International Journal of Multidisciplinary Research and Growth Evaluation.

Advances in Non-Intrusive Inspection of Pressure Vessels: Reducing Shutdown Frequency and OPEX in Oil and Gas Operations

Paul Chibuike Obetta [1*], Nwakamma Ninduwezuor-Ehiobu [2], Henry Chukwuemeka Olisakwe [3]
[1] STIS Nigeria Ltd for TotalEnergies, Nigeria
[2] FieldCore Canada, A GE Vernova company, Canada
[3] Department of Mechanical Engineering, Nnamdi Azikiwe University Awka, Anambra State, Nigeria

* Corresponding Author: **Paul Chibuike Obetta**

Article Info

ISSN (online): 2582-7138
Volume: 02
Issue: 06
November-December 2021
Received: 19-11-2021
Accepted: 21-12-2021
Page No: 1137-1153

Abstract
Pressure vessels in upstream, midstream and downstream oil and gas facilities have traditionally been assessed through periodic internal visual inspection (IVI), a practice that requires the vessel to be isolated, depressurised, drained, purged, cleaned, scaffolded and entered under confined space permit. The cumulative cost of this preparation, combined with the deferred production associated with the shutdown window, represents one of the largest recurring line items in fixed equipment operating expenditure. Non-intrusive inspection (NII), in which the internal condition of a vessel is characterised entirely from the external surface using non-destructive examination (NDE), offers a route to replace or defer IVI without compromising integrity.
This paper reviews the technical, procedural and economic advances in NII that consolidated around 2021, a period shaped by three converging pressures: the post-2020 collapse and partial recovery of hydrocarbon prices, the operational restrictions imposed by the COVID-19 pandemic on personnel mobilisation and confined space work, and the maturation of a dedicated recommended practice framework in the form of HOIS-RP-103 and its accompanying guidance notes. The review covers advances in ultrasonic corrosion mapping including full matrix capture and total focusing method reconstruction, pulsed eddy current profiling for corrosion under insulation, permanently installed thickness monitoring sensors, robotic and remotely operated deployment platforms, automated and digital radiography, and the analytics layer that converts dense NDE datasets into inspection decisions.
A cost model is developed that decomposes the operating expenditure differential between IVI and NII, and an illustrative worked example for a representative offshore separator is presented. The analysis indicates that the dominant economic driver is rarely the inspection itself but the vessel preparation and deferred production it avoids, and that NII becomes financially compelling well before it becomes technically trivial. The paper closes by identifying the residual barriers to wider adoption: inspection qualification and probability of detection evidence, cladded and internally lined vessels, jurisdictional acceptance, competence assurance and the organisational challenge of managing inspection data at a scale that manual workflows were never designed to handle.

DOI: https://doi.org/10.54660/.IJMRGE.2021.2.6.1137-1153

Keywords: non-intrusive inspection, pressure vessels, risk-based inspection, corrosion mapping, permanently installed sensors, turnaround optimisation, operating expenditure, asset integrity management, HOIS-RP-103, API 510

1. Introduction

1.1. The Problem of The Internal Inspection

A pressure vessel is a closed container designed to hold gases or liquids at a pressure substantially different from ambient. In oil and gas service these vessels include separators, scrubbers, knockout drums, contactors, absorbers, coalescers, filters, surge drums, reactors, columns and heat exchanger shells. Their failure mode of concern is loss of containment, and the consequence of that failure can extend from a minor process upset to a multiple fatality event with severe environmental and commercial consequences. Consequently, pressure vessels are subject to statutory and code driven periodic inspection in nearly every jurisdiction in which hydrocarbons are processed.

The historical mechanism for satisfying that obligation is the internal visual inspection. An inspector enters the vessel and, with supplementary surface flaw detection methods such as magnetic particle inspection and dye penetrant inspection, examines the internal surfaces for evidence of degradation. IVI is well understood, widely accepted by regulators, and carries the intuitive authority of direct human observation.

It is also expensive and hazardous. To enable entry, the vessel must be taken off line, isolated by positive means, depressurised, drained, steamed or nitrogen purged, gas tested, cleaned of scale, sludge and pyrophoric deposits, internally scaffolded where the geometry demands it, and entered under a confined space permit with rescue provision on standby. The management burden this class of maintenance work places on an operating organisation is well documented (Obogo *et al*., 2020c; Obogo *et al*., 2021b), and hazard identification and near-miss reporting practice in these environments has been examined in the same body of work (Obogo *et al*., 2019c). Internals such as demister pads, vane packs, cyclones, distributor trays and coalescing elements may need to be removed and reinstated. Each of these activities introduces its own hazard: line breaking, hydrocarbon release, hydrogen sulphide exposure, oxygen deficiency, work at height, manual handling and lifting operations. Vessel entry also carries a less obvious cost, in that the cleaning and mechanical disturbance associated with preparation can itself damage internal coatings, linings and cladding, and can occasionally leave the vessel in a worse condition than it was found.

Above all, IVI is a shutdown activity. Because it can generally only be performed with the vessel off line, it must be scheduled into a planned turnaround, and the inspection interval for the vessel therefore becomes a constraint on the turnaround interval for the entire process unit. A single vessel with a six-year inspection requirement can anchor an otherwise extendable turnaround cycle.

1.2. The Non-Intrusive Alternative

Non-intrusive inspection reverses the geometry of the problem. Rather than bringing the inspector to the internal surface, NII brings the examination to the external surface and infers internal condition through the wall. The core methods are ultrasonic, electromagnetic and radiographic, augmented in modern practice by permanently installed sensors and by robotic carriers that place conventional probes where humans cannot conveniently reach.

The benefits follow directly from the avoided activities. There is no vessel entry and therefore no confined space exposure, no rescue standby and no entry permit. There are fewer line breaks and consequently fewer opportunities for leaks. Preparation costs fall dramatically because the vessel does not need to be cleaned to inspection standard, and in many cases the inspection can be performed with the vessel fully on line and producing, which removes the deferred production penalty entirely. The inspection produces a dense, quantitative, digitally archived dataset rather than a qualitative narrative report, which supports trending, corrosion rate calculation and remaining life assessment in a way that photographs and written observations do not. Structured non-destructive testing programmes have been shown to serve as the evidential backbone of integrity management and corrosion risk assessment for refinery process equipment on exactly this basis (Atta *et al*., 2020).

These advantages are not free. NII substitutes a direct observation with an inference, and the validity of that inference depends on whether the chosen technique is capable of detecting and sizing the specific degradation mechanisms that the vessel is credibly subject to, at the locations where they would credibly occur, with sufficient coverage and sufficient reliability. Getting that judgement wrong does not produce an obviously bad inspection. It produces a clean report on a degraded vessel, which is the most dangerous outcome available in asset integrity management.

1.3. Why 2021

Three factors make the period around 2021 a coherent unit of analysis for this review.

First, the codes and recommended practices reached a settled state. The recommended practice that had begun life as DNV-RP-G103 in 2007, was updated in 2011 to address deferment of IVI as well as replacement, and was renamed DNVGL-RP-G103 following the DNV and GL merger, was superseded by the 2020 edition of HOIS-RP-103 issued by the HOIS joint industry project managed by ESR Technology. A companion set of guidance notes, HOIS-G-103, was published alongside it with support from the Oil and Gas Technology Centre. Both documents were released as freely available publications, which materially lowered the barrier to entry for smaller operators (British Institute of Non-Destructive Testing, 2020). 2021 was the first full year in which practitioners were applying this consolidated framework, and it was accompanied by supplementary HOIS guidance addressing specific hard cases such as clad vessels.

Second, the commercial environment forced the issue. The 2020 price collapse drove deep reductions in operating expenditure across the sector, and turnarounds, being large, discretionary looking and capital intensive, were among the first activities to be deferred. Operators that deferred a turnaround still needed a defensible basis for continued operation of the pressure equipment within it, and NII combined with risk-based inspection provided that basis. What had been an efficiency measure became, for many operators, a necessity.

Third, the pandemic changed the calculus of manned intervention. Restrictions on personnel movement, reduced offshore bed space, quarantine requirements and the general reluctance to place multiple workers in an enclosed steel vessel during a respiratory pandemic all raised the effective cost and lowered the practical availability of IVI. Technologies that had been positioned as incremental improvements, particularly remote and robotic deployment and permanently installed sensors that could be interrogated without a site visit, found themselves solving an urgent operational problem.

1.4. Scope and Objectives

This paper reviews the state of NII practice as it stood in 2021, with particular attention to the mechanisms by which NII reduces shutdown frequency and operating expenditure. The objectives are:

1. To summarise the code, standard and recommended

practice framework governing NII of pressure vessels as of 2021.
2. To review the principal NDE technologies applied in NII, their capabilities, their limitations and the specific advances that matured in the period under review.
3. To describe the integration of NII into risk-based inspection and integrity operating window frameworks.
4. To develop and apply a decomposed cost model for the operating expenditure differential between IVI and NII.
5. To identify the residual technical, organisational and regulatory barriers to adoption.

The paper does not address the design or fabrication of pressure vessels, in-line inspection of pipelines, storage tank floor inspection, or the inspection of pressure relieving devices, except where these intersect with vessel NII practice.

2. The Code and Recommended Practice Framework
2.1. The Inspection Code Layer
In refining and petrochemical service, the governing in-service code for pressure vessels in most of the world is API 510, the Pressure Vessel Inspection Code. Throughout 2021 the applicable edition was the tenth, issued in May 2014, incorporating Addendum 1 of May 2017 and Addendum 2 of March 2018. A revision expanding the treatment of the analysis of inspection results was in ballot through 2021, and its drafting activity reflects the direction of travel.
API 510 is significant for NII because it does not mandate internal visual inspection as such. It requires that the internal condition of the vessel be established, and it permits on-stream inspection as a substitute for internal inspection under defined conditions relating to the corrosion rate, the remaining life, the effectiveness of the on-stream methods for the anticipated damage mechanisms and, in some circumstances, the involvement of a corrosion specialist in the inspection plan. The code creates the space in which NII operates. What it does not do is tell the practitioner how to determine whether the on-stream methods are in fact effective for the damage mechanisms in question. That is the gap that the NII recommended practices fill.
In the United Kingdom continental shelf and in installations following European practice, the relevant statutory framework is provided by the Pressure Systems Safety Regulations and the associated written scheme of examination, with the competent person retaining the responsibility for determining the nature and interval of examination. This framework is outcome based rather than prescriptive, which in principle accommodates NII readily, but which in practice places the burden of justification squarely on the operator and the competent person.
It is worth noting a constraint that the recommended practices themselves acknowledge: national legislation in certain jurisdictions may preclude the substitution of non-intrusive methods for internal examination regardless of the technical justification. Operators working across multiple regulatory regimes cannot assume that a technically sound NII case is a legally sufficient one.

