

Integrating Safety Engineering into Infrastructure and Industrial Frameworks: The Nigerian Experience and the Way Forward

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ABSTRACT

Nigeria's infrastructure and industrialisation agenda is central to economic diversification, employment generation, poverty reduction and sustainable development. However, the value of infrastructure and industrial assets cannot be measured solely by their capacity, cost or physical completion; their ability to protect human life, preserve the environment, maintain operational continuity and remain resilient throughout their life cycle is equally important. Safety engineering therefore needs to move from being predominantly an occupational or compliance function to becoming a core engineering and development discipline embedded in policy formulation, feasibility studies, planning, design, procurement, construction, commissioning, operation, maintenance, modification and decommissioning. Nigeria has established important foundations for this transition through its occupational safety and health policy framework, petroleum-sector regulations, engineering and building requirements, and sector-specific regulatory institutions. Nevertheless, evidence from construction, transportation, petroleum, power and chemical industries indicates persistent gaps between regulatory intent and implementation. Recent Nigerian studies associate safety deficiencies with weak management commitment, safety violations, inadequate design, poor maintenance, regulatory weaknesses, deficient risk assessment, quality-management gaps and limited safety culture. This article adopts an integrative documentary review of recent peer-reviewed literature and Nigerian government publications to examine the extent to which safety engineering is integrated into infrastructure and industrial development. The analysis proposes a life-cycle, risk-informed framework based on seven pillars: governance and regulation; safety-by-design; risk assessment and assurance; competent people and safety culture; asset integrity and maintenance; digital safety intelligence; and learning and continuous improvement. The article argues that Nigeria's way forward requires a shift from reactive accident prevention to anticipatory risk management in which safety is treated as an engineering performance requirement and a national development investment. Such integration would strengthen infrastructure reliability, industrial productivity, public confidence and sustainable development while reducing the human, environmental and economic consequences of preventable failures.

Keywords: safety engineering; infrastructure; industrialisation; process safety; asset integrity; safety-by-design; risk management; resilience; sustainable development

INTRODUCTION

Infrastructure constitutes the physical foundation upon which economic and social activities depend. Roads, bridges, buildings, electricity systems, water facilities, telecommunications networks, ports, airports, pipelines, industrial plants and other critical assets enable production, movement, communication and access to essential services [1][2][3]. Their contribution to development, however, depends not simply on whether they are constructed but on whether they remain safe, reliable, resilient and fit for purpose throughout their operating lives [1][2][3].

Nigeria's infrastructure challenge is therefore simultaneously a development challenge and a safety challenge. Fiscal constraints, inadequate maintenance, infrastructure deficits and institutional weaknesses have historically

affected the quality and reliability of infrastructure delivery [3][4]. At the same time, evidence from Nigerian construction, transportation, petroleum and power sectors demonstrates that failures in design, construction, operation, maintenance, regulation and human factors can transform infrastructure deficiencies into threats to life, property, economic productivity and environmental quality [5]-[8].

Safety engineering provides an appropriate framework for addressing this challenge because its fundamental purpose is to identify hazards systematically, understand risk, prevent unwanted events and design systems capable of tolerating foreseeable deviations and failures [9]. Contemporary safety practice increasingly recognises that accidents in complex socio-technical systems cannot be addressed solely by instructing workers to behave safely; risk must also be controlled through engineering design, system architecture, organisational arrangements, competent management and resilient infrastructure [7]-[13].

The Nigerian policy environment has progressively recognised the importance of safety. Nigeria's occupational safety and health framework identifies safety and health as multidisciplinary responsibilities involving government, employers, workers and professional institutions [2]. Nigeria also ratified International Labour Organization Convention No. 187 in 2022, strengthening the country's formal commitment to a preventive national occupational safety and health system [1][14].

In the petroleum sector, the Nigerian Upstream Petroleum Regulatory Commission (NUPRC) has developed increasingly explicit requirements for safety management, technical safety studies, safety-critical equipment, pre-start-up safety review, emergency preparedness and operational safety assurance [15]-[18].

The central problem, therefore, is no longer simply the absence of safety requirements [7]. Rather, it is the degree to which safety engineering is systematically integrated into the broader infrastructure and industrial development process [7]. Nigerian experience suggests that regulations may exist while unsafe designs, weak implementation, poor supervision, inadequate maintenance and safety violations persist [7][17]-[20].

This article examines that problem and argues that Nigeria needs to reposition safety engineering from a predominantly compliance-oriented function to a strategic engineering and development discipline. The article specifically examines the Nigerian experience, identifies major barriers to integration, and proposes a practical framework for embedding safety engineering into infrastructure and industrial frameworks.

Conceptualising Safety Engineering within Infrastructure and Industrial Development

A. Safety engineering as a life-cycle discipline

Safety engineering should be understood as a systematic approach to ensuring that facilities, equipment, processes, infrastructure and organisations perform their intended functions without exposing people, assets or the environment to unacceptable risks [9]. Its application should begin before physical construction and continue through commissioning, operation, maintenance, modification and eventual decommissioning [10].

This life-cycle perspective is particularly important because many catastrophic failures originate from decisions made long before an incident occurs. Choices concerning location, materials, equipment selection, process configuration, structural loading, drainage, electrical systems, fire protection, access, maintainability and emergency response can establish the risk profile of an asset before construction begins [16][21][22].

