering Journals*, 1(8), 118-132. <https://doi.org/10.64388/IREV1I8-1713586>
- Aminu-Ibrahim, A. Y., Ogbete, J. C., & Ambali, K. B. (2019). Capital project delivery models for high risk healthcare infrastructure in developing national health systems. *Iconic Research and Engineering Journals*, 2(10), 626-649. <https://doi.org/10.64388/IREV2I10-1713588>
- Aminu-Ibrahim, A. Y., Ogbete, J. C., & Ambali, K. B. (2024). Governance and accountability models for public private partnerships in healthcare infrastructure development. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 2943-2960. <https://doi.org/10.62225/2583049X.2024.4.6.5699>
- Ogbete, J. C., Aminu-Ibrahim, A. Y., & Ambali, K. B. (2018). Optimizing laboratory spatial planning strategies to improve diagnostic accuracy, safety, and clinical throughput. *Iconic Research and Engineering Journals*, 2(1), 87-113. <https://doi.org/10.64388/IREV1I7-1713587>
- Ogbete, J. C., Aminu-Ibrahim, A. Y., & Ambali, K. B. (2019). Regulatory compliant design systems for molecular and pathology laboratories in highly controlled environments. *Iconic Research and Engineering Journals*, 3(4), 607-631. <https://doi.org/10.64388/IREV3I4-1713589>
- Ogbete, J. C., Aminu-Ibrahim, A. Y., & Ambali, K. B. (2020). Sustainable materials selection and energy efficiency strategies for modern medical laboratory facilities. *International Journal*

of Multidisciplinary Research and Growth Evaluation, 1(5), 674-690.
<https://doi.org/10.54660/IJMRGE.2020.1.5.674-690>

Ogbete, J. C., Aminu-Ibrahim, A. Y., & Ambali, K. B. (2021). Risk managed construction strategies for complex and highly regulated healthcare facility developments. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 7(5), 362-392. <https://doi.org/10.32628/CSEIT217561>

Ogbete, J. C., Aminu-Ibrahim, A. Y., & Ambali, K. B. (2023). Lifecycle performance evaluation of purpose built diagnostic laboratories supporting long term healthcare delivery. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2605-2621. <https://doi.org/10.62225/2583049X.2023.3.6.5698>

Seed literature: ESG auditing, carbon governance, and sustainable procurement

Abioye, R. F., Okojie, J. S., Filani, O. M., Ike, P. N., Idu, J. O. O., Nnabueze, S. B., Okojokwu-Idu, J. O., & Ihwughwavwe, S. I. (2023). Automated ESG reporting in energy projects using blockchain-driven smart compliance management systems. *International Journal of Multidisciplinary Evolutionary Research*, 4(2), 120-129. <https://doi.org/10.54660/IJMER.2023.4.2.120-129>

Ike, P. N., Aifuwa, S. E., Nnabueze, S. B., Olatunde-Thorpe, J., Ogbuefi, E., Oshoba, T. O., & Akokodaripon, D. (2024a). Quantitative risk architecture for public-private partnerships: A multi-layered model for allocating public and private risk. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 2669-2682. <https://doi.org/10.62225/2583049X.2024.4.6.5021>

Ike, P. N., Aifuwa, S. E., Nnabueze, S. B., Olatunde-Thorpe, J., Ogbuefi, E., Oshoba, T. O., & Akokodaripon, D. (2024b). Utilizing nanomaterials in healthcare supply chain management for improved drug delivery systems. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(4), 1567-1572. <https://doi.org/10.62225/2583049X.2024.4.4.5154>

Ike, P. N., Ogbuefi, E., Nnabueze, S. B., Olatunde-Thorpe, J., Aifuwa, S. E., Oshoba, T. O., & Akokodaripon, D. (2022). Lean supply chain practices improving operational efficiency, reducing waste, and enhancing organizational competitiveness globally. *Journal of Frontiers in Multidisciplinary Research*, 3(2), 182-192. <https://doi.org/10.54660/IJFMR.2022.3.2.182-192>

Okojie, J. S., Filani, O. M., Ike, P. N., Okojokwu-Idu, J. O., Nnabueze, S. B., & Ihwughwavwe, S. I. (2023b). Integrating AI with ESG metrics in smart infrastructure auditing for high-impact urban development projects. *International Journal of Multidisciplinary Futuristic Development*, 4(1), 32-44. <https://doi.org/10.54660/IJMFD.2023.4.1.32-44>

Seed literature: strategic procurement, supplier risk, and supply chain resilience

Akin-Oluyomi, O. T., Atima, M. E., & Akinleye, O. K. (2023a). Green procurement strategies for balancing cost efficiency with long-term environmental responsibility. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2183-2193.

