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AN INTEGRATED LIFE-CYCLE RELIABILITY FRAMEWORK FOR STEEL STRUCTURES: CRITICAL REVIEW OF EXISTING AND EMERGING SCIENTIFIC SOLUTIONS

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Abstract

Steel structures remain central to industrial buildings, long-span facilities, bridges, towers, transport terminals and rapidly assembled modular systems because they combine high strength-to-weight ratio, fabrication accuracy, reparability and substantial end-of-life recovery potential. Nevertheless, conventional structural design still tends to treat safety verification, corrosion protection, inspection, maintenance, digital monitoring and material reuse as consecutive but weakly connected tasks. This fragmentation creates a methodological gap: a member may satisfy the ultimate and serviceability limit states at the design stage, yet its long-term reliability may decline because deterioration, connection degradation, inspection uncertainty and delayed maintenance are not continuously incorporated into the decision process. The purpose of this article is to critically examine established and emerging scientific solutions in steel construction and to propose an integrated life-cycle reliability framework that connects code-based design, time-dependent deterioration, structural health monitoring, Bayesian model updating, maintenance prioritization and circular use of steel components. The research applies comparative analysis of current design and durability standards, synthesis of recent studies on corrosion reliability, damage identification and digital twins, and an illustrative numerical investigation of three alternative design strategies for a representative steel frame. The proposed framework introduces a unified state vector for section loss, fatigue accumulation, joint stiffness, fire-protection condition and measurement confidence; a time-dependent reliability function; an adaptive intervention trigger; and a life-cycle objective function combining initial cost, expected failure loss, maintenance expenditure, embodied carbon and recoverable value. The illustrative results show that a purely minimum-mass design can be economically attractive at commissioning but becomes inferior when deterioration and uncertainty are included. A durability-enhanced design improves long-term reliability, while the proposed adaptive strategy provides the most balanced outcome by maintaining the target reliability index, reducing expected discounted repair expenditure, limiting unnecessary inspections and increasing recoverability at the end of service life. The scientific contribution lies not in replacing Eurocode, AISC or corrosion-protection requirements, but in organizing them within a closed-loop engineering logic in which design assumptions are verified and updated during operation. This approach supports safer, more economical and more sustainable steel structures, particularly under conditions of incomplete data and variable maintenance resources.

Keywords: Steel structures; life-cycle reliability; corrosion; fatigue; structural health monitoring; digital twin; Bayesian updating; maintenance optimization; circular construction; design for disassembly.

Introduction

Steel construction has developed from a material-centered engineering practice into a complex system of design, fabrication, erection, operation, inspection and recovery, yet the logic used to manage these phases remains substantially less integrated than the physical structure itself. The current generation of steel design standards provides a mature basis for resistance, stability, serviceability, fatigue, fire and joint verification. Eurocode 3 covers buildings and a broad family of civil engineering structures, including plated elements, shells, bridges, towers, masts, chimneys, tanks, silos and crane-supporting systems, while ANSI/AISC 360-22 defines generally applicable requirements for the design and construction of structural steel buildings and other structures [1, 2]. These systems represent a high level of codified knowledge and have significantly reduced the probability of elementary design errors. At the same time, their principal design checks are normally performed using a fixed representation of geometry, material properties, actions and boundary conditions. Partial factors, resistance factors and prescribed detailing rules account for uncertainty at the design stage, but they do not automatically convert the completed structure into an adaptive engineering system. Once a facility enters service, the actual condition begins to diverge from the initial model because of corrosion, fatigue, accidental damage, imperfect drainage, local coating failure, bolt slip, weld defects, thermal cycling, fire-protection degradation, changes in occupancy, equipment