Consequently, safety engineering should not be treated as an activity added to an already completed engineering design [9]. Safety should be incorporated into the design itself [9]. The principle of inherently safer design illustrates this approach by seeking to eliminate or reduce hazards at source rather than depending primarily on administrative controls or protective systems [7][10].

B. Safety engineering and infrastructure performance

Infrastructure safety should be understood as a multidimensional concept that extends beyond the traditional protection of workers in the workplace. It encompasses the protection of workers, including employees, contractors and other persons engaged in construction, maintenance and operational activities; users and the

public, who may be exposed to hazards associated with roads, buildings, bridges, transportation systems, utilities and industrial facilities; assets and processes, through the prevention or mitigation of structural failures, equipment breakdowns, fires, explosions, loss of containment and other process-related events; and the environment and wider society, through the prevention or limitation of environmental damage, service disruption and cascading consequences that may affect communities and interconnected economic systems [9][23]-[25]. This broader perspective is consistent with contemporary infrastructure-risk and resilience research, which emphasises that infrastructure systems are interconnected socio-technical systems whose failures can propagate across physical, environmental and societal boundaries [24][25]. Nigeria's National Occupational Safety and Health framework similarly emphasises prevention and protection against hazards while recognising the responsibilities of employers, workers, manufacturers, transporters and other stakeholders in creating safer systems [23].

The various dimensions are interdependent. A poorly maintained electrical network, for example, can cause operational interruptions while simultaneously increasing fire and electrocution risks [7]. Similarly, inadequate road design can produce both infrastructure deterioration and road traffic injuries [7][22][26][27].

The implication is that safety performance should become an explicit infrastructure performance criterion alongside cost, schedule, functionality, quality and sustainability.

METHODOLOGICAL APPROACH

This study adopted an integrative documentary review approach to examine the relationship between safety engineering and infrastructure and industrial development in Nigeria. The review incorporated evidence from peer-reviewed journal articles, scholarly publications, Nigerian government reports, legislation and regulatory documents, and authoritative publications from relevant international institutions. Literature was searched systematically across major academic databases, including Scopus, Web of Science, ScienceDirect, PubMed, Google Scholar, and the Directory of Open Access Journals (DOAJ). In addition, institutional and governmental repositories were searched, including the Federal Government of Nigeria/Ministry of Labour and Employment, National Bureau of Statistics (NBS), Federal Road Safety Corps (FRSC), Nigerian Upstream Petroleum Regulatory Commission (NUPRC), Nigerian Midstream and Downstream Petroleum Regulatory Authority (NMDPRA), National Environmental Standards and Regulations Enforcement Agency (NESREA), Standards Organisation of Nigeria (SON), Energy Commission of Nigeria (ECN), and International Labour Organization (ILO), World Health Organization (WHO), and International Organization for Standardization (ISO) repositories. These sources were selected to capture both scholarly evidence and the regulatory, institutional and policy context within which safety engineering is practised in Nigeria.

The literature search employed combinations of keywords and Boolean operators, including “safety engineering” AND infrastructure, “infrastructure safety” AND Nigeria, “industrial safety” AND Nigeria, “process safety” AND petroleum, “construction safety” AND Nigeria, “road infrastructure” AND safety, “electricity infrastructure” AND reliability, “asset integrity” AND Nigeria, “occupational safety” AND regulation, and “infrastructure resilience” AND Nigeria. Priority was given to publications issued between 2021 and 2026, thereby emphasising recent evidence and contemporary developments. However, earlier seminal publications were retained where they provided indispensable theoretical, conceptual, methodological or regulatory foundations for understanding safety engineering and infrastructure risk.

Source selection was conducted in four sequential stages: identification, screening, eligibility assessment and final inclusion. During the identification stage, potentially relevant records were retrieved from the academic databases and institutional repositories using the predefined search terms. Titles and abstracts were subsequently screened for relevance to safety engineering, infrastructure, industrial systems, risk management, reliability, resilience, occupational safety or regulatory governance. During the eligibility stage, potentially relevant full-text publications were assessed against predefined inclusion criteria. Sources were included when they: (i) addressed safety, risk, reliability, resilience, asset integrity, human factors, regulatory compliance or institutional governance; (ii) concerned infrastructure, industrial systems or occupational safety; (iii) provided empirical, analytical, regulatory, policy or conceptual evidence; and (iv) were sufficiently authoritative and relevant to the Nigerian context or offered transferable evidence from comparable settings. Duplicate publications, sources with

insufficient scholarly or institutional credibility, unsupported opinion pieces, and publications whose substantive focus fell outside the scope of infrastructure, industrial or occupational safety were excluded. Where several publications addressed the same issue, preference was given to recent peer-reviewed studies, primary government or regulatory sources, systematic reviews, and authoritative institutional publications.

Because the review was integrative rather than a statistical systematic review or meta-analysis, the evidence was synthesised using a structured thematic and narrative synthesis approach. Following source selection, relevant findings were extracted and grouped according to the principal safety-engineering issues addressed by each source. The evidence was then organised into five interconnected domains: (i) construction and built-environment safety; (ii) transport and road infrastructure safety; (iii) petroleum and process safety; (iv) electricity and industrial infrastructure reliability; and (v) occupational safety, regulation and institutional governance. Within each domain, findings were compared according to hazard and risk characteristics, engineering controls, human and organisational factors, regulatory requirements, infrastructure reliability, institutional capacity, implementation challenges and reported safety outcomes.