2.2. The NII Recommended Practice Layer
The lineage of the NII recommended practice runs from group sponsored project work in the late 1990s, through the first DNV published edition in 2007, a 2011 revision that extended the framework from replacement of IVI to include deferment, a 2017 reformatting as DNVGL-RP-G103, and the 2020 HOIS-RP-103 edition that superseded it. The decision to publish through HOIS rather than DNV reflected the maturation of HOIS as a recognised source of industry guidance, and returned the document to the joint industry project that had developed its technical content.
HOIS-RP-103 provides a structured process covering, in sequence:
- **Screening and suitability assessment:** Determining whether NII is an appropriate substitute for IVI on the vessel in question, taking account of the credible damage mechanisms, the vessel geometry, materials and construction, the accessibility of the external surface, and the consequence of failure.
- **Definition of performance requirements:** Establishing what the inspection must be capable of detecting and sizing, expressed in terms of flaw type, dimensions and location, derived from the degradation assessment and the fitness for service tolerance of the vessel.
- **Technique selection:** Matching NDE methods to the defined performance requirements, taking account of the capability and limitation data available for each method.
- **Coverage and sampling strategy:** Determining what proportion of the vessel surface must be examined and where, recognising that full coverage is rarely achievable and rarely necessary if the degradation is well localised and well understood.
- **Execution and quality control:** Procedural control, personnel qualification, equipment calibration and data integrity.
- **Evaluation:** Assessing whether the inspection as performed met the performance requirements, and if it did not, determining what follow up is required.

The framework is deliberately risk aware. It recognises that NII is most often applied precisely to equipment where the consequence of failure is severe, and it structures the process so that the residual risk of an inadequate inspection is managed explicitly rather than assumed away.
The recommended practice has two acknowledged boundaries relevant to this paper. It addresses technical considerations only and does not compare the relative costs of inspection options, and it does not address external degradation mechanisms, on the grounds that inspection for external damage is intrinsically non-intrusive already. The economic analysis in Section 6 of this paper therefore sits deliberately outside the recommended practice framework rather than within it.
The 2020 guidance notes HOIS-G-103 were developed to lower the barrier to correct application of the recommended practice, with worked examples and responses to common questions. Their publication is arguably as significant as the recommended practice itself: the most common failure mode in NII is not the absence of a framework but the misapplication of one.

2.3. The Supporting Standards
Several adjacent documents shape NII practice:

Table 1

Document	Role in NII
API RP 571	Catalogues damage mechanisms in refining equipment, providing the basis for the degradation assessment that drives technique selection
API RP 580 and API RP 581	Establish the qualitative and quantitative risk-based inspection frameworks within which NII intervals and coverage are justified
API 579-1 / ASME FFS-1	Provides the fitness for service assessment methods that convert measured wall loss and flaw dimensions into a run, repair or replace decision, and that define the flaw sizes the inspection must be capable of detecting
ASME PCC-3	Inspection planning using risk-based methods, widely used outside the API refining context
API RP 583	Addresses corrosion under insulation and fireproofing, the mechanism most often driving external NII scope on insulated vessels
API RP 584	Integrity operating windows, providing the process parameter envelope within which the assumed corrosion rates remain valid

The relationship between API 579-1 and NII deserves emphasis. Fitness for service assessment defines the critical flaw size, and the critical flaw size defines the detection requirement. An inspection specification written without reference to the fitness for service tolerance of the vessel is a specification written without a target. Weld quality and welding inspection standards form a parallel layer of assurance, since welds are simultaneously the most likely initiation sites for several damage mechanisms and among the hardest regions to examine reliably from the outside (Atta *et al*., 2021). The current edition of API 579-1 consolidates a decade of methodological development in local thin area assessment, crack-like flaw assessment and remaining life calculation, and in doing so gives NII practitioners a firmer basis for defining what constitutes an adequate inspection.

3. Methodology

This paper is a structured technical review rather than an experimental study. The evidence base comprises:

1. Primary standards and recommended practices current in 2021, principally HOIS-RP-103 and HOIS-G-103, API 510 tenth edition with addenda, API RP 580 and 581, API 579-1 / ASME FFS-1, ASME PCC-3 and the associated API recommended practice series.
2. Peer reviewed and conference literature to the end of 2021, with emphasis on material presented at AMPP and NACE CORROSION conferences, the ASME Pressure Vessels and Piping conference series, and BINDT and Energy Institute technical events.
3. Trade and practitioner literature, principally the Inspectioneering Journal and Materials Performance, which carries a disproportionate share of the applied case study material in this field because much of the underlying work is commercially sensitive and does not reach the academic literature.
4. Vendor technical documentation and published case studies, treated with appropriate caution given the obvious selection bias toward successful applications.
5. Adjacent engineering and management literature on predictive and reliability-centred maintenance, sensor-based condition monitoring, robotic and UAV inspection deployment, and occupational safety management in oil and gas maintenance environments. This body of work is drawn on for comparative context rather than for direct evidence on pressure vessel NII, on the reasoning that several of the organisational obstacles to NII adoption are not specific to pressure vessels and have been characterised more fully in these adjacent domains.

A structural limitation of the evidence base must be stated plainly. The most valuable evidence for the economic case, namely detailed cost comparisons on named assets, is almost universally commercially confidential. Published savings figures are therefore drawn from a self-selected and vendor-influenced sample, and headline percentages should be read as indicative of the direction and rough magnitude of the effect rather than as reliable central estimates. The cost model presented in Section 6 is offered as a framework into which an operator can insert its own verified figures, and the worked example is explicitly illustrative.

4. Technology Advances

4.1. Ultrasonic Corrosion Mapping

Ultrasonic thickness measurement is the workhorse of NII. A pulse is launched into the wall, reflects from the internal surface, and the transit time yields the remaining wall thickness. Repeated across a grid, the result is a corrosion map.

The advances that consolidated around 2021 were less about the physics, which is settled, than about acquisition density, positional accuracy and data handling.

Phased array and encoded scanning: Phased array ultrasonic testing (PAUT) uses a multi-element array with electronically controlled delay laws to sweep or focus the beam without mechanical movement. For corrosion mapping the practical benefit is coverage rate: a single encoded pass with a wide aperture array captures a swathe of thickness data at a resolution that would require an impractical number of single element spot readings. Encoded scanning, in which position is recorded synchronously with the A-scan data, converts a set of readings into a spatially registered map that can be overlaid on previous inspections to compute local corrosion rates rather than global averages. This distinction matters economically: a vessel condemned on a worst case global corrosion rate may be perfectly serviceable when the actual spatial distribution of wall loss is known.

Full matrix capture and the total focusing method: FMC acquisition records the response at every receiving element for every transmitting element, producing the complete transfer matrix of the array. TFM reconstruction then focuses synthetically at every point in the region of interest during post-processing. The result is improved resolution and improved characterisation of small or awkwardly oriented flaws, and the ability to reprocess archived data with different focusing assumptions without returning to site. By 2021 FMC/TFM had moved from research instrumentation into commercially supported field equipment, though acquisition times and data volumes remained a practical constraint on large area application.

High temperature capability: A recurring limitation of on-stream ultrasonic inspection is that conventional piezoelectric transducers and couplants degrade at elevated temperature. Developments in transducer materials, delay line design and dry coupling extended reliable on-stream inspection to higher operating temperatures, which in refining service is precisely where several important mechanisms, notably high temperature sulphidic corrosion, are active. Work reported in 2021 specifically addressed in-service detection and monitoring of sulphidic corrosion at temperature and at high resolution, an application that had previously been a significant gap in on-stream coverage (Stevenson, 2021).

Limitations: Ultrasonic methods require adequate external surface preparation and coupling, are degraded by heavy external corrosion, coatings, weld caps and geometric transitions, and struggle with clad or weld overlaid vessels where the bond line generates confusing reflections. Weld regions in particular warrant dedicated technique development, because the cap geometry and the metallurgical variation across the weld both degrade the ultrasonic response (Atta *et al*., 2021). Access to the full external surface is often obstructed by supports, nozzles, platforms, insulation and fireproofing, and the cost of gaining that access can approach the cost of vessel preparation for entry.

4.2. Pulsed Eddy Current

Pulsed eddy current (PEC) applies a step change in the field of a transmitting coil and measures the decay of the induced eddy currents in the wall. The decay characteristic is a function of the average wall thickness beneath the probe footprint. Crucially, PEC operates through insulation, weather cladding, fireproofing, marine growth and coatings without removal, and does not require surface contact or coupling.

PEC is therefore the principal screening tool for corrosion under insulation on vessels and associated pipework. CUI is a mechanism of first rank importance in oil and gas facilities: it develops out of sight, it is driven by water ingress and cyclic thermal operation, and it is frequently discovered only when insulation is stripped or when a leak occurs. The mechanism, its drivers and the inspection and mitigation options available against it have been reviewed comprehensively (De Landtsheer, 2020). Insulation removal for inspection is itself a major cost, and PEC allows that cost to be targeted rather than applied blanket. Screening also informs the mitigation side of CUI management, where coating selection, inhibitor chemistry and insulation design govern how rapidly the mechanism progresses once water ingress has occurred (Atta *et al*., 2018).

The 2021 advances were in resolution and interpretation. PEC returns an averaged thickness over a footprint that is a function of standoff distance, and its historical weakness has been the underestimation of small, deep, localised pitting whose signal is diluted across the averaging area. Improvements in array configuration, footprint reduction, standoff compensation and inversion algorithms narrowed this gap. Equally important was the maturation of interpretation practice: PEC is properly used as a screening tool that identifies areas for follow up by ultrasonic examination, and the integration of PEC screening with targeted UT confirmation became standard workflow rather than an innovation.

4.3. Permanently Installed Monitoring Sensors

The conceptual shift represented by permanently installed thickness monitoring is from inspection as an event to inspection as a data stream. A sensor is bonded, clamped or otherwise permanently fixed at a condition monitoring location and interrogated repeatedly, either by wireless telemetry or by a passive reader brought to the sensor.

The advantages are structural rather than incremental. Repeatability is transformed: a permanently installed sensor measures at precisely the same location with precisely the same geometry every time, eliminating the positional variance that dominates the uncertainty in manual spot thickness readings and that makes short interval corrosion rate determination unreliable. Measurement frequency increases by orders of magnitude at negligible marginal cost. Locations that are hazardous, elevated, insulated or otherwise expensive to access for manual reading become as cheap to monitor as convenient ones. And the resulting time series supports correlation of corrosion rate with process conditions, which converts corrosion management from a periodic audit into a controllable process variable. This is the same transition from reactive to predictive practice documented across mechanical plant more broadly (Sunday *et al*., 2020),.

The practical significance for maintenance planning was well articulated in the 2021 practitioner literature: manual thickness readings carry sufficient uncertainty that the resulting maintenance window spans years, forcing a choice between premature intervention with unnecessary lifecycle cost and deferred intervention with elevated leak risk. Higher precision monitoring narrows that window and converts the repair or replace decision from a judgement call into a data-driven one (*Inspectioneering Journal*, 2021).