Akin-Oluyomi, O. T., Atima, M. E., & Akinleye, O. K. (2024). Cross-border supplier relationship management frameworks for pharmaceutical and global construction sectors. *International Journal of Multidisciplinary Research and Growth Evaluation*, 5(6), 1709-1718.

Akin-Oluyomi, O. T., Atima, M. E., Akinleye, O. K., & Akokodaripon, D. A. (2020). Using Tableau and Excel for comprehensive profitability analysis in retail procurement operations. *International Journal of Multidisciplinary Research and Growth Evaluation*, 1(5), 385-393.

- Akin-Oluyomi, O. T., Atima, M. E., Akinleye, O. K., & Okoruwa, P. O. (2023d). Predictive analytics approaches for improving demand forecasting accuracy in e-commerce procurement systems. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2173-2182.
- Akinleye, O. K., & Adeyoyin, O. (2021). Process automation framework for enhancing procurement efficiency and transparency. *Shodhshauryam, International Scientific Refereed Research Journal*, 4(4), 356-387.
- Akinleye, O. K., & Adeyoyin, O. (2022a). A negotiation optimization model for reducing procurement costs in manufacturing firms. *Shodhshauryam, International Scientific Refereed Research Journal*, 5(5), 398-435. <https://doi.org/10.32628/SHISRRJ225891>
- Akinleye, O. K., & Adeyoyin, O. (2022b). Supplier relationship management framework for achieving strategic procurement objectives. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(4), 565-598. <https://doi.org/10.32628/GISRRJ225430>
- Akinleye, O. K., Okoruwa, P. O., Babatope, O. M., & Akokodaripon, D. A. (2023). Leveraging big data and business intelligence for optimization of manufacturing sector procurement. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2164-2172.
- Babatope, O. M., Akokodaripon, D. A., Akinleye, O. K., & Okoruwa, P. O. (2023). The role of data visualization in enhancing strategic procurement decision-making effectiveness. *International Journal of Advanced Multidisciplinary Research and Studies*, 3(6), 2205-2212.
- Efobi, O. Z., Akinleye, O. K., & Fasawe, O. (2022a). Conceptual framework for sustainable procurement practices in local manufacturing enterprises in Africa. *Gyanshauryam, International Scientific Refereed Research Journal*, 5(6), 248-266.
- Efobi, O. Z., Akinleye, O. K., & Fasawe, O. (2022b). Conceptual model for data-driven lean supply chain optimization in manufacturing and retail operations. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8(2), 703-734. <https://doi.org/10.32628/CSEIT2541335>
- Okojie, J. S., & Abioye, R. F. (2020). Reconciling chemical safety with circular-economy targets: A decision framework for post-consumer recycled polymers in consumer-goods packaging balancing REACH compliance, lifecycle GHG footprint, and regulatory risk. *International Journal of Multidisciplinary Research and Growth Evaluation*, 1(5), 992-1006.
- Seed literature: anomaly detection, fraud analytics, and audit intelligence**
- Abetoh, N. F., & Atakpa, M. I. (2024). Audit analytics in healthcare financial oversight: Leveraging data science to strengthen accountability in multilateral grant ecosystems. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 10(6), 2710-2747. <https://doi.org/10.32628/CSEIT2410791>
- Atakpa, M. I. (2021). A review of predictive analytics models for anti-money laundering detection in commercial banking systems. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 7(2), 778-804. <https://doi.org/10.32628/CSEIT2064813>
- Atakpa, M. I., & Abetoh, N. F. (2022). A systematic review of machine learning advances in financial fraud detection for banking systems. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8(2), 771-801. <https://doi.org/10.32628/CSEIT23906220>