Construction and built-environment safety was included because the integrity and safety of buildings and other civil infrastructure depend on the quality of design, materials, construction practices, supervision and quality-management processes; recent evidence from Nigeria highlights the relationship between weaknesses in quality-management practices and construction failures and building collapse [28][29]. Transport and road infrastructure safety was considered because transportation infrastructure is a critical component of national infrastructure, and its safety performance is influenced by infrastructure condition, road design, traffic characteristics, maintenance and the interaction between infrastructure and road users [30][31]. Petroleum and process safety was selected because petroleum operations involve complex, high-hazard systems in which process safety, human factors, hazard control, equipment integrity and prevention of loss of containment are fundamental to protecting workers, assets, communities and the environment [32][33]. Electricity and industrial infrastructure reliability was included because reliable infrastructure is essential for industrial and economic activity, while deterioration or failure of critical infrastructure can result in service disruption, equipment damage and potentially significant safety consequences [34][35]. Finally, occupational safety, regulation and institutional governance were incorporated as a cross-cutting domain because effective safety engineering requires the interaction of technical safeguards with competent personnel, regulatory oversight, organisational systems, compliance mechanisms and management commitment [36][37]. Collectively, these domains provide a multidisciplinary evidence base for examining safety engineering as an integrated life-cycle function encompassing design, construction, operation, maintenance, reliability, human factors and governance, rather than as a narrowly defined workplace accident-prevention activity.

The synthesis subsequently involved identifying convergent findings, divergent findings, recurring safety deficiencies, regulatory and institutional gaps, emerging technological approaches, and opportunities for engineering intervention. Evidence from Nigerian studies was prioritised when drawing conclusions about the country's specific circumstances, while international literature was used to provide comparative perspectives and identify established approaches that may have relevance to Nigeria. Rather than assigning numerical quality scores to heterogeneous sources, the review considered the authority, methodological robustness, recency, contextual relevance and consistency of evidence when interpreting findings. The resulting synthesis was used to develop an integrated understanding of how safety engineering can be embedded throughout the design, construction, commissioning, operation, maintenance, modification and eventual decommissioning of infrastructure and industrial systems in Nigeria.

This methodological structure provides a transparent basis for moving from literature identification → source selection → thematic classification → comparative synthesis → identification of gaps → development of the proposed way forward, thereby strengthening the methodological credibility of the article as an integrative review.

The analysis was organised around four questions:

- What evidence exists concerning the current state of safety integration in Nigerian infrastructure and industry?

- What institutional, technical and organisational factors constrain effective integration?
- What safety-engineering principles can address these weaknesses?
- What framework should guide Nigeria's future infrastructure and industrial development?

The article is conceptual rather than empirical and does not claim to provide a statistical estimate of the national incidence of infrastructure or industrial failures.

The Nigerian Infrastructure and Industrial Context

Nigeria's development prospects remain closely connected to the availability, quality and reliability of infrastructure. Recent World Bank assessments have continued to identify infrastructure, electricity, transport connectivity and the business environment as important components of Nigeria's inclusive-growth challenge [3][4].

However, infrastructure development cannot be reduced to increasing the quantity of physical assets. Infrastructure that is constructed cheaply but fails prematurely, requires excessive maintenance, causes accidents or cannot withstand foreseeable hazards may ultimately impose greater economic costs than infrastructure designed with higher initial safety and reliability requirements [3][4][21].

The appropriate development question is therefore not merely: *how much infrastructure can Nigeria build?* It should also be: *how safely, reliably and resiliently can Nigeria design, construct, operate and maintain the infrastructure it builds?*

This distinction is central to integrating safety engineering into national development.

The Nigerian Experience: Evidence from Key Sectors

A. Construction and the built environment

Construction provides perhaps the clearest demonstration of the consequences of insufficient integration of safety engineering into infrastructure development. Nigerian construction research has repeatedly identified unsafe acts and conditions, inadequate implementation of safety programmes and weak regulatory enforcement as persistent challenges [6][19][20].

A 2023 mixed-method study of Nigerian construction projects identified several strategies capable of improving health and safety implementation and argued for stronger institutional mechanisms, including statutory structures capable of promoting standardisation and good safety practices [19].

Similarly, research on safety violations in Nigerian construction sites found that the problem is not simply a lack of safety rules but weaknesses in their implementation. The study's findings reinforce the need to understand safety as an organisational and institutional issue rather than solely as individual worker behaviour [20].

Management commitment is particularly significant. Research involving Nigerian construction workers found positive relationships among management safety priority, commitment, competence and empowerment, reinforcing the importance of leadership in determining safety outcomes [6].

Research on resilient safety culture in Nigerian construction organisations likewise found a significant positive relationship between resilient safety culture and safety performance, with hazard recognition and effective safety response identified as important components [5][8].

B. Building collapse as an infrastructure safety failure

Building collapse represents one of the most visible consequences of inadequate safety integration. Recent Nigerian research identifies multiple interacting contributors, including defective design, substandard materials,

poor workmanship, inadequate supervision, weak quality management, regulatory non-compliance and environmental conditions [21][28].