Developments visible in 2021 included battery-free passive sensors interrogated by a handheld reader, which remove the battery replacement burden that had undermined earlier wireless deployments; thin film and flexible transducer materials capable of conforming to curved surfaces and tolerating both extreme and ambient conditions, extending permanent installation to geometries that rigid ceramic transducers could not accommodate (*Materials Performance*, 2021); ATEX and equivalent hazardous area certification enabling deployment in zoned areas without special provision; installation under insulation and at temperature, so that sensor placement does not itself require a shutdown; and wireless mesh integration allowing thickness data to reach the plant historian alongside process data.

Sensor deployment on midstream and pipeline assets accelerated in the same period in response to regulatory pressure for more diligent monitoring between scheduled in-line inspections, and the same technology base transferred readily to vessels (Strachan, 2021).

The limitation of permanently installed monitoring is coverage. A sensor measures a point. A vessel has a surface area measured in tens or hundreds of square metres. Permanently installed monitoring is therefore complementary to, not a substitute for, area coverage methods: it provides high confidence corrosion rate data at selected locations, which then informs the interval and scope of the area inspection. Where the damage mechanism is genuinely localised and its location is not predictable, point monitoring can give false reassurance. Sensor placement must follow from the degradation assessment, not from convenience of access.

4.4. Robotic and Remotely Operated Deployment

Robotic deployment does not usually change what is measured. It changes what it costs to measure it and who is exposed while measuring.

External magnetic crawlers: Wheeled or tracked platforms with magnetic adhesion climb the external shell of vessels, columns and reactors carrying ultrasonic, phased array, eddy current or visual payloads. The economic effect is the elimination of scaffolding and rope access for external corrosion mapping of tall or elevated equipment. Scaffolding is a substantial and frequently underestimated cost in offshore and refinery inspection campaigns, and it is a cost that scales with vessel height and congestion rather than with the amount of inspection actually performed.

Internal robotic inspection: Where internal access is necessary but human entry is not, compact crawlers can be introduced through manways to perform visual and ultrasonic examination of internal surfaces. This is not strictly non-intrusive, since the vessel must still be opened, but it removes confined space entry, reduces the required standard of cleaning and can shorten the critical path substantially. Comparative assessments have reported that robotic in-service inspection eliminates a long list of cost drivers associated with out of service inspection, including scaffolding, downtime, alternative tankage, surface preparation and blasting, cleaning and manpower hours, with reported cost reductions in the region of eighty percent for specific tank applications. Such figures are asset specific and should be treated as illustrative of the mechanism rather than as a general expectation.

Unmanned aerial systems: Drone based external visual inspection of flare stacks, column exteriors, vessel heads and structural steel matured through 2021, principally as a screening and documentation tool that identifies where contact NDE is needed. The economic benefit is again access cost avoidance. The trajectory of UAV inspection across energy infrastructure, from transmission line and pipeline corridor survey through to integration with enterprise geospatial asset records, illustrates both the access cost savings available and the regulatory and data management questions that follow adoption (Dagodzo, 2018b; Dagodzo & Ahiaeke Patrick, 2020; Dagodzo & Ahiaeke Patrick, 2021b).

Deployment in constrained conditions: The pandemic period accelerated interest in inspection modes that reduce the number of personnel required on site and the duration of their presence. Remotely operated deployment, combined with remote expert review of streamed data, allowed the specialist interpretation function to be performed away from the asset, which in offshore operations relieves bed space constraints that are frequently the binding limit on turnaround manning.

4.5. Long Range and Screening Methods

Guided wave testing propagates low frequency ultrasonic modes along the wall, allowing screening of extended lengths from a single transducer ring. Its principal application is pipework rather than vessels, but it is relevant to vessel NII in the inspection of associated nozzles, skirt penetrations and connected piping, and to the screening of the vessel shell for gross section loss.

Acoustic emission: monitors for the elastic waves emitted by active flaw growth during a controlled pressurisation. It provides global coverage and identifies active discontinuities, but it detects activity rather than geometry and requires follow up by other methods to characterise what has been found. It remains valuable as a first pass on vessels with poor inspection history where the objective is to identify where to look.

Automated and digital radiography: The transition from film to digital detectors transformed the economics of radiographic inspection. Digital detectors offer wider dynamic range, immediate image availability, no consumables or processing chemistry, and direct digital archiving. Crawler mounted digital radiography enables profile radiography of insulated components without insulation removal, screening for internal corrosion and CUI with the product still flowing. The remaining constraints are radiological: exclusion zones, source handling and licensing, and the operational disruption of establishing a controlled area in a live plant.

4.6. Data Analytics, Integration and The Digital Thread

The technologies described above share a common consequence: they generate volumes of data that manual workflows cannot absorb. A single encoded corrosion map may contain hundreds of thousands of thickness values. A permanently installed sensor network generates a continuous time series across dozens or hundreds of locations. The value of this data is realised only if it can be registered to a common asset model, trended against previous inspections and correlated with process conditions.

Developments in this layer through 2021 included integration of NDE data with asset integrity management systems and process historians, so that corrosion rate can be evaluated against the integrity operating window defined under API RP 584; automated defect detection and classification applied to corrosion maps and radiographic images, reducing analyst workload and improving consistency, though with the important caveat that automated classification requires validation against qualified human interpretation before it can be relied upon in a safety critical decision chain; and asset digital twins in which the geometric model of the vessel carries the inspection history spatially, so that a fitness for service assessment can be performed against the actual measured wall profile rather than a bounding minimum. The wider enterprise systems literature describes the same movement toward decision making built on integrated digital records rather than document sets (Mbonu *et al*., 2020b; Mbonu *et al*., 2021a), and equivalent data stream approaches have been applied to proactive hazard recognition and near-miss reporting in operational safety (Obogo *et al*., 2021a).

The analytics layer is where the OPEX benefit of NII is ultimately banked. Dense data acquired but not analysed produces the cost of NII without the benefit. Dense data properly analysed permits interval extension, targeted rather than blanket inspection scope, and confident deferral decisions, which is where the money is.

5. Integration with Risk-Based Inspection

5.1. The Logic of Substitution

NII does not exist independently of the inspection planning framework. Under API RP 580 and API RP 581, or under ASME PCC-3, the inspection plan for a pressure vessel is derived from the probability and consequence of failure, and the function of inspection within that framework is to reduce the uncertainty in the probability term. Inspection effectiveness, categorised in API RP 581 on a scale from highly effective to ineffective, quantifies how much uncertainty reduction a given inspection achieves.

The question that NII poses to the RBI framework is therefore not whether NII is as good as IVI in some absolute sense, but whether the proposed NII scope achieves an inspection effectiveness sufficient to hold the calculated risk below the operator's threshold over the proposed interval. Framed this way, several things become clear.

First, effectiveness is mechanism specific. An NII scope that is highly effective for general internal corrosion may be ineffective for localised pitting at a liquid interface, and vice versa. The degradation assessment therefore precedes and governs technique selection.

Second, effectiveness is not binary and neither is the outcome. NII may be sufficient to replace IVI, or it may be sufficient only to defer it, extending the interval to the next turnaround without removing the requirement permanently. The 2011 revision of the recommended practice explicitly addressed deferment as a distinct objective, and in practice deferment is the more commonly achieved and more readily justified outcome, particularly on first application to a given vessel.

Third, a partial NII scope combined with a reduced interval may deliver a lower cost and lower risk outcome than either full NII at extended interval or IVI at code interval. The optimisation is over the combination of method, coverage and interval, not over method alone. The same optimisation logic underlies the move from reactive to predictive maintenance in other asset classes, where the objective is to minimise downtime for a stated reliability target rather than to maximise inspection coverage for its own sake (Sunday *et al.*, 2020).

5.2. Coverage and Sampling

Complete coverage of a vessel's internal surface by NII is rarely achievable. Nozzle penetrations, support skirts, saddles, reinforcing pads, insulation supports, platforms and adjacent equipment all obstruct the external surface, and the cost of removing those obstructions can exceed the cost of the inspection.

The recommended practice framework handles this through targeted coverage informed by the degradation assessment. If the credible mechanism is aqueous corrosion at the water draw off, the inspection concentrates there. If the mechanism is CUI, the inspection concentrates at insulation penetrations, supports, damaged cladding and the locations where water ingress and retention are credible. If the mechanism is erosion at an inlet nozzle, the inspection concentrates on the impingement zone.

The risk in targeted coverage is obvious and must be stated: it assumes the degradation assessment is correct. A mechanism that was not anticipated will not be found where it was not looked for. This is the principal argument advanced by advocates of retaining periodic IVI, and it is not a weak argument. The mitigation is the discipline of the degradation assessment itself, informed by API RP 571, by the operating history of the vessel, by experience on analogous equipment, and by the integrity operating window that establishes whether the process conditions on which the assessment relies have actually been maintained.

5.3. Competence and Qualification

The inspection is only as good as the person performing and interpreting it. NII places substantially greater demands on personnel competence than IVI does, because the inspector is not observing a condition but inferring one through a physical measurement chain with its own error modes.

Two distinct competences are involved. The first is the NDE technician competence to acquire valid data, certified through schemes such as PCN, ASNT or ISO 9712. The second, and the more frequently deficient, is the integrity engineering competence to specify what the inspection must achieve, to select techniques against that specification, and to evaluate whether the inspection as executed met it. The HOIS guidance notes were developed in explicit recognition that the second competence is the limiting factor in many organisations.

A related requirement is inspection qualification: documented evidence, ideally from trials on representative specimens with representative flaws, that the proposed technique and procedure will detect and size the defects of concern with the required reliability. HOIS trial programmes have provided a substantial part of the publicly available capability data in this field, particularly for the harder cases such as inspection through cladding. Where qualification evidence does not exist for a given combination of technique, geometry and defect type, the honest conclusion is that the effectiveness of the inspection is unknown, and an unknown effectiveness cannot support a risk-based interval extension.

6. Economic Analysis

6.1. Decomposing the Cost

The operating expenditure associated with establishing the internal condition of a pressure vessel can be decomposed into four categories.

Direct inspection cost (C_{insp}): personnel, equipment mobilisation, consumables and reporting for the examination itself.

Preparation and reinstatement cost (C_{prep}): isolation, depressurisation, draining, purging, gas testing, cleaning, waste handling and disposal, internals removal and reinstatement, scaffolding erection and dismantling, insulation removal and replacement, permit administration, standby and rescue provision, and post-inspection reinstatement and leak testing.

Deferred production (C_{prod}): the margin foregone on production not achieved during the shutdown window attributable to the inspection, which is nonzero only where the inspection extends the shutdown duration or forces a shutdown that would not otherwise occur.

Risk cost (C_{risk}): the expected cost of the incremental safety, environmental and integrity risk associated with the inspection approach, including both the hazards introduced by the activity itself and the residual risk of undetected degradation.