- Atakpa, M. I., & Abolaji, T. O. (2022). A privacy-preserving data architecture model for regulated industry analytics under GDPR and HIPAA compliance. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 8(3), 781-808. <https://doi.org/10.32628/CSEIT22558>
- Atakpa, M. I., & Fobellah, A. N. (2023). Anomaly detection in financial time-series data: A conceptual model for healthcare and banking applications. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 9(2), 967-997. <https://doi.org/10.32628/CSEIT2342441>
- Atakpa, M. I., Abetoh, N. F., & Akeju, B. (2024). Advances in artificial intelligence for healthcare payment fraud detection: A review of NHS applications. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 10(4), 1161-1194. <https://doi.org/10.32628/CSEIT26123240>
- Eboh, E. E., & Aliliele, C. (2023). Portfolio risk optimization models for venture capital investment strategy and fraud exposure analysis. *Iconic Research and Engineering Journals*, 7(4), 759-792. <https://doi.org/10.64388/IREV714-1715305>

Seed literature: regulatory science, quality assurance, and supply reliability

- Eze, F. I., Akinleye, O. K., & Anene, U. N. (2024a). Development of a cross-border regulatory harmonization model for African pharmaceutical markets: The ARCH-Model framework. *International Journal of Health and Pharmaceutical Research*, 9(5), 148-186. <https://doi.org/10.56201/ijhpr.v9.no5.2024.pg148.186>
- Eze, F. I., Akinleye, O. K., & Anene, U. N. (2024b). Development of a risk-based accelerated approval decision model balancing speed, safety, and evidence quality in pharmaceutical regulatory science. *Research Journal of Pure Science and Technology*, 7(6), 120-161. <https://doi.org/10.56201/rjpst.v7.no6.2024.pg120.161>
- Eze, F. I., Anene, U. N., & Akinleye, O. K. (2022a). Creation of a drug shortage early warning and regulatory response model for essential medicines in global health systems. *Research Journal of Pure Science and Technology*, 5(1), 57-95. <https://doi.org/10.56201/rjpst.v5.no1.2022.pg57.95>
- Eze, F. I., Anene, U. N., & Akinleye, O. K. (2022b). Design of an integrated regulatory readiness maturity model for pharmaceutical companies seeking global market entry. *International Journal of Health and Pharmaceutical Research*, 7(1), 77-112. <https://doi.org/10.56201/ijhpr.v7.no1.2022.pg77.112>
- Eze, F. I., Anene, U. N., & Akinleye, O. K. (2023). Pharmaceutical supply chain governance, environmental risk management, and sustainable access to essential medicines in emerging economies: The PSCG-ERM framework. *International Journal of Health and Pharmaceutical Research*, 8(4), 192-241. <https://doi.org/10.56201/ijhpr.v8.no4.2023.pg192.241>

Seed literature: technology law, algorithmic accountability, and compliance

- Annan, A. O. (2022). Data privacy governance models for cross-border digital platforms. *International Journal of Multidisciplinary Research and Growth Evaluation*, 3(6), 949-964.
- Annan, A. O. (2023). Intellectual property ownership and authorship in AI-generated works. *Gyanshauryam, International Scientific Refereed Research Journal*, 6(3), 425-450.
- Annan, A. O. (2024). Algorithmic accountability and trade secret protection in artificial intelligence. *Shodhshauryam, International Scientific Refereed Research Journal*, 7(5), 315-347.

Seed literature: energy transition, distributed generation, and socio-technical durability