Importantly, evidence from Lagos demonstrates that geotechnical and environmental conditions can also contribute to structural risk. Ohenhen et al. demonstrated a relationship between land subsidence and building-collapse risk in Lagos, indicating that infrastructure safety cannot be separated from site investigation, geotechnical engineering and environmental hazard assessment [21]. This illustrates a fundamental safety-engineering principle: hazard identification must precede design decisions. A structural design that is technically adequate under assumed ground conditions may still be unsafe when those assumptions are wrong.

Quality management is another important dimension. Okonta et al. reported substantial weaknesses in the adoption of formal quality-management systems among Nigerian construction organisations and highlighted top-management support, communication and training as important determinants of quality performance [28]. The lesson is clear: structural safety cannot be separated from quality assurance, competence, procurement integrity, site supervision and regulatory enforcement.

Transport Infrastructure and Road Safety

Road infrastructure illustrates another important dimension of safety engineering because safety is determined by interaction between infrastructure, vehicles, users, operating speeds and emergency response. Research on road safety in Nigeria identified poor road design, weaknesses in implementation of road-safety legislation, user behaviour and inadequate research as barriers to improved road safety [7][30]. This finding supports the broader Safe System philosophy, which treats road crashes as a systems problem rather than solely as a consequence of driver error. Recent systematic evidence indicates that effective road safety requires coordinated interventions involving safe roads, safe speeds, safe vehicles, safe road users and post-crash care [7][38].

Nigeria's experience with pavement deterioration further demonstrates the need for engineering risk assessment. Research on the Minna–Kateri–Bida road linked pavement collapse to traffic diversion, overloaded trucks, geological conditions and subgrade characteristics [22]. The engineering lesson is that infrastructure safety should incorporate loading assumptions, geotechnical conditions, drainage, traffic behaviour, maintenance requirements and changing operational conditions rather than relying solely on original design specifications.

Digital technologies can strengthen this process. Contemporary research on smart roads shows that sensors, monitoring technologies and industrial informatics can support condition detection, predictive maintenance and safer road operations [39]. For Nigeria, this suggests a transition from periodic and reactive road inspection towards continuous or risk-based infrastructure condition monitoring.

Electricity Infrastructure and Industrial Reliability

Electricity infrastructure is another area where reliability and safety are closely interconnected. Recent research on Nigeria's power sector identifies persistent challenges involving generation, transmission, distribution, energy losses, financial constraints and system reliability [27][35].

The safety implications extend beyond electricity availability. Poorly maintained electrical infrastructure can increase risks associated with electrical faults, fires, equipment failure, unplanned shutdowns and unsafe maintenance interventions [7]. Reliability engineering and safety engineering therefore need to operate together rather than as separate technical disciplines.

Recent reliability analysis of Nigerian distribution feeders demonstrates the usefulness of quantitative reliability assessment for evaluating network performance and supporting maintenance planning [34]. The broader implication is that Nigeria's electricity development programme should incorporate:

- reliability-centred maintenance;
- asset integrity management;

- protection-system assurance;
- electrical safety engineering;
- condition monitoring;
- emergency preparedness;
- failure-mode analysis; and
- resilience against environmental and operational disturbances.

In other words, reliability contributes to safety where infrastructure functions are safety critical.

Petroleum, Process and Industrial Safety

The petroleum industry provides perhaps the most developed example of formal safety engineering within Nigeria. Nigerian Upstream Petroleum Regulatory Commission's (NUPRC) regulatory framework explicitly addresses occupational safety, process safety, safety-critical equipment, technical safety studies and safety management systems [5]. The Upstream Petroleum Safety Regulations 2024 establish a legal framework for safety and environmental management in upstream petroleum operations and impose responsibilities on licensees, lessees, contractors and managers [5][17][18].

NUPRC's 2023 guidelines for the design, construction and operation of oil and gas production facilities also require pre-start-up safety audits and reviews before hydrocarbon introduction [16]. These reviews consider mechanical completion, safety-critical systems, operating and emergency procedures, worker training and readiness of people, procedures and systems [16]. This represents a significant movement towards life-cycle safety assurance. The important lesson for other sectors is that safety should be verified before an infrastructure or industrial asset is permitted to enter service.

However, formal systems do not automatically guarantee safe outcomes [7][17][18]. Recent Nigerian research involving 462 frontline oil and gas workers found significant relationships between safety management practices, safety participation and safety compliance [40]. The study also identified concerns regarding production pressure and safety reporting [40].

Research on safety-barrier failures in Nigerian oil and gas facilities similarly identified technical failures, process upsets and equipment degradation as important risk factors and emphasised proactive maintenance and regulatory compliance [32]. This demonstrates why safety engineering must combine technical barriers, human factors, management systems and organisational culture.

Chemical Industry and Industrialisation

Industrialisation inevitably increases the use of hazardous substances, particularly in chemical manufacturing, petroleum refining, fertiliser production, pharmaceuticals, food processing and other process industries. Consequently, industrialisation without corresponding investment in chemical and process safety can create new categories of societal risk. Omokpariola observed that chemicals are important to Nigeria's industrial development but identified the need for stronger institutional arrangements, regulatory implementation and sound chemical management [41].