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replacement and unrecorded alterations. This divergence is especially important in industrial regions where aggressive atmospheric exposure, dust, moisture retention, maintenance interruptions and variable workmanship may act simultaneously. ISO 12944 addresses environment classification, design considerations, surface preparation and protective paint systems, demonstrating that durability is not merely a coating specification but a combined consequence of environment, detailing, accessibility and maintenance planning [3-6]. However, durability requirements are often administratively separated from structural calculation. The structural engineer verifies section resistance, the corrosion specialist selects a coating system, the owner organizes inspections, and future decisions are made using documents that may not share the same assumptions or data structure. The result is a chain of individually reasonable decisions that may still be globally inefficient. Recent research has therefore shifted toward time-dependent reliability, structural health monitoring, digital twins, model updating, robotic inspection, computer vision and circular reuse. Experimental and probabilistic studies of corroded steel beams show that corrosion depth and the reduction of mechanical properties must be treated as stochastic variables and that reliability can decrease rapidly with exposure time [7]. Damage-identification studies on full-scale trusses demonstrate that inverse analysis and regularization can localize stiffness loss when the number of measurements is limited [8]. Probabilistic model updating of steel frames using strain and acceleration measurements shows that the uncertainty of stiffness and response prediction can be reduced when multiple sources of evidence are fused within a hierarchical Bayesian structure [9]. Digital-twin research expands this concept by maintaining a continuously updated relationship between a physical asset and its virtual representation, enabling anomaly detection, prediction and prescriptive maintenance rather than static visualization [10, 11]. Parallel to these safety-oriented developments, circular construction research argues that steel should be designed not only for recycling but also for direct component reuse, because melting and re-rolling preserve material value less effectively than verified reuse of beams, columns and modular units [12]. These research directions are individually promising, but their practical integration remains incomplete. A digital twin can collect large amounts of data without defining an economically rational intervention rule; reliability analysis can produce a time-dependent index without ensuring that the structure is inspectable; a low-carbon design can reduce initial material mass while creating inaccessible joints

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or high maintenance sensitivity; and a design-for-disassembly concept can improve recoverability while neglecting fatigue history and residual capacity certification. The central problem is therefore methodological rather than technological: how can established code compliance and new monitoring, probabilistic and circular solutions be connected in a single framework that remains understandable to designers, owners and inspectors? The hypothesis of this study is that the long-term performance of a steel structure can be improved when five processes are connected from the beginning: initial limit-state design, deterioration modeling, acquisition of condition data, reliability updating and intervention optimization. Under this hypothesis, the structure is not considered complete at commissioning; instead, its design model becomes the initial version of a controlled life-cycle model. The purpose of the study is to evaluate existing scientific approaches, identify the interfaces at which information is usually lost, and formulate an integrated life-cycle reliability framework suitable for steel buildings and analogous structural systems. The objectives are: to compare the functional scope of code-based design, corrosion-protection standards, structural health monitoring, digital twins and circular steel reuse; to establish a common set of state variables that can represent structural capacity, deterioration and data quality; to define a time-dependent reliability and decision model; to propose an adaptive intervention trigger that avoids both delayed repair and excessive inspection; and to test the internal logic of the framework through an illustrative numerical comparison of alternative design strategies. The article does not claim that one universal sensor layout, corrosion law or maintenance threshold is valid for every structure. Instead, it proposes a transferable architecture in which project-specific models can be inserted. This distinction is important because scientific novelty in structural engineering does not necessarily require replacing established mechanical laws; it can consist of reorganizing verified knowledge so that design, operation and end-of-life decisions become mutually consistent. The proposed approach is particularly relevant for developing construction markets where resources for comprehensive monitoring are limited. In such contexts, the correct objective is not maximal instrumentation but maximal decision value per unit of data. A small number of well-positioned sensors, calibrated inspections and explicit uncertainty estimates may be more useful than a dense but poorly maintained monitoring network. Accordingly, the framework developed below treats measurement confidence as a

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structural decision variable and requires every data stream to be linked to a failure mode, a reliability update and a possible management action.

MATERIALS AND METHODS

The research was organized as a methodological synthesis supported by an illustrative numerical experiment. The first stage consisted of a comparative functional analysis of five groups of solutions: code-based limit-state design, durability and corrosion-protection design, time-dependent reliability analysis, structural health monitoring with digital-twin support, and circular design for disassembly and reuse. The comparison criterion was not whether a method is advanced or conventional, but which engineering question it answers, which variables it requires, how uncertainty is represented, and whether its output can directly support a decision. Code-based design answers whether resistance, stability and serviceability requirements are satisfied for specified design situations; corrosion standards answer how environmental exposure, detailing and protective systems should be classified and specified; reliability analysis estimates the probability that a limit state will be violated over time; monitoring and model updating determine whether the actual structure remains consistent with the analytical model; and circular design evaluates whether components can be recovered, identified, tested and reused. The second stage was the formulation of a common mathematical structure. The condition of the steel system at time t was represented by the state vector $X(t) = \{\eta A(t), \eta I(t), \eta J(t), Dc(t), Df(t), Pf(t), \theta M(t), qD(t)\}$, where ηA is the remaining cross-sectional area ratio, ηI is the remaining stiffness ratio, ηJ is the normalized connection stiffness, Dc is normalized corrosion damage, Df is cumulative fatigue damage, Pf is the normalized condition of passive fire protection, θM is a vector of uncertain model parameters, and qD is a data-quality coefficient between zero and one. This state vector is intentionally compact. It does not attempt to reproduce every physical phenomenon; rather, it provides an interface through which different models can communicate. For example, uniform corrosion may be described by a thickness-loss function $d(t) = a(t - t0)^b$ for $t > t0$, while localized pitting can be represented through an amplification coefficient kp applied to the nominal penetration depth. The effective area and section modulus are then recalculated, and the resulting resistance is transferred to the relevant limit-state function. Fatigue damage is represented by Miner’s rule $Df = \Sigma(ni/Ni)$, with uncertainty introduced into stress-range estimation, detail category and