The total cost of an inspection strategy over a planning horizon is then:

$$C_{total} = \Sigma_{i=1}^{n} [(C_{insp,i} + C_{prep,i} + C_{prod,i} + C_{risk,i}) \div (1 + r)^{t_i}]$$

where n is the number of inspection events in the horizon, t_i is the year of event i and r is the discount rate. The number of events is determined by the interval, which is itself a function of the inspection effectiveness and the calculated risk.

6.2. Where the Money Actually Is

The structure of this decomposition explains a result that is initially counterintuitive to those new to the field: NII is frequently more expensive than IVI on the C_{insp} term alone. Advanced ultrasonic corrosion mapping across a large vessel surface, performed by qualified technicians with encoded scanning and full data analysis, is not a cheap activity. A visual inspection by a single inspector with a torch and a notebook is.

The economics turn entirely on C_{prep} and C_{prod}. Vessel preparation for entry routinely exceeds the cost of the entry inspection by a large multiple, and where the inspection is on the turnaround critical path, C_{prod} can exceed everything else combined. On a high throughput facility, deferred production during a shutdown is typically measured in hundreds of thousands of currency units per day, against inspection costs measured in thousands.

The practical implication is that the business case for NII is strongest where preparation is hardest and production loss is greatest: large vessels, heavily contaminated services, vessels with extensive internals, offshore installations where logistics and bed space compound every cost, and vessels that sit on the critical path of a unit turnaround. It is weakest on small, clean, easily prepared vessels in units that shut down frequently for other reasons.

A second implication is that NII delivers its greatest value not by making an individual inspection cheaper but by changing the shutdown schedule. If a single vessel with a six-year internal inspection requirement is the sole constraint anchoring a turnaround cycle, and NII permits that requirement to be satisfied on line, the avoided cost is not the preparation of one vessel. It is the deferral or elimination of an entire turnaround, or at minimum the removal of a critical path item from it. Realising that benefit depends on readiness elsewhere in the organisation, since an inspection finding that cannot be actioned within the window converts a planned shutdown into an extended one (Okonkwo *et al.*, 2018b; Okonkwo *et al.*, 2021a).

6.3. Illustrative Worked Example

The following example is constructed to demonstrate the structure of the calculation. The figures are representative order of magnitude values for an offshore separator and are not drawn from a specific asset. Any operator applying this framework should substitute verified internal cost data.

Asset: three phase production separator, offshore fixed platform, 3.5 m diameter, 12 m tangent to tangent, carbon steel, internally coated, containing inlet device, coalescing plates and demister pack. Credible damage mechanisms: aqueous CO2 corrosion at the water phase and interface, under deposit corrosion in the water boot, erosion at the inlet, and CUI beneath insulation at supports and penetrations.

Baseline strategy: IVI at six-year intervals during unit turnaround.

Proposed strategy: NII by external ultrasonic corrosion mapping of the lower shell, water boot and interface band, PEC screening for CUI at insulation penetrations and supports, permanently installed thickness sensors at eight condition monitoring locations, with IVI deferred to twelve years.

Table 2

Cost element	IVI (per event)	NII (per event)
Isolation, depressurisation, purge, gas test	45,000	0
Cleaning, sludge removal, waste handling	120,000	0
Internals removal and reinstatement	85,000	0
Scaffolding, internal and external	60,000	25,000
Insulation removal and replacement	40,000	8,000
Confined space provision, permits, standby, rescue	35,000	0
Inspection execution and reporting	25,000	95,000
Reinstatement, leak test, recommissioning	30,000	5,000
Subtotal, direct and preparation	440,000	133,000
Deferred production (4 critical path days at 600,000 per day)	2,400,000	0
Total per event	2,840,000	133,000

Over a twelve-year horizon, the baseline strategy incurs two IVI events. The NII strategy incurs, say, four NII campaigns at three-year intervals plus a single IVI at year twelve, together with a one off sensor installation cost of 60,000 and annual monitoring and data management costs of 15,000.

Undiscounted totals over twelve years:

- **Baseline:** 2 × 2,840,000 = 5,680,000
- **NII strategy:** (4 × 133,000) + 2,840,000 + 60,000 + (12 × 15,000) = 3,612,000

The indicated saving is approximately 2,068,000 over twelve years, or roughly 36 percent. Note that almost the entire saving derives from the single avoided critical path shutdown, and that the NII inspection execution cost is nearly four times the IVI execution cost. Note also that the calculation is highly sensitive to two assumptions: whether the vessel is genuinely on the turnaround critical path, and whether the deferral to twelve years is technically justifiable. Remove either assumption and the case changes materially. If the vessel is not on the critical path, C_{prod} falls to zero and the saving reduces to approximately 614,000, still positive but no longer transformative. If deferral cannot be justified beyond nine years, the horizon calculation must be redone.

This sensitivity is the central practical message of the economic analysis. The NII business case is not a property of the technology. It is a property of the specific asset, its position in the shutdown schedule, and the defensibility of the interval extension.

6.4. Costs and Risks Not in The Table

Several items resist quantification but belong in the decision.

Safety exposure: Confined space entry is among the highest consequence routine activities in process plant operation. Eliminating an entry eliminates a set of low probability, high consequence exposures. Whether this is valued explicitly or treated as a constraint, it is real. Incident prevention research in industrial maintenance environments consistently identifies entry, isolation and line breaking as the activities that generate disproportionate exposure (Obogo *et al*., 2020c).

Preparation damage: Cleaning, blasting and mechanical disturbance during preparation can damage internal coatings and linings, creating a maintenance liability that would not otherwise exist.

Emissions and waste: Purging, venting and cleaning generate fugitive emissions and hazardous waste streams. As emissions accounting tightened through the period under review, this became a more visible cost. Work on end-to-end visibility in supplier networks describes the reporting infrastructure through which environmental terms of this kind become disclosable rather than merely incurred (Nnabueze *et al*., 2021).

The cost of being wrong: An NII programme that misses an active degradation mechanism results in continued operation of a vessel in a condition the operator believes it is not in. The expected cost of this outcome is the product of a low probability and a very high consequence, and it is not adequately captured by treating NII as simply a cheaper inspection. This term is the reason the recommended practice framework exists, and it is the reason that the appropriate response to marginal or ambiguous NII results is escalation rather than acceptance.

7. Barriers and Limitations

7.1. Clad and Internally Lined Vessels

Vessels with corrosion resistant cladding, weld overlay or internal linings present the hardest technical case for NII. The acoustic impedance mismatch at the bond line generates reflections that complicate thickness interpretation, disbonding may be present, and the degradation of interest may be in the clad layer, at the bond, or in the substrate beneath. HOIS issued dedicated guidance on NII of clad vessels in 2020 precisely because the general framework was insufficient for this class. Techniques showing potential in trials for inspection through clad layers were identified, but clad vessel NII in 2021 remained a specialist application requiring case by case qualification rather than a routine capability.

7.2. Access and Obstruction

The assumption underlying all NII is that the external surface is accessible. In practice a substantial fraction of the external surface of an installed vessel is not: supports, skirts, saddles, reinforcement pads, nozzle transitions, platform steelwork, cable trays, adjacent equipment and, on offshore installations, extreme congestion. Removing insulation and fireproofing to gain access is itself a significant cost, and in the case of fireproofing may require reinstatement to a certified standard. Robotic and remote deployment addresses the height and reach problem but not the obstruction problem.

7.3. Qualification Evidence and Probability of Detection

The credibility of a risk-based interval extension depends on the claimed inspection effectiveness, and the claim depends on evidence. For well characterised combinations of technique, geometry and defect type, that evidence exists. For the long tail of unusual geometries, unusual materials, unusual defect morphologies and marginal access conditions, it frequently does not. The honest treatment of that situation is to treat the effectiveness as unknown, which usually means a shorter interval or a supplementary method. The commercially convenient treatment is to assume effectiveness by analogy. The gap between these two responses is where NII programmes fail.

7.4. Regulatory and Jurisdictional Acceptance

Acceptance of NII varies substantially by jurisdiction, by regulator and by insurer. Some regimes accommodate it readily within an outcome-based framework. Others retain prescriptive internal examination requirements that no amount of technical justification will displace. The recommended practices explicitly disclaim any statement on legislative requirements and place responsibility for legal compliance on the user. Operators with multinational portfolios face the resulting inconsistency as an ongoing planning problem.

7.5. Organisational and Cultural Factors

Adoption requires an inspection organisation to accept that a number derived from a wave transit time is a more reliable statement about internal condition than a photograph of that condition. This is a genuine cultural shift, and resistance to it is not irrational: it reflects an accurate intuition that the inference chain in NII has more failure modes than direct observation does. The appropriate response is not exhortation but demonstration, typically through parallel application of NII and IVI on the same vessel during a planned turnaround, which builds the local evidence base and calibrates confidence.

A second organisational barrier is data. NII generates data at volumes that overwhelm inspection management systems designed around narrative reports and spot readings. Operators that adopted NII without correspondingly upgrading their data management found themselves paying for dense data they could not use.

7.6. The Limits of The Economic Case

Finally, NII is not universally economic. On small, clean, easily prepared vessels in units that shut down frequently for process reasons, the preparation and production terms that drive the NII business case are small, and the higher execution cost of NII may not be recovered. Blanket NII policies are as inappropriate as blanket IVI policies. The correct unit of decision is the individual vessel within its unit shutdown context.

8. Cross-Sector Evidence and the Wider Literature Base

The preceding sections drew on the pressure vessel inspection literature directly. That literature is comparatively small, heavily practitioner oriented, and constrained by the commercial sensitivity of the underlying data. Several of the questions that determine whether an NII programme succeeds are not, however, specific to pressure vessels. How an organisation manages hazardous maintenance work, how it powers and secures distributed instrumentation, how it governs the data those instruments produce, how it sequences a shutdown against materials availability, and how a regulator decides that a novel assurance method is acceptable are all questions that have been examined more fully in adjacent engineering and management domains.

This section surveys that adjacent evidence. Two cautions apply throughout. The first is that analogical evidence is weaker than direct evidence, and nothing in this section should be read as establishing the effectiveness of any NII technique. The second is that the transferability of a finding depends on whether the underlying mechanism is shared, and the paragraphs below attempt to state the shared mechanism rather than to assert similarity by category alone.

8.1. Inspection Within the Wider Safety Management System

The safety case for NII rests on the elimination of confined space entry and the associated line breaking, isolation and cleaning activities. That case is only as strong as the operator's understanding of where its exposure actually lies. A substantial literature on occupational safety management in construction, maintenance and industrial project environments addresses exactly this question, covering hazard identification and near-miss reporting practice, contractor and subcontractor safety governance across multi-contract sites, human error causation in high hazard activity, behavioural safety programmes, safety leadership and culture in temporary project organisations, and the design of incident investigation systems that produce prevention-oriented learning rather than attribution, and risk-managed delivery of complex projects in highly regulated facility environments (Arumosoye & Obriki, 2018, 2019, 2020, 2021; Obogo *et al*., 2019a, 2019b, 2019c, 2020a, 2020b, 2021c; Obriki & Arumosoye, 2018, 2019, 2020, 2021; Ogbete *et al*., 2021).