Contemporary process-safety research emphasises that chemical-process hazards should be assessed as interacting systems rather than isolated equipment failures. Dynamic risk approaches, for example, recognise that failures can propagate through interconnected process systems and accumulate over time [42]. This is especially relevant to Nigeria as industrial facilities become larger, more interconnected and increasingly automated.

The appropriate engineering response includes:

- process hazard analysis;
- HAZOP;
- Layers of Protection Analysis;
- failure-mode and effects analysis;
- fault-tree analysis;
- consequence modelling;
- safety-critical equipment management;
- management of change;
- permit-to-work systems;
- emergency response planning;
- safety instrumented systems; and
- mechanical integrity programmes.

These should not be treated as specialist activities performed only when regulators require them. They should be integrated into the normal engineering project-development cycle.

Mining, Manufacturing and Other Industrial Sectors

Nigeria's industrial transformation also involves mining and manufacturing. Recent review evidence on Nigerian mining indicates significant occupational injury and illness concerns associated with hazards and unsafe practices [43].

Manufacturing presents similar challenges because production systems increasingly combine people, machinery, automation, chemicals, electrical systems and information technologies. Contemporary safety research indicates that Industry 4.0 technologies such as the Internet of Things, cloud computing, augmented reality and big-data systems can support safety management and risk-based decision-making [13][44]. The opportunity for Nigeria is therefore not merely to digitise industrial processes but to digitise safety intelligence.

Sensors can detect abnormal conditions; predictive analytics can identify deteriorating equipment; digital twins can test operational scenarios; machine learning can support incident prediction; and integrated dashboards can provide decision-makers with near-real-time information on safety-critical conditions [13][44].

Digitalisation should, however, complement rather than replace sound engineering, competent people and effective governance.

Climate Change and Emerging Infrastructure Safety Risks

Nigeria's infrastructure safety agenda must also respond to climate-related hazards. Extreme heat, flooding, intense rainfall, erosion, coastal hazards and changing environmental conditions can alter the risk profile of infrastructure originally designed under different assumptions. Recent research on Nigerian construction workers demonstrates that extreme heat can influence safety awareness, adaptation and safe work practices [45][46]. This means that infrastructure design and occupational safety systems should increasingly incorporate climate risk assessment. Examples include heat-resistant materials; improved drainage; flood-resistant infrastructure; climate-informed structural design; heat-stress management; emergency-weather protocols; improved ventilation; resilient power systems; and climate-informed maintenance planning.

Safety engineering must therefore become increasingly forward-looking, accounting for future operating conditions rather than relying exclusively on historical experience [7][9][46].

Major Barriers to Integrating Safety Engineering in Nigeria

A. Reactive rather than preventive safety management

One of the most significant challenges is the tendency to respond to incidents after they occur rather than systematically identifying and controlling hazards before failure [7]. A reactive model asks: *what happened and who was responsible?*

A safety-engineering model asks: *what could fail, how could it fail, what would happen if it failed, and what can be designed into the system to prevent or contain it?*

Evidence from construction and petroleum operations suggests that Nigeria still needs a stronger preventive orientation [5][7][19][40].

B. Fragmented institutional responsibilities

Nigeria's safety responsibilities are distributed among multiple institutions and regulatory regimes. The occupational safety system involves labour, health, environment, petroleum, fire and other agencies, while infrastructure safety is additionally influenced by sectoral regulators and state and local authorities [2][5][18][46]. Fragmentation can create overlaps, regulatory gaps and inconsistent enforcement.

The way forward is not necessarily to eliminate sector-specific regulators but to establish a stronger national safety-governance architecture capable of coordinating safety-critical standards, data, competencies, inspections and lessons learned.

C. Weak enforcement

The existence of a regulation does not guarantee compliance. Nigerian construction research demonstrates that safety violations can persist despite the existence of regulations and formal safety requirements [20][46]. Effective enforcement requires:

- adequately resourced inspectors;
- competent technical personnel;
- transparent approval systems;
- risk-based inspections;
- meaningful sanctions;
- professional accountability;
- reliable incident reporting; and
- consistent application of requirements.

D. Procurement and cost pressure

Safety can be compromised when projects are evaluated predominantly on initial cost and completion time. Cutting expenditure on geotechnical investigation, material testing, supervision, maintenance, competent personnel or safety-critical equipment may reduce immediate expenditure while increasing life-cycle risk [21][26].

Nigeria therefore needs to move from lowest initial cost towards lowest life-cycle risk and cost.

E. Weak maintenance culture

Safety is not achieved when infrastructure is commissioned; it must be sustained throughout its operational life. Poor maintenance can transform a safe design into an unsafe asset. This is particularly important for bridges, roads, power systems, pressure vessels, pipelines, lifting equipment, fire systems, electrical installations and structural components. Asset integrity management should therefore be treated as a national infrastructure priority [5][16][34].

F. Competence gaps

Safety engineering requires multidisciplinary competence. Engineers, architects, quantity surveyors, planners, project managers, operators, technicians, contractors and regulators need sufficient understanding of hazard identification, risk assessment and safety assurance [6][19].

Professional development should therefore move beyond generic safety awareness towards competence in risk assessment; systems thinking; human factors; process safety; structural safety; reliability engineering; emergency engineering; asset integrity; safety assurance; and resilience engineering.