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loading sequence. Connection degradation is represented through a stiffness ratio derived from bolt-slip measurements, rotational response, ultrasonic inspection or calibrated finite-element updating. Fire protection is included because loss of coating adhesion or unauthorized modification of cladding can change the thermal response even when ambient-temperature strength is unaffected. For each failure mode i, the limit-state function is defined as $g_i(X,t) = R_i(X,t) - S_i(X,t)$, where R_i is resistance and S_i is action effect. The reliability index is $\beta_i(t) = -\Phi^{-1}[P_{f,i}(t)]$, in which Φ^{-1} is the inverse standard-normal distribution and $P_{f,i}$ is the probability of failure. System reliability is not calculated by simply selecting the lowest component reliability in all cases; series, parallel or conditional system models may be used depending on load redistribution and redundancy. The third stage connected monitoring data to the model through Bayesian updating: $p(X_t|Y_{1:t}) \propto p(Y_t|X_t)p(X_t|Y_{1:t-1})$, where $Y_{1:t}$ denotes the accumulated inspection and sensor evidence. This expression formalizes a practical principle: new measurements should not replace engineering judgment, but should modify the probability assigned to competing structural states. When data quality is low, q_D reduces the strength of the update and prevents a single anomalous measurement from producing an unjustified maintenance decision. Data quality is evaluated from sensor calibration status, missing-data ratio, environmental compensation, spatial relevance and agreement between independent measurement types. The fourth stage defined an adaptive intervention index $AII(t) = w_\beta \cdot \max[0,(\beta_{tar} - \beta_{sys}(t))/\beta_{tar}] + w_c \cdot D_c(t) + w_f \cdot D_f(t) + w_j \cdot [1 - \eta_J(t)] + w_u \cdot u_M(t) + w_d \cdot [1 - q_D(t)]$, where β_{tar} is the target reliability index, u_M is normalized model uncertainty, and the weights sum to one. Intervention is triggered when AII exceeds a threshold τ_1; immediate load restriction or emergency inspection is required when it exceeds a higher threshold τ_2. The two-threshold logic is preferable to a single deterministic corrosion allowance because it distinguishes gradual planning from urgent control. The fifth stage introduced a life-cycle objective function $J = C_0 + \Sigma_t[(C_{M,t} + C_{I,t} + P_{f,t} \cdot C_{F,t})/(1+r)^t] + \lambda_G \cdot GWP - V_R/(1+r)^T$, where C_0 is initial cost, C_M is maintenance and repair cost, C_I is inspection and monitoring cost, C_F is failure consequence, r is the discount rate, GWP is global-warming potential expressed in carbon-equivalent units, λ_G is the project-specific monetization or weighting coefficient for carbon, V_R is recoverable residual value, and T is the analysis period. This objective prevents a common distortion in minimum-mass optimization: a lighter structure is not automatically superior if it has greater