Three findings from that body of work bear directly on NII. First, the activities that generate disproportionate exposure in maintenance environments are consistently the preparatory ones, isolation, entry, and work at height, rather than the technical task itself, which is precisely the exposure NII removes. Second, exposure reduction achieved by eliminating an activity is more durable than exposure reduction achieved by managing it, because the latter depends on sustained procedural compliance across a rotating contractor workforce. Third, safety performance in project organisations is dominated by organisational rather than technical variables, which suggests that the organisational barriers to NII adoption identified in Section 7 are likely to be more binding than the technical ones.

Process improvement research in operations management reinforces the same point from a different direction, in that the recurring obstacle to adopting a demonstrably better method is rarely the method itself but the change management, stakeholder alignment and acceptance testing that surround it (Ambali *et al*., 2021; Eyetsemitan *et al*., 2020, 2021).

8.2. Condition-Based Maintenance in Adjacent Mechanical and Building Systems

Section 4.3 identified permanently installed monitoring as the most structurally significant of the technology developments reviewed. The wider engineering literature on mechanical and building services plant reached the equivalent conclusion earlier, because those systems carry cheap, easily retrofitted instrumentation and therefore encountered the practical consequences of continuous condition data before heavy process equipment did. That literature covers the transition from reactive to predictive maintenance practice, sensor-based fault detection, and the control and efficiency strategies that continuous measurement makes possible (Sunday & Omoegun, 2018, 2019; Sunday *et al*., 2019).

Three transferable observations follow. The first is that the value of continuous data is realised through the change in maintenance decision rules, not through the measurement itself, and organisations that install instrumentation without revising those rules capture little of the available benefit. The second is that measurement repeatability, rather than measurement accuracy, is what makes short-interval trending possible, which is precisely the argument advanced for permanently installed thickness sensors over manual spot readings. The third is that instrumentation reliability over a multi-year service life, and not initial accuracy, determines whether a monitoring programme survives its first budget review.

8.3. Data Governance, Security and Assurance of Inspection Information

Dense inspection data creates two obligations that periodic manual inspection did not. The first is data management at a volume and cadence that document-based systems cannot absorb, discussed in Section 4.6. The second is security. A permanently installed sensor network that reports wall thickness into a plant historian is an operational technology asset, and it inherits the threat model of that domain.

The operational technology and industrial control system security literature addresses the architecture of that problem, covering the securing of OT networks in regulated utility environments, IT and OT convergence and its governance implications, anomaly detection and threat detection architectures for industrial control systems, adversarial machine learning against AI-enabled OT systems, network resilience for critical infrastructure, and the human factors that determine whether technical controls survive contact with an operating workforce (Adegbite *et al*., 2020; Ahmed *et al*., 2021). Complementary work on data governance, IT risk and cybersecurity frameworks address the assurance layer, including the role of governance frameworks in translating technical controls into auditable practice (Dosunmu & Ogundele, 2019, 2020, 2021; Mbonu *et al*., 2018, 2019a, 2019b, 2020a, 2020b, 2020c, 2021a, 2021b, 2021c).

Two consequences follow for NII. The first is that inspection data used to justify continued operation of a high consequence asset is safety-relevant data, and its integrity and provenance must be assured to a standard commensurate with that use. Undetected corruption or manipulation of thickness data would produce exactly the failure mode identified in Section 1.2, a clean record on a degraded vessel. The second is that the enterprise systems carrying that data, including asset management platforms, historians and the service delivery arrangements around them, become part of the integrity management system rather than adjacent to it (Badmus *et al*., 2020; Ladapo *et al*., 2018, 2019; Ogbole *et al*., 2021; Okoruwa *et al*., 2020).

8.4. Remote, Robotic and Airborne Deployment Across Infrastructure Classes

Section 4.4 argued that robotic and airborne deployment changes the cost and the exposure of an inspection rather than its physics. The clearest evidence for that proposition comes from infrastructure classes where remote deployment matured earlier than it did on pressure vessels, principally power transmission corridors, pipelines and rights of way. The relevant literature covers UAV integration into national grid inspection programmes, corridor and encroachment monitoring using geospatial technologies, the integration of UAV, LiDAR and GIS data into enterprise asset records, AI-based classification applied to corridor imagery, regulatory frameworks for UAV operation in developing economies, and autonomous mobile robot coordination and path planning in structured environments (Dagodzo, 2018a; Dagodzo & Ahiaeke Patrick, 2021a).

The transferable findings concern the surrounding system rather than the platform. Access cost avoidance is realised only when the captured data is registered into the asset record rather than delivered as a standalone survey report. Regulatory acceptance of the deployment method is frequently the pacing constraint rather than the capability of the platform. And the operational value of remote deployment rises sharply where the alternative access method is expensive or hazardous, which is the same condition that determines where NII is economic on vessels.

8.5. Analytics, Prediction and Decision Support

The analytics layer described in Section 4.6 converts inspection data into inspection decisions. The wider predictive analytics literature addresses the general form of that conversion, including data-driven decision support and performance intelligence models, forecasting applied to operational and financial series, and the design of predictive systems intended to inform rather than replace expert judgement (Basnet *et al*., 2021; Tonoyan *et al*., 2021a, 2021b).

A parallel literature on financial analytics, enterprise decision systems, internal audit and risk governance addresses the evaluation and assurance side of the same problem: how an organisation quantifies the value of a deferral decision, how it maintains an auditable basis for that decision, and how internal control functions verify that the models informing operational spending are used within their validated envelope (Akomolafe & Agu, 2018, 2019a, 2019b, 2019c; Atakpa, 2021; Dogbatsey & Ebhojie, 2018; Dogbatsey *et al*., 2019, 2021; Lawal & Oduleye, 2018a, 2018b, 2019a, 2019b, 2021a, 2021b). This is directly relevant to the economic analysis in Section 6, since an NII-based deferral is an expenditure decision justified by a technical model, and the governance of such decisions determines whether the saving is real or merely deferred cost.

8.6. Turnaround Readiness: Procurement and Materials Supply

Section 6.2 argued that the dominant economic benefit of NII is the removal of inspection-driven constraints on the shutdown schedule. That benefit is contingent on the rest of the turnaround system being able to absorb the change. Procurement and supply chain research in energy and infrastructure settings addresses this contingency, covering materials readiness and maintenance-driven supply chain performance, predictive procurement planning to sustain operational uptime, inventory availability and plant uptime, supply chain risk and resilience for EPC and gas processing projects, regulatory-compliant procurement in high risk energy environments, supplier evaluation and contract governance, and digital supply chain models directed at cost control and operational continuity (Agbabiaka *et al*., 2019; Ahiaeke Patrick *et al*., 2020, 2021; Akin-Oluyomi *et al*., 2020; Akinleye & Adeyoyin, 2021; Efobi *et al*., 2021; Ogunwole *et al*., 2021; Okojie & Abioye, 2020; Okonkwo *et al*., 2018a, 2019, 2020, 2021b).

Work on sustainable procurement and ESG auditing extends the same analysis to the environmental and disclosure dimension, including carbon-aware decision gates in project delivery, real-time risk assessment in supplier networks, and the maturity models used to structure net-zero delivery commitments (Aifuwa *et al*., 2020; Ike *et al*., 2021; Nnabueze *et al*., 2021; Yeboah & Ike, 2020). This connects to the emissions and waste terms identified in Section 6.4, which are increasingly reported rather than merely incurred.

8.7. Regulatory Oversight and Cross-Sector Compliance Analogies

Section 7.4 identified jurisdictional acceptance as a persistent constraint on NII. Other safety-critical sectors have worked through structurally similar problems, in which a regulator must decide whether an alternative assurance method provides equivalent confidence to an established one.

Aviation safety oversight offers the closest analogy, in that it combines prescriptive certification requirements with performance-based safety management obligations, and has developed predictive compliance monitoring, adaptive safety management system implementation models, regulatory evidence frameworks for assessing violations, and risk-based approaches to hazards around operating environments (Adeyelu, 2018, 2019, 2020, 2021). The pharmaceutical regulatory literature contributes the concept of a risk-based accelerated approval pathway and cross-border regulatory harmonisation, both of which describe how a regulator accommodates a novel method without abandoning the evidentiary standard. Technology law and AI governance work addresses the question, directly relevant to the automated defect classification discussed in Section 4.6, of how accountability is allocated when a decision is informed by an algorithmic system.

The transferable principle is that regulators accept alternative methods when the applicant can demonstrate equivalence against a stated evidentiary standard, and that the burden of constructing that demonstration falls on the operator rather than the regulator. This is the same conclusion reached in Section 5.3 from the inspection qualification literature.

8.8. Energy Transition Context and The Changing Value of Avoided Downtime

Finally, the economic value of avoided downtime is not constant. It is a function of the margin on the production foregone, which is in turn a function of the energy market in which the asset operates. Research on energy transition, renewable forecasting and the social and distributional dimensions of energy systems describes the direction in which that market is moving, including grid architectures for high renewable penetration, forecasting under uncertainty and its market consequences, and the treatment of community and workforce effects as measurable variables rather than externalities (Amayo, 2017; Amayo & Popoola, 2017a, 2017b; Amayo *et al*., 2015; Komi, 2021; Komi & Adamolekun, 2021; Komi & Adeniji, 2020; Oshevire *et al*., 2017).

Two implications bear on the argument of this paper. The first is that assets facing an uncertain remaining commercial life are poor candidates for capital-intensive monitoring installations but strong candidates for deferral-oriented NII, since the objective becomes safe operation to a defined end date rather than indefinite optimisation. The second is that environmental performance is becoming a reported rather than an incidental output of inspection strategy, which strengthens the non-financial terms identified in Section 6.4. Work on produced water management and other environmental engineering functions in energy operations illustrates how lifecycle environmental risk assessment is being integrated into operating decisions that were previously treated as purely technical.

9. Discussion

The picture that emerges from the 2021 evidence is of a field that had substantially resolved its framework problem and was working through its evidence and execution problems.

The framework problem was the absence, for many years, of an agreed and structured process for deciding when NII is appropriate and how it should be specified. The consolidation of two decades of joint industry project work into HOIS-RP-103 and its guidance notes, published as freely available documents, resolved this. A practitioner in 2021 had access to a coherent process where a practitioner in 2001 had access to a collection of vendor claims and local precedent.