A Proposed Nigerian Framework for Integrating Safety Engineering

A practical Nigerian framework can be organised around seven mutually reinforcing pillars. This framework was developed through an integrative synthesis of the literature reviewed, Nigerian regulatory and institutional requirements, and the recurring safety challenges identified across the five evidence domains. Rather than treating safety as a stand-alone occupational function, the framework conceptualises it as a life-cycle, multidisciplinary and system-wide responsibility extending from infrastructure planning and design through construction, commissioning, operation, maintenance, modification and decommissioning.

The seven mutually reinforcing pillars were derived by identifying recurring themes that cut across construction, transportation, petroleum and process industries, electricity and industrial infrastructure, and occupational safety and governance. Particular attention was given to areas where the literature indicated that technical safety measures require complementary organisational, regulatory and human interventions. The pillars were therefore designed to address both engineering controls and the enabling conditions required for their effective implementation.

Briefly, the seven pillars were developed as follows:

- Safety-by-Design and Inherently Safer Engineering – derived from evidence emphasising the importance of incorporating hazard identification, risk reduction and human-factor considerations at the earliest stages of infrastructure and process design.
- Risk-Based Asset Integrity and Reliability Management – developed from recurring evidence on equipment deterioration, structural failure, inadequate maintenance, loss of containment and infrastructure reliability. It emphasises lifecycle integrity and proactive rather than predominantly reactive maintenance.
- Competence, Professionalism and Human Factors – reflects evidence that engineering controls can be undermined by inadequate competence, poor decision-making, communication failures, fatigue, procedural deficiencies and weak human–system interaction. It therefore places competency development and human-factors engineering within the safety framework.
- Process Safety and Major-Accident Prevention – developed from the high-consequence risks associated with petroleum, gas, chemical and other hazardous industrial operations. It incorporates systematic hazard identification, safety barriers, emergency preparedness, management of change and prevention of major accidents.

- Regulatory Integration, Compliance and Institutional Governance – emerged from the recognition that effective safety engineering requires coherent legislation, clear institutional responsibilities, effective regulatory oversight, enforcement, standards and accountability across government, industry and professional institutions.
- Safety Culture, Leadership and Stakeholder Participation – reflects evidence that technical safeguards alone cannot guarantee sustained safety performance. Leadership commitment, worker participation, organisational learning, communication and a positive safety culture are therefore treated as complementary components of engineering risk control.
- Monitoring, Learning, Innovation and Continuous Improvement – developed from the need to move beyond incident-driven intervention through systematic performance monitoring, reporting, investigation, learning from failures and near misses, use of emerging technologies and continuous improvement of safety systems.

The seven pillars are mutually reinforcing rather than sequential or independent. For example, safety-by-design may reduce inherent hazards, but its effectiveness depends on competent professionals, reliable assets, effective regulation and strong leadership. Similarly, incident learning can identify weaknesses in design, maintenance, competence or governance and feed those lessons back into subsequent projects and operational decisions. The framework therefore represents an attempt to establish a closed-loop safety engineering system in which technical, human, organisational, regulatory and learning mechanisms continuously strengthen one another.

Conceptually, the framework can be expressed as:

Design → Risk Control → Integrity & Reliability → Competence & Human Factors → Governance → Safety Culture → Learning & Innovation → Continuous Improvement → back to Design.

This provides the suggested conceptual foundation for positioning safety engineering in Nigeria not merely as an occupational accident-prevention discipline, but as an integrated mechanism for achieving safe, reliable, resilient and sustainable infrastructure and industrial development.

Pillar 1: Safety Governance and Regulatory Integration

Safety requirements should be incorporated into national, state and sectoral infrastructure policies from the earliest planning stage [46]. Every major infrastructure and industrial programme should have a documented Safety Governance Plan defining:

- applicable laws and standards;
- safety responsibilities;
- competent persons;
- approval requirements;
- risk-assessment requirements;
- inspection arrangements;
- emergency responsibilities;
- reporting requirements; and
- assurance mechanisms.

The National Policy on Occupational Safety and Health provides a foundation for such an approach [2].

Pillar 2: Safety-by-Design

Safety should be treated as a design criterion alongside functionality, cost and aesthetics. Major projects should incorporate formal design-safety reviews addressing:

- hazard identification;
- inherent risk reduction;
- structural integrity;
- fire and explosion protection;
- human factors;
- maintainability;
- emergency access;
- evacuation;
- environmental hazards;
- foreseeable misuse; and
- future modification.

The principle of inherently safer design is particularly relevant to industrial facilities because risks can often be reduced more effectively at the design stage than through subsequent procedural controls [10][42].

Pillar 3: Risk-Based Project Assurance

Every major infrastructure project should pass through defined safety gates:

- Gate 1 – Concept: preliminary hazard identification and site-risk assessment.
- Gate 2 – Feasibility: quantitative or semi-quantitative risk assessment where appropriate.
- Gate 3 – Detailed design: HAZOP, design review, structural review, fire-safety review, constructability and maintainability assessment.
- Gate 4 – Construction: inspection, testing, quality assurance and safety verification.
- Gate 5 – Pre-commissioning: mechanical completion and safety verification.
- Gate 6 – Commissioning: operational readiness and emergency preparedness.
- Gate 7 – Operation: periodic inspection, maintenance and risk reassessment.
- Gate 8 – Modification: management of change.
- Gate 9 – Decommissioning: safe isolation, dismantling and environmental restoration.