- Komi, N. M. (2023). When accurate forecasts are not fair forecasts: Deep learning load prediction and equity across districts. *Shodhshauryam, International Scientific Refereed Research Journal*, 6(6), 476-546. <https://doi.org/10.32628/SHISRRJ247102>
- Komi, N. M. (2024). Turning social license into a measurable variable: Predicting community trust in renewable energy development. *International Journal of Engineering and Modern Technology*, 10(11), 239-296. <https://doi.org/10.56201/ijemt.v10.no11.2024.pg239.296>
- Komi, N. M., & Adamolekun, A. (2024). Quantifying a just transition: An econometric and skills-mapping analysis of worker displacement in the coal-to-renewable shift. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 10(3), 1242-1299. <https://doi.org/10.32628/CSEIT25113587>
- Komi, N. M., & Adeniji, I. O. (2020). Co-optimizing technical performance and community affordability in smart solar microgrids for underserved regions. *International Journal of Engineering and Modern Technology*, 6(3), 173-212. <https://doi.org/10.56201/ijemt.vol.6.no3.2020.pg173.212>
- Komi, N. M., & Adeniji, I. O. (2024a). No single instrument reaches the poor: A systematic review of financing mechanisms for inclusive renewable energy. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, 10(3), 1185-1241. <https://doi.org/10.32628/CSEIT25113586>

Seed literature: renewable fuels, photovoltaic materials, and degradation science

- Atta, S., Onyishi, E. E., Appiah, S. A., & Adenuga, O. M. (2024). Theoretical analysis of charge transport and recombination losses in thin film solar cell architectures. *International Journal of Engineering and Modern Technology*, 10(10), 147-170. <https://doi.org/10.56201/ijemt.v10.no10.2024.pg147.170>
- Bello, K. A., Azeez, T. M., Tawose, O. M., Odesanya, K. O., Odumosu, O. A., & Oyelaran, O. A. (2023). Investigating the influence of rubber seed oil and used cooking oil on diesel. *E3S Web of Conferences*, 430, Article 01217. <https://doi.org/10.1051/e3sconf/202343001217>

Seed literature: machine development, fabrication, and performance evaluation

- Bello, K. A., Adama, A., Tawose, O. M., & Bolaji, B. O. (2022a). Development and performance evaluation of a poultry bird de-feathering machine. *FUOYE Journal of Engineering and Technology*, 7(4). [DOI placeholder in source; verify.]
- Bello, K. A., Oyelaran, O. A., Tawose, O. M., Omoyi, C. O., & Yussouff, A. A. (2024). Development of a gum production machine from *Manihot esculenta* waste peels. *FUOYE Journal of Innovation Science and Technology*, 2(1). <https://www.jist.fuoye.edu.ng/index.php/jist/article/view/48>
- Bello, K. A., Tawose, O. M., Adama, A., & Bolaji, B. O. (2022b). Factor analysis of poultry birds de-feathering machines. *FUOYE Journal of Engineering and Technology*, 7(3). <https://doi.org/10.46792/fuoyejet.v7i3.829>

Seed literature: electrical machine optimisation and network deployment

- Amayo, E. B., & Popoola, T. T. (2017a). Multi algorithm of weight objective function of a single phase induction motor. *International Journal of Trend in Research and Development*, 4(2), 184-188.
- Amayo, E. B., & Popoola, T. T. (2017b). Scientific study of telecommunication deployment in achieving quality network. *International Journal of Trend in Research and Development*, 4(5), 311-314.

Amayo, E. B., Ubeku, E., & Oshevire, P. (2015). Multi algorithm of a single objective function of a single phase induction motor. *Journal of Multidisciplinary Engineering Science and Technology*, 2(12), 3400-3403.

Seed literature: autonomous robotics and automated material handling

Akanbi, O., & Sunday, E. A. (2024). An integrated path-planning and slotting optimization model for AMR-enabled high-density warehousing. *International Journal of Advanced Multidisciplinary Research and Studies*, 4(6), 3226-3243.
<https://doi.org/10.62225/2583049X.2024.4.6.6181>

Seed literature: applied information systems, automation, and human-in-the-loop learning

Ladapo, O. O., Dosunmu, A. A., Jooda, D., & Abolaji, T. O. (2022b). Human-in-the-loop machine learning: A state of the art. *Journal of Frontiers in Multidisciplinary Research*, 3(1), 656-669. <https://doi.org/10.54660/JFMR.2022.3.1.656-669>

Ladapo, O. O., Jooda, D., Dosunmu, A. A., & Abolaji, T. O. (2024b). Keeping humans in the loop: Human-centered automated annotation with generative AI. *International Journal of Multidisciplinary Futuristic Development*, 5(1), 81-95.
<https://doi.org/10.54660/IJMFD.2024.5.1.81-95>