The evidence problem is more stubborn. Risk-based interval extension requires quantified inspection effectiveness, quantified effectiveness requires probability of detection data, and probability of detection data requires trials on representative specimens with representative flaws. Such trials are expensive and their results are commercially valuable. The joint industry project model, in which competing operators and service providers jointly fund and share trial results, is the mechanism the industry has found for producing this evidence, and its coverage in 2021 remained partial. The hard cases, clad vessels prominently among them, were precisely the cases where evidence was thinnest.

The execution problem is organisational. The technologies work. The framework exists. What frequently does not exist is an integrity engineering function with the competence and the authority to specify an NII scope against a fitness for service derived performance requirement, to evaluate whether the delivered inspection met that requirement, and to escalate when it did not. NII implemented as a procurement decision, in which a vendor is asked to inspect a vessel non-intrusively without a specification of what the inspection must achieve, produces data without assurance.

There is a broader observation about the direction of travel. The individual technologies reviewed here point consistently away from inspection as a discrete periodic event and toward condition monitoring as a continuous process. Permanently installed sensors are the clearest expression of this, but the same logic runs through encoded corrosion mapping registered to a persistent asset model, through integration with process historians and integrity operating windows, and through the analytics layer that trends rather than snapshots. In the limiting case, the question shifts from what condition the vessel was in at the last inspection to what condition it is in now and what rate it is changing at. That is a materially different and more useful question, and it is the one that determines whether a shutdown is needed at all. The parallel movement toward continuous hazard monitoring in occupational safety suggests that the organisational obstacles to this shift are more consistent across domains than the technical ones (Obogo *et al*., 2021a).

The pandemic period accelerated this shift for contingent reasons. Whether the acceleration persisted once the contingent pressures eased is a question this review cannot answer from within the period. What can be said is that the operators that had invested in monitoring infrastructure before 2020 were substantially better placed to justify deferred turnarounds during it than those that had not, and that this experience is likely to have durable effects on investment priorities.

10. Conclusions

1. **The framework matured.** By 2021 the industry had a consolidated, freely available recommended practice for NII of pressure vessels in HOIS-RP-103, supported by guidance notes and by specific guidance for hard cases such as clad vessels. This resolved a long-standing gap between the permissive language of inspection codes such as API 510 and the practical question of how to determine whether a non-intrusive scope is adequate.
2. **The technology advances were in density, repeatability and deployment rather than in physics.** Phased array and FMC/TFM ultrasonics, higher resolution pulsed eddy current, permanently installed and battery-free thickness sensors, robotic external and internal deployment, and digital radiography collectively increased the amount, quality and spatial registration of data obtainable without vessel entry, and reduced the access cost of obtaining it.
3. **The economic case is driven by preparation and deferred production, not by inspection cost.** NII execution is frequently more expensive than IVI execution. The saving arises from avoided vessel preparation and, decisively, from removal of inspection driven constraints on the shutdown schedule. The business case is therefore asset specific and schedule specific, and blanket adoption policies are inappropriate.
4. **Deferment is more readily justified than replacement.** In most applications, particularly first applications to a given vessel, NII supports extension of the internal inspection interval rather than permanent elimination of internal inspection. This is a legitimate and valuable outcome and should not be treated as a failure to achieve the full benefit.
5. **The binding constraint is evidence of effectiveness, not availability of technology.** Risk-based interval extension requires quantified inspection effectiveness, which requires qualification evidence. Where that evidence is absent, the technically honest position is that effectiveness is unknown, and unknown effectiveness cannot support interval extension.
6. **Competence is the limiting organisational factor.** The scarce capability is not NDE technician certification but integrity engineering judgement: the ability to derive a performance requirement from a fitness for service assessment, specify techniques against it, and evaluate delivery against it.
7. **The trajectory is from periodic inspection toward continuous monitoring.** The most consequential development of the period is not any single technique but the shift in what inspection data is for: from establishing a condition at a point in time to characterising a rate of change that can be managed as a process variable.

10.1. Recommendations for practice

- Apply NII selectively, prioritising vessels where preparation cost is high, where the vessel sits on a turnaround critical path, and where the credible damage mechanisms are well characterised and spatially predictable.
- Derive the inspection performance requirement from a fitness for service assessment before selecting techniques, not after.
- Treat pulsed eddy current and similar screening methods as screening methods, with defined ultrasonic follow up on indications.
- Install permanent monitoring at locations determined by the degradation assessment, and treat point monitoring as complementary to area coverage rather than a substitute for it.
- Run NII in parallel with IVI on at least one turnaround before relying on NII alone, to build local evidence and calibrate organisational confidence.
- Invest in data management ahead of, not after, investing in data generation.
- Verify jurisdictional acceptance before building a shutdown plan on an NII based deferral.

10.2. Directions for Further Work

Priority areas identified by this review include the extension of qualification and probability of detection evidence to clad and weld overlaid vessels; validated inversion methods for pulsed eddy current that recover localised pitting from the averaged response; long term drift, bond durability and calibration stability of permanently installed sensors over intervals comparable to vessel inspection intervals; validation frameworks for machine learning based defect classification adequate to safety critical decision chains; and quantitative treatment of the residual risk of undetected degradation within risk-based interval extension, so that the cost of being wrong enters the economic comparison explicitly rather than implicitly.

References

Standards, Codes and Recommended Practices

1. HOIS. Recommended practice for non-intrusive inspection of pressure vessels. HOIS-RP-103. ESR Technology Ltd; 2020 Feb.
2. HOIS, Oil and Gas Technology Centre. Guidance notes for HOIS-RP-103. HOIS-G-103. ESR Technology Ltd; 2020.
3. HOIS. Guidance on non-intrusive inspection of clad vessels. HOIS-G-026. ESR Technology Ltd; 2020.
4. Det Norske Veritas. Recommended practice DNV-RP-G103: non-intrusive inspection. DNV; 2007 Oct. Revised 2011 Jan; reissued as DNVGL-RP-G103, 2017. Retired following publication of HOIS-RP-103.
5. American Petroleum Institute. API 510: pressure vessel inspection code, in-service inspection, rating, repair, and alteration. 10th ed. Washington, DC: API; 2014 May. Addendum 1, 2017 May; Addendum 2, 2018 Mar.
6. American Petroleum Institute. API RP 571: damage mechanisms affecting fixed equipment in the refining industry. Washington, DC: API.
7. American Petroleum Institute. API RP 572: inspection practices for pressure vessels. 4th ed. Washington, DC: API; 2016 Dec.
8. American Petroleum Institute. API RP 580: risk-based inspection. 3rd ed. Washington, DC: API.
9. American Petroleum Institute. API RP 581: risk-based inspection methodology. 3rd ed with addendum. Washington, DC: API.
10. American Petroleum Institute. API RP 583: corrosion under insulation and fireproofing. Washington, DC: API.
11. American Petroleum Institute. API RP 584: integrity operating windows. Washington, DC: API.
12. American Petroleum Institute, American Society of Mechanical Engineers. API 579-1/ASME FFS-1: fitness-for-service. Washington, DC: API.
13. American Society of Mechanical Engineers. ASME PCC-3: inspection planning using risk-based methods. New York: ASME.
14. International Organization for Standardization. ISO 9712: non-destructive testing, qualification and certification of NDT personnel. Geneva: ISO.
15. Health and Safety Executive. Pressure Systems Safety Regulations 2000 and associated guidance on written schemes of examination. United Kingdom: HSE.

Technical and Scholarly Literature

16. Adegbite MP, Adebayo A, Ahmed MO. Securing operational technology networks in electric utilities: a systematic review of NERC CIP compliance and architectural threat mitigation. Int J Eng Mod Technol. 2020;6(3):103-146. doi:10.56201/ijemt.vol.6.no3.2020.pg103.146.
17. Adeyelu OO. A predictive compliance monitoring framework for detecting systemic safety risks through aviation consumer complaint data. Iconic Res Eng J. 2018;1(8):250-276. doi:10.64388/IREV1I8-1718478.
18. Adeyelu OO. An adaptive safety management system implementation model for aerodromes in developing economy contexts. Iconic Res Eng J. 2019;3(4):628-654. doi:10.64388/IREV3I4-1718479.
19. Adeyelu OO. An artificial intelligence-driven conceptual model for wildlife strike risk quantification and aircraft airworthiness impact assessment at high-traffic African airports. Iconic Res Eng J. 2020;4(1):339-368. doi:10.64388/IREV4I1-1718482.
20. Adeyelu OO. A framework for managing encroachments and unauthorized structures around airport boundaries: regulatory evidence, enforcement, and corrective action protocols for Nigerian civil aviation. Int J Multidiscip Res Growth Eval. 2021;2(6):954-972. doi:10.54660/.IJMRGE.2021.2.6.954-972.
21. Agbabiaka J, Okonkwo CS, Ogunwole O, Mayo W, Okeke OT. Supply chain risk management model for EPC and gas processing projects. Iconic Res Eng J. 2019;3(2):968-980. doi:10.64388/IREV3I2-1713124.
22. Ahiaeke Patrick MC, Okonkwo CS, Mayo W, Okeke OT. A GIS enabled framework for modern ERP procurement processes. Int J Multidiscip Res Growth Eval. 2020;1(5):499-508. doi:10.54660/IJMRGE.2020.1.5.499-508.
23. Ahiaeke Patrick MC, Okonkwo CS, Mayo W, Okeke OT. Model for data driven vendor evaluation and bid selection using geospatial intelligence. Shodhshauryam Int Sci Ref Res J. 2021;4(4):426-443. doi:10.32628/SHISRRJ214461.
24. Ahmed MO, Adegbite MP, Adebayo A. Zero trust architecture for operational technology in North American critical infrastructure: a framework for