NUPRC's pre-start-up safety audit and review process provides an existing Nigerian example of this life-cycle assurance philosophy [16].

Pillar 4: Safety Culture and Human Factors

Engineering controls cannot operate independently of human and organisational systems. Nigerian evidence shows that management commitment, communication, empowerment, safety participation and safety culture are important determinants of safety performance [5][6][40].

Consequently, infrastructure organisations should establish visible leadership commitment; worker participation; stop-work authority; non-punitive reporting systems; safety learning systems; competency assurance; fatigue management; contractor safety management; human-factors engineering; and continuous safety communication.

The objective should be to create organisations where safety information moves upward as readily as instructions move downward.

Pillar 5: Asset Integrity and Reliability Management

Infrastructure should be managed as an asset throughout its entire life cycle. A national asset-integrity framework should cover inspection; preventive maintenance; predictive maintenance; corrosion control; structural health monitoring; electrical integrity; pressure equipment integrity; pipeline integrity; fire-protection integrity; safety-critical equipment; and ageing infrastructure. The combination of safety engineering and reliability engineering is especially important because failures that appear initially as reliability problems can become major safety events when they involve safety-critical systems [5][32][34].

Pillar 6: Digital Safety Engineering

Nigeria should exploit emerging digital technologies to improve infrastructure safety. A National Digital Safety Intelligence Platform could progressively integrate incident and near-miss data; infrastructure inspection records; structural-health monitoring; road-condition data; equipment reliability data; environmental monitoring; regulatory inspection findings; fire incidents; occupational injuries; process-safety events; and emergency-response information [7].

Artificial intelligence and machine-learning technologies can support accident prediction, anomaly detection and risk prioritisation, while sensors and smart infrastructure can provide continuous information on asset condition [13][39][44]. Such a system would allow Nigeria to move from incident statistics to risk intelligence.

Pillar 7: Learning, Investigation and Continuous Improvement

A mature safety system does not merely investigate accidents to establish blame. It investigates failures to identify weaknesses in systems and controls [7]. Every significant infrastructure or industrial incident should therefore generate immediate containment; technical investigation; root and systemic-cause analysis; identification of failed barriers; corrective actions; verification of corrective actions; and communication of lessons across relevant sectors.

This is particularly important because similar hazards often exist across multiple organisations. A major incident in one facility should therefore become a learning opportunity for the entire industry [7].

Institutionalising Safety Engineering in Nigerian Infrastructure Development

Institutionalising safety engineering in Nigerian infrastructure development requires the following institutional reforms:

A. Establish safety requirements at project approval stage

No major infrastructure project should receive final approval without evidence that significant safety risks have been identified and addressed. This aligns with the code of practice issued by the Nigerian Institution of Safety Engineers in 2023 to enhance the management of health and safety during construction work [47]. In line with the code of practice, project approval should consider:

Technical feasibility + economic feasibility + environmental feasibility + safety feasibility + resilience feasibility.

This would fundamentally change the current development philosophy by treating safety as a project-enabling criterion rather than a project-afterthought.

C. Strengthen the role of engineers

Professional engineers should have explicit responsibilities for safety assurance within their areas of competence. Engineering curricula and continuing professional development should place greater emphasis on systems safety; risk engineering; process safety; reliability; human factors; resilience; emergency engineering; climate-risk engineering; and safety-critical systems.

Safety engineering should not remain confined to specialised safety professionals. Every engineer involved in designing, constructing or operating safety-critical infrastructure should possess core safety-engineering competence.

D. Integrate safety into procurement

Government and private-sector procurement should move beyond the traditional emphasis on price, technical compliance and delivery schedule. Tender evaluation should explicitly consider contractor safety performance; technical competence; safety-management maturity; quality-management systems; previous incidents; competence of key personnel; maintenance strategy; and life-cycle cost. This approach would create market incentives for safer contractors and reduce the tendency to treat safety expenditure as unnecessary overhead.

A National Infrastructure Safety Performance Index

Nigeria should consider establishing a National Infrastructure Safety Performance Index (NISPI). The index could assess major infrastructure and industrial assets using indicators such as those presented in Table 1.

Table 1: Recommended National Infrastructure Safety Performance Index

Dimension	Illustrative indicators
Design safety	Design reviews, hazard studies, safety-critical design verification
Construction safety	Incident rates, quality failures, inspection findings
Asset integrity	Inspection compliance, maintenance backlog, equipment condition
Operational safety	Process-safety events, emergency readiness, safety violations
Human factors	Competence, fatigue, reporting culture, worker participation
Regulatory compliance	Inspection performance, unresolved non-conformities
Resilience	Flood, heat, climate and emergency resilience
Digital maturity	Sensors, predictive maintenance, digital records
Learning	Near-miss reporting, investigations and corrective-action closure

Such an index could provide government and asset owners with a common mechanism for comparing safety performance and prioritising interventions.