implementation and resilience optimization. Int J Eng Mod Technol. 2021;7(1):66-113. doi:10.56201/ijemt.vol.7.no1.2021.pg66.113.
25. Aifuwa SE, Oshoba TO, Ogbuefi E, Ike PN, Nnabueze SB, Olatunde-Thorpe J. Predictive analytics models enhancing supply chain demand forecasting accuracy and reducing inventory management inefficiencies. Int J Multidiscip Res Growth Eval. 2020;1(3):171-181. doi:10.54660/.IJMRGE.2020.1.3.171-181.
26. Akin-Oluyomi OT, Atima ME, Akinleye OK, Akokodaripon DA. Using Tableau and Excel for comprehensive profitability analysis in retail procurement operations. Int J Multidiscip Res Growth Eval. 2020;1(5):385-393.
27. Akinleye OK, Adeyoyin O. Process automation framework for enhancing procurement efficiency and transparency. Shodhshauryam Int Sci Ref Res J. 2021;4(4):356-387.
28. Akomolafe O, Agu MU. A conceptual model for enhancing internal audit quality through technology-enabled risk assessment frameworks. Iconic Res Eng J. 2018;1(9):458-475.
29. Akomolafe O, Agu MU. A conceptual framework for developing risk-based internal control models in the insurance and banking sectors. Iconic Res Eng J. 2019;2(8):335-354.
30. Akomolafe O, Agu MU. A review of data-driven risk evaluation models for emerging market financial institutions. Iconic Res Eng J. 2019;3(6):433-448.
31. Akomolafe O, Agu MU. Advances in financial resilience through integrated governance and compliance strategies. Iconic Res Eng J. 2019;2(10):607-620.
32. Amayo EB. Multi algorithm of loss objective function of a single phase induction motor. Int J Dev Res. 2017;7(5):12805-12810.
33. Amayo EB, Popoola TT. Multi algorithm of weight objective function of a single phase induction motor. Int J Trend Res Dev. 2017;4(2):184-188.
34. Amayo EB, Popoola TT. Scientific study of telecommunication deployment in achieving quality network. Int J Trend Res Dev. 2017;4(5):311-314.
35. Amayo EB, Ubeku E, Oshevire P. Multi algorithm of a single objective function of a single phase induction motor. J Multidiscip Eng Sci Technol. 2015;2(12):3400-3403.
36. Ambali KB, Eyetsemitan RA, Oyeleye AO, Fadayomi O. Lean Six Sigma for small enterprises: a systematic review and Lite-DMAIC adaptation framework for resource-constrained organizations. Iconic Res Eng J. 2021;5(5):562-583. doi:10.64388/IREV5I5-1716957.
37. Arumosoye OM, Obriki OD. Development of an integrated heat stress risk conceptual model for industrial operations in extreme environments. Iconic Res Eng J. 2018;1(12):141-160. doi:10.64388/IREV1I12-1714415.
38. Arumosoye OM, Obriki OD. Systematic review of near-miss and hazard observation data utilization in industrial safety management. Iconic Res Eng J. 2019;3(2):981-999. doi:10.64388/IREV3I2-1714417.
39. Arumosoye OM, Obriki OD. A governance-oriented conceptual model for contractor safety performance in multi-contract industrial projects. Int J Multidiscip Res Growth Eval. 2020;1(5):728-740. doi:10.54660/.IJMRGE.2020.1.5.728-740.
40. Arumosoye OM, Obriki OD. Organizational learning-based conceptual maturity model for continuous safety performance improvement. Int J Multidiscip Res Growth Eval. 2021;2(1):970-980. doi:10.54660/.IJMRGE.2021.2.1.970-980.
41. Atakpa MI. A review of predictive analytics models for anti-money laundering detection in commercial banking systems. Int J Sci Res Comput Sci Eng Inf Technol. 2021;7(2):778-804. doi:10.32628/CSEIT2064813.
42. Atta S, Asomani E, Adenuga OM. A systematic review of green corrosion inhibitors from agricultural extracts for mild steel protection in acidic and alkaline media. Int J Eng Mod Technol. 2018;4(1):64-97. doi:10.56201/ijemt.vol.4.no1.2018.pg64.97.
43. Atta S, Tofah P, Kankam MA, Adenuga OM. A critical review of NDT-based integrity management and corrosion risk assessment strategies for refinery process equipment. Int J Eng Mod Technol. 2020;6(2):19-46. doi:10.56201/ijemt.vol.6.no2.2020.pg19.46.
44. Atta S, Tofah P, Adenuga OM. Advances in non-destructive testing methods for weld integrity evaluation in high-capacity power infrastructure. Int J Eng Mod Technol. 2021;7(1):20-47. doi:10.56201/ijemt.vol.7.no1.2021.pg20.47.
45. Badmus O, Dosunmu AA, Ozowara DE, Anunagba CO. A comparative framework for Salesforce DevOps tooling: evaluating Copado, Flosum, and Salesforce DX across enterprise deployment contexts. Int J Multidiscip Res Growth Eval. 2020;1(5):1021-1031. doi:10.54660/.IJMRGE.2020.1.5.1021-1031.
46. Basnet A, Oghenemaiga E, Anene UN. Audience segmentation and forecasting models for enhancing targeted digital marketing effectiveness. Shodhshauryam Int Sci Ref Res J. 2021;4(5):279-305.
47. British Institute of Non-Destructive Testing. Publication of HOIS recommended practice for non-intrusive inspection and guidance notes. BINDT News. 2020 Mar.
48. Dagodzo D. A conceptual framework for UAV integration into national power grid inspection programs. Iconic Res Eng J. 2018;2(5):391-412. doi:10.64388/IREV2I5-1716082.
49. Dagodzo D. A review of UAV applications in electrical transmission line inspection: methods, technologies, and challenges. Iconic Res Eng J. 2018;2(6):234-254. doi:10.64388/IREV2I6-1716083.
50. Dagodzo D, Ahiaeke Patrick MC. UAV-based pipeline and corridor monitoring: a review of current practices and emerging technologies. Iconic Res Eng J. 2020;3(10):574-597. doi:10.64388/IREV3I10-1716084.
51. Dagodzo D, Ahiaeke Patrick MC. A review of GIS applications in utility asset management and infrastructure planning. Iconic Res Eng J. 2021;5(3):468-492. doi:10.64388/IREV5I3-1716085.
52. Dagodzo D, Ahiaeke Patrick MC. An integrated framework for UAV, LiDAR, and GIS in infrastructure corridor management. Int J Sci Res Comput Sci Eng Inf Technol. 2021;7(5):497-524. doi:10.32628/CSEIT217566.
53. De Landtsheer G, editor. Corrosion under insulation (CUI) guidelines: technical guide for managing CUI. 3rd ed. Vol. 55. European Federation of Corrosion. Elsevier; 2020.
54. Dogbatsey EA, Ebhojie O. Budget compliance and statutory reporting in Sub-Saharan Africa: a systematic review of frameworks, gaps, and reform pathways.

Zenodo. 2018. doi:10.5281/zenodo.20446859. [Originally numbered 2(6); journal name not captured in source.]
55. Dogbatsey EA, Ebhojie O, Oyeleye AO. Reconciliation control and financial workflow redesign in emerging market organizations: a conceptual framework. Zenodo. 2019. doi:10.5281/zenodo.20447103. [Originally numbered 3(5); journal name not captured in source.]
56. Dogbatsey EA, Ebhojie O, Oyeleye AO. Cross-border segregation of duties and acces… 2021. [Entry truncated in source; title incomplete and no identifier provided. Verify and complete.]
57. Dosunmu AA, Ogundele PO. Security audit and enterprise risk assessment frameworks for resilient information systems. Iconic Res Eng J. 2019;3(5):434-447. doi:10.64388/IREV3I5-1713225.
58. Dosunmu AA, Ogundele PO. Intrusion detection and prevention models for enhancing organizational cyber defense effectiveness. Iconic Res Eng J. 2020;4(6):310-324. doi:10.64388/IREV4I6-1713226.
59. Dosunmu AA, Ogundele PO. Incident response and digital forensics strategies for rapid cyber attack containment. Gyanshauryam Int Sci Ref Res J. 2021;4(4):239-258.
60. Efobi OZ, Akinleye OK, Fasawe O. Framework for data-driven operations management and performance improvement in educational institutions. Gyanshauryam Int Sci Ref Res J. 2021;4(6):127-158.
61. Eyetsemitan RA, Ambali KB, Oyeleye AO, Fadayomi O. Multi-stakeholder governance alignment in joint venture operations: a conceptual framework for coordinating business processes in highly regulated environments. Iconic Res Eng J. 2020;4(4):418-441. doi:10.64388/IREV4I4-1716955.
62. Eyetsemitan RA, Ambali KB, Oyeleye AO, Fadayomi O. Translating tax and regulatory requirements into SME compliance workflows: a conceptual framework for implementing IAS 12, VAT, PAYE, and withholding tax. Iconic Res Eng J. 2021;4(11):621-641. doi:10.64388/IREV4I11-1716956.
63. Ike PN, Ogbuefi E, Nnabueze SB, Olatunde-Thorpe J, Aifuwa SE, Oshoba TO, *et al*. Supplier relationship management strategies fostering innovation, collaboration, and resilience in global supply chain ecosystems. Int J Multidiscip Evol Res. 2021;2(2):52-62. doi:10.54660/IJMER.2021.2.2.52-62.
64. Inspectioneering Journal. Ultrasonic corrosion monitoring, a holistic approach. Inspectioneering Journal. 2021 Feb.
65. Komi NM. Hybrid deep learning for wind power forecasting: from grid stability to market equity for small generators. Int J Multidiscip Res Growth Eval. 2021;2(6):989-1014. doi:10.54660/.IJMRGE.2021.2.6.989-1014.
66. Komi NM, Adamolekun A. Interpretable machine learning for early failure prediction in distributed renewable energy assets. Int J Multidiscip Res Growth Eval. 2021;2(6):1015-1038. doi:10.54660/.IJMRGE.2021.2.6.1015-1038.
67. Komi NM, Adeniji IO. Co-optimizing technical performance and community affordability in smart solar microgrids for underserved regions. Int J Eng Mod Technol. 2020;6(3):173-212. doi:10.56201/ijemt.vol.6.no3.2020.pg173.212.
68. Ladapo OO, Dosunmu AA, Jooda D, Abolaji TO. Lessons learned from offline assessment of security-critical systems: the case of Microsoft Active Directory. Iconic Res Eng J. 2018;2(6):277-299. doi:10.64388/IREV2I6-1717205.
69. Ladapo OO, Jooda D, Dosunmu AA, Abolaji TO. Implementation of Active Directory for efficient management of enterprise networks. Iconic Res Eng J. 2019;3(4):608-627. doi:10.64388/IREV3I4-1717206.
70. Lawal OA, Oduleye TE. A conceptual model for financial analytics driven enterprise value creation in technology firms. Iconic Res Eng J. 2018;2(2).
71. Lawal OA, Oduleye TE. A review and conceptual framework for tax governance and cross-border compliance analytics. Iconic Res Eng J. 2018;2(5).
72. Lawal OA, Oduleye TE. A conceptual risk assessment model for transfer pricing in multinational corporations. Iconic Res Eng J. 2019;2(12).
73. Lawal OA, Oduleye TE. Conceptualizing data driven executive decision systems for strategic financial planning. Iconic Res Eng J. 2019;3(3).
74. Lawal OA, Oduleye TE. A conceptual decision model for capital allocation using financial analytics. Gyanshauryam Int Sci Ref Res J. 2021;4(2):269-295.
75. Lawal OA, Oduleye TE. Aligning financial planning analytics with corporate strategy: a conceptual integration model. Shodhshauryam Int Sci Ref Res J. 2021;4(3):319-346.
76. Materials Performance. How ultrasonic sensors can enable permanent corrosion monitoring. Materials Performance. 2021 Jul.
77. Mbonu IS, Aliliele C, Iwuanyanwu U, Oluoha OM. A conceptual framework for legal and ethical risk modeling in enterprise data protection governance systems. Iconic Res Eng J. 2018;2(2):207-226. doi:10.64388/IREV2I2-1714911.
78. Mbonu IS, Aliliele C, Uzoka E, Oluoha OM. A review of comparative data protection regulations and secure cloud implementation strategies across jurisdictions. Iconic Res Eng J. 2019;2(9):482-501. doi:10.64388/IREV2I9-1714912.
79. Mbonu IS, Iwuanyanwu U, Uzoka E, Oluoha OM. Advances in enterprise log analytics and automated incident response architectures using Python and SIEM platforms. Iconic Res Eng J. 2019;3(2):1000-1019. doi:10.64388/IREV3I2-1714915.
80. Mbonu IS, Aliliele C, Iwuanyanwu U, Uzoka E. A review of identity and access management integration strategies in hybrid and multi cloud environments. Int J Multidiscip Res Growth Eval. 2020;1(5):795-810. doi:10.54660/.IJMRGE.2020.1.5.795-810.
81. Mbonu IS, Iwuanyanwu U, Aliliele C, Uzoka E. A conceptual framework for agile supply chain digital transformation with embedded IT risk and ISO compliance controls. Iconic Res Eng J. 2020;3(11):566-593. doi:10.64388/IREV3I11-1714916.
82. Mbonu IS, Iwuanyanwu U, Aliliele C, Uzoka E. Advances in infrastructure as code governance for secure Terraform based enterprise cloud deployments. Int J Multidiscip Res Growth Eval. 2020;1(5):811-828. doi:10.54660/.IJMRGE.2020.1.5.811-828.
83. Mbonu IS, Aliliele C, Iwuanyanwu U, Uzoka E. A conceptual framework for risk based business intelligence architecture in financial technology

platforms. Int J Multidiscip Res Growth Eval. 2021;2(6):731-746. doi:10.54660/.IJMRGE.2021.2.6.731-746.

84. Mbonu IS, Alilièle C, Iwuanyanwu U, Uzoka E. Advances in artificial intelligence techniques for secure software testing and automated regression control mechanisms. Int J Sci Res Comput Sci Eng Inf Technol. 2021;7(5):468-496. doi:10.32628/CSEIT217565.
85. Mbonu IS, Iwuanyanwu U, Alilièle C, Uzoka E. A review of VoIP forensic analytics models for financial fraud detection and regulatory compliance monitoring. Int J Multidiscip Res Growth Eval. 2021;2(6):711-730. doi:10.54660/.IJMRGE.2021.2.6.711-730.
86. Nnabueze SB, Ike PN, Olatunde-Thorpe J, Aifuwa SE, Oshoba TO, Ogbuefi E, *et al*. End-to-end visibility frameworks improving transparency, compliance, and traceability across complex global supply chain operations. Int J Multidiscip Futur Dev. 2021;2(2):50-60. doi:10.54660/IJMFD.2021.2.2.50-60.
87. Obogo SF, Ozobu CO, Uduokhai DO. Advances in leadership driven safety culture transformation in large construction workforces. Iconic Res Eng J. 2019;3(5):507-523. doi:10.64388/IREV3I5-1715497.
88. Obogo SF, Ozobu CO, Uduokhai DO. Development of a construction safety risk governance model for multi contractor high rise projects. Iconic Res Eng J. 2019;2(9):502-522. doi:10.64388/IREV2I9-1715495.
89. Obogo SF, Uduokhai DO, Ozobu CO. Systematic review of hazard identification and risk control practices in urban construction projects. Iconic Res Eng J. 2019;2(12):666-681. doi:10.64388/IREV2I12-1715496.
90. Obogo SF, Arumosoye OM, Obriki OD. Advances in internal QHSE audit systems for industrial engineering operations. Iconic Res Eng J. 2020;4(4):399-417. doi:10.64388/IREV4I4-1715499.
91. Obogo SF, Arumosoye OM, Obriki OD. Conceptual risk management model for heavy lifting and crane installation engineering operations. Shodhshauryam Int Sci Ref Res J. 2020;3(4):122-144. doi:10.32628/SHISRRJ214441.
92. Obogo SF, Arumosoye OM, Obriki OD. Critical review of occupational safety management systems in oil and gas maintenance projects. Shodhshauryam Int Sci Ref Res J. 2020;3(4):145-166. doi:10.32628/SHISRRJ214442.
93. Obogo SF, Arumosoye OM, Obriki OD. Advances in proactive hazard recognition and near miss reporting systems. Int J Multidiscip Res Growth Eval. 2021;2(6):835-846. doi:10.54660/IJMRGE.2021.2.6.835-846.
94. Obogo SF, Obriki OD, Arumosoye OM. Conceptual model for incident prevention in industrial maintenance engineering environments. Int J Multidiscip Res Growth Eval. 2021;2(6):847-858. doi:10.54660/IJMRGE.2021.2.6.847-858.
95. Obogo SF, Uduokhai DO, Ozobu CO. Review of contractor safety compliance systems in infrastructure engineering projects. Int J Sci Res Civil Eng. 2021;5(4):76-100. doi:10.32628/IJSRCE215412.
96. Obriki OD, Arumosoye OM. Conceptual modeling of data-driven occupational safety risk control in large-scale energy infrastructure projects. Iconic Res Eng J. 2018;1(7):169-189. doi:10.64388/IREV1I7-1714414.
97. Obriki OD, Arumosoye OM. A conceptual framework linking management safety walkthrough frequency and coverage to safety culture outcomes in mega projects. Iconic Res Eng J. 2019;2(8):355-374. doi:10.64388/IREV2I8-1714416.
98. Obriki OD, Arumosoye OM. Conceptual framework for human error causation in high-risk construction and industrial activities. Int J Multidiscip Res Growth Eval. 2020;1(5):715-727. doi:10.54660/.IJMRGE.2020.1.5.715-727.
99. Obriki OD, Arumosoye OM. Conceptual model for institutionalizing life-preserving safety practices across project-based organizations. Int J Multidiscip Res Growth Eval. 2021;2(1):961-969. doi:10.54660/.IJMRGE.2021.2.1.961-969.
100. Ogbete JC, Aminu-Ibrahim AY, Ambali KB. Risk managed construction strategies for complex and highly regulated healthcare facility developments. Int J Sci Res Comput Sci Eng Inf Technol. 2021;7(5):362-392. doi:10.32628/CSEIT217561.
101. Ogbole JI, Okoruwa PO, Fadayomi O, Abolaji TO, Edivri J, Akeju B. Conceptual model for identity-centric zero trust architecture in enterprise security governance. Int J Sci Res Comput Sci Eng Inf Technol. 2021;7(5):393-415. doi:10.32628/IJSRCSEIT217562.
102. Ogunwole O, Okonkwo CS, Agbabiaka J, Mayo W, Okeke OT. Supply chain resilience framework for critical infrastructure and gas processing plants. Shodhshauryam Int Sci Ref Res J. 2021;4(4):444-461. doi:10.32628/SHISRRJ214462.
103. Okojie JS, Abioye RF. 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. Int J Multidiscip Res Growth Eval. 2020;1(5):992-1006.
104. Okonkwo CS, Ogunwole O, Okeke OT. Framework for strategic procurement optimization in oil and gas operations. Iconic Res Eng J. 2018;1(7):153-168. doi:10.64388/IREV1I7-1713119.
105. Okonkwo CS, Ogunwole O, Okeke OT. Model for inventory availability and plant uptime improvement in energy facilities. Iconic Res Eng J. 2018;2(4):160-172. doi:10.64388/IREV2I4-1713120.
106. Okonkwo CS, Ogunwole O, Okeke OT, Mayo W. Conceptual framework for cost reduction through contract negotiation and vendor governance. Iconic Res Eng J. 2019;2(9):468-482. doi:10.64388/IREV2I9-1713121.
107. Okonkwo CS, Agbabiaka J, Ogunwole O, Mayo W, Okeke OT. Model for demurrage elimination and port logistics efficiency in emerging economies. Int J Multidiscip Res Growth Eval. 2020;1(5):552-562. doi:10.54660/IJMRGE.2020.1.5.552-562.
108. Okonkwo CS, Agbabiaka J, Ogunwole O, Mayo W, Okeke OT. Conceptual model for materials readiness and maintenance-driven supply chain performance. Int J Multidiscip Res Growth Eval. 2021;2(6):584-594. doi:10.54660/IJMRGE.2021.2.6.584-594.
109. Okonkwo CS, Ogunwole O, Mayo W, Okeke OT. Framework for regulatory-compliant procurement in high-risk energy environments. Int J Multidiscip Res Growth Eval. 2021;2(6):595-605. doi:10.54660/IJMRGE.2021.2.6.595-605.
110. Okoruwa PO, Fadayomi O, Akeju B, Edivri J, Ogbole JI,

Abolaji TO. Conceptual model for privacy-centric security engineering in digital and cloud computing systems. Int J Sci Res Comput Sci Eng Inf Technol. 2020;7(5):371-389.

111. Oshevire P, Eyenubo OJ, Amayo B. Voltage control in the presence of distributed generation. ATBU J Sci Technol Educ. 2017;5(2):165-173.
112. Stevenson T. Ultrasonic in-service detection and monitoring of sulphidic corrosion. Inspectioneering Journal. 2021 Jul-Aug.
113. Strachan S. Buried ultrasonic sensors for midstream asset-integrity corrosion monitoring. In: Proceedings of CORROSION 2021. Paper C2021-16499. AMPP; 2021 Apr.
114. Sunday EA, Omoegun GO. Integrating solar power solutions in small-scale manufacturing industries in Nigeria. Int J Sci Res Sci Eng Technol. 2018;4(8):832-853.
115. Sunday EA, Omoegun GO. Optimizing electrical load distribution for hybrid solar installations in developing economies. Int J Sci Res Mech Mater Eng. 2019;3(6):27-47.
116. Sunday EA, Omoegun GO, Essien MA, Oluokun OA. Thermodynamic efficiency and control strategies in residential air conditioning systems. Int J Sci Res Civil Eng. 2019;3(3):52-76.
117. Sunday EA, Omoegun GO, Essien MA, Oluokun OA. Transitioning from reactive to predictive maintenance in mechanical systems. Int J Sci Res Comput Sci Eng Inf Technol. 2020;6(6):425-447.
118. Tonoyan A, Dada O, Ayivi-Donkor SS. Advances in demand forecasting: machine learning algorithms for revenue projection and financial planning accuracy. Gyanshauryam Int Sci Ref Res J. 2021;4(1):282-317.
119. Tonoyan A, Dada O, Ayivi-Donkor SS. Predictive cash flow modeling in retail: a review of advanced forecasting and working capital optimization. Shodhshauryam Int Sci Ref Res J. 2021;4(3):366-397.
120. Yeboah BK, Ike PN. Programmatic strategy for renewable energy integration: lessons from large-scale solar projects. Int J Multidiscip Res Growth Eval. 2020;1(3):306-315. doi:10.54660/.IJMRGE.2020.1.3.306-315.