Financing Safety as Infrastructure Investment

One of the greatest barriers to safety integration is the perception that safety is a cost rather than an investment. This perception should change. Investment in safety can reduce fatalities; injuries; downtime; equipment damage; litigation; insurance losses; environmental remediation; emergency-response costs; production losses; reputational damage; and premature infrastructure replacement.

In infrastructure projects, therefore, the relevant financial question should not simply be *"How much does the safety measure cost?"* but *"What risk does the safety measure eliminate or reduce, and what is the life-cycle economic consequence of not implementing it?"* This approach aligns safety engineering with asset-management and investment decision-making.

Safety Engineering and Sustainable Development

Integrating safety engineering into infrastructure development is also consistent with the Sustainable Development Goals, particularly SDGs 3, 8, 9, 11 and 13 [9].

- SDG 3 – Good Health and Well-being: safer workplaces and infrastructure reduce injury and occupational-health risks.
- SDG 8 – Decent Work and Economic Growth: safe workplaces support productivity and decent work.
- SDG 9 – Industry, Innovation and Infrastructure: resilient and safe infrastructure is essential to sustainable industrialisation.
- SDG 11 – Sustainable Cities and Communities: safe buildings, transport networks and urban infrastructure support resilient communities.
- SDG 13 – Climate Action: climate-informed safety engineering strengthens infrastructure resilience.

The connection is particularly relevant to Nigeria because infrastructure expansion, industrialisation and urbanisation are occurring simultaneously with increasing climate and environmental pressures [3][4][9][45].

A Strategic Road Map for Nigeria

The following three-phase way forward is hereby proposed.

A. Phase I: Foundation (2026–2028)

The relevant Nigerian government agencies and bodies should:

- establish a national infrastructure safety policy;
- harmonise major safety requirements across sectors;
- strengthen regulatory capacity;
- develop a national infrastructure incident database;
- introduce safety requirements into major project approvals;
- strengthen engineering and safety competencies;
- establish minimum safety-engineering requirements for public projects.

B. Phase II: Integration (2028–2031)

The relevant government agencies and bodies should:

- implement risk-based infrastructure inspection;
- establish national safety performance indicators;
- integrate safety into public procurement;
- expand asset-integrity management;
- introduce digital safety monitoring;
- strengthen contractor safety qualification systems;
- institutionalise lessons-learned mechanisms.

C. Phase III: Maturity (2031 onward)

Nigeria should progressively move towards:

- predictive safety management;
- digital twins for critical infrastructure;
- AI-supported risk analysis;
- national infrastructure resilience modelling;
- integrated safety and reliability databases;
- Life-cycle safety certification; and
- continuous independent safety assurance.

The ultimate objective should be a system in which safety is embedded in the infrastructure's DNA rather than attached to it after design or construction.

DISCUSSION

The Nigerian experience demonstrates that the central challenge is not the complete absence of safety regulation or technical knowledge [7][16][18]. Nigeria possesses multiple regulatory instruments, professional institutions and sector-specific safety frameworks [2][5][16]. The deeper challenge is integration.

Safety frequently exists as a parallel function rather than as an integral part of engineering decision-making. Construction safety may be separated from structural design; occupational safety may be separated from procurement; process safety may be separated from project economics; road safety may be separated from road design; and maintenance may be separated from the original engineering design. Such fragmentation creates opportunities for hazards to pass through organisational boundaries.

The alternative is a systems approach in which safety is considered at every decision point. This is consistent with contemporary safety engineering, resilience engineering and systems-based risk approaches [5][10][42]. The Nigerian petroleum sector demonstrates that such integration is achievable. Requirements for design, construction, pre-start-up review, safety-critical equipment and operational readiness already demonstrate a life-cycle approach [5][16].

The challenge is to extend comparable principles to roads, bridges, public buildings, power infrastructure, water systems, manufacturing plants, mining operations and other critical infrastructure.

CONCLUSION

Nigeria's infrastructure and industrial development cannot be considered successful merely because projects are completed, factories are constructed, roads are opened or equipment is commissioned. Development becomes sustainable only when infrastructure and industrial assets can perform their intended functions safely, reliably and resiliently throughout their life cycles [9].

The evidence reviewed in this article indicates that Nigeria has made significant progress in establishing safety policies, regulations and sector-specific safety systems. Nevertheless, persistent problems involving construction safety, building failures, road infrastructure, power reliability, process safety, asset integrity, regulatory enforcement and safety culture indicate that safety engineering has not yet been fully integrated into national infrastructure and industrial development. The fundamental shift required is from reactive safety management to preventive and anticipatory safety engineering.

Safety should begin at policy formulation and continue through concept development, site selection, feasibility, design, procurement, construction, commissioning, operation, maintenance, modification and decommissioning. It must be supported by competent professionals, effective regulation, strong leadership, quality management, reliable data, digital technologies and continuous organisational learning.

The proposed seven-pillar framework - safety governance, safety-by-design, risk-based assurance, safety culture and human factors, asset integrity, digital safety intelligence, and learning and continuous improvement - provides a practical basis for this transformation. Nigeria's infrastructure future should therefore be guided by a simple principle: Infrastructure should not merely be built to serve people; it should be engineered to protect the people it serves.

Embedding safety engineering into infrastructure and industrial frameworks would not constitute an additional burden on development. Rather, it would represent an investment in the reliability, productivity, resilience and sustainability of Nigerian development itself.

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