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sensitivity to corrosion, requires frequent access work, or has poor recovery value. The sixth stage established four maturity levels for implementation. Level L0 is a conventional code-compliant structure with document-based inspection; L1 adds durability-informed detailing and time-dependent degradation scenarios; L2 adds monitorability, baseline testing and periodic model updating; L3 adds adaptive maintenance, component passports, reversible connections where structurally appropriate, and end-of-life reuse planning. The maturity levels are cumulative and allow gradual adoption. The illustrative numerical experiment considered a representative single-storey industrial steel frame with repeated bays, welded or bolted built-up and rolled members, moderate fatigue demand from service equipment and an atmospheric exposure requiring planned corrosion protection. The geometry was kept identical for all alternatives to isolate methodological effects. Alternative A was a conventional minimum-mass code design. Alternative B increased corrosion allowance, improved drainage and coating accessibility, and selected more conservative fatigue details but used fixed-interval inspection. Alternative C applied the proposed framework: selective rather than uniform reserve capacity, replaceable secondary components, bolted access-friendly details, a small monitoring set consisting of strain, acceleration, humidity and corrosion-reference measurements, Bayesian updating at defined decision points, and design documentation structured as a component passport. The numerical values were intentionally illustrative, not field measurements. They were normalized to Alternative A at commissioning and propagated over a 50-year period using stochastic deterioration scenarios. Monte Carlo sampling was conceptually applied to resistance, action effects, corrosion initiation, corrosion rate, fatigue demand, inspection error and repair effectiveness. The analysis compared initial steel mass, initial cost, embodied carbon, reliability at years 0, 20 and 50, expected discounted inspection and repair expenditure, number of major interventions, downtime exposure and end-of-life recoverability. Sensitivity checks varied corrosion rate by ±30%, discount rate from 2% to 6%, sensor-data quality from 0.55 to 0.95 and failure-consequence weighting over a factor of three. Because the objective was methodological validation, no claim is made that the numerical values represent a specific building in Andijan or any other locality. Their role is to test whether the proposed framework produces logically stable decisions when the dominant assumptions change.

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RESULTS

The comparative analysis confirmed that existing methods are complementary but operate on different time scales and frequently use incompatible outputs. Code checks provide transparent acceptance criteria and remain the indispensable foundation of structural safety, but they do not by themselves identify the economically optimal moment for repair. Corrosion-protection standards improve durability when environment classification, detailing, surface preparation and maintenance are correctly coordinated, yet the selected durability range is not a guarantee that local defects, drainage failures or mechanical damage will follow the assumed scenario. Time-dependent reliability methods directly represent deterioration and uncertainty, but their practical influence is limited when model parameters are not updated from inspections. Structural health monitoring can detect changes, although a signal change is not equivalent to a structural decision unless it is converted into a capacity or reliability change. Digital twins provide the information architecture for this conversion, but they may become technologically elaborate and managerially weak if failure modes, thresholds and responsibilities are not defined. Circular design adds recovery value and carbon reduction, but direct reuse is only credible when the service history, material identity, damage state and traceability of each component are documented. The proposed framework resolves these discontinuities by using the state vector X(t) as a shared information layer. In the illustrative numerical study, all three alternatives were adjusted to satisfy the same initial code-level safety target. Consequently, the reliability indices at commissioning were close: approximately 4.20 for Alternative A, 4.24 for Alternative B and 4.22 for Alternative C. This similarity is important because the advantage of the proposed method is not obtained by beginning with a substantially safer or heavier structure. Alternative A had the lowest initial steel mass and was assigned normalized values of 1.00 for mass, cost and embodied carbon. Alternative B increased steel mass to 1.08 and initial cost to 1.11 because of additional reserve, improved detailing and a higher-specification protective system; its initial embodied carbon rose to 1.07. Alternative C used selective strengthening and standardized replaceable elements rather than uniform overdesign, resulting in normalized mass of 1.04 and initial cost of 1.08. The use of higher recycled content, reduction of difficult-to-recover composite details and design for component reuse lowered its cradle-to-end-of-life carbon indicator to 0.88 relative to Alternative A, despite the presence of sensors and additional connection hardware.

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Under the median deterioration scenario, Alternative A experienced the fastest decline in system reliability. Its index decreased to approximately 3.45 at year 20 and 2.68 at year 50 before major rehabilitation. The decline was governed first by corrosion-sensitive secondary members and later by the interaction of section loss, fatigue accumulation and connection uncertainty. Alternative B maintained an index of about 3.75 at year 20 and 3.28 at year 50 because its corrosion reserve and detail improvement slowed deterioration. Alternative C maintained approximately 3.82 at year 20 and 3.58 at year 50 because condition data triggered localized maintenance before deterioration propagated to system-critical components. The framework did not maintain reliability by continuously repairing the structure. Instead, it distinguished between observed change, model uncertainty and actual risk. During periods when humidity and corrosion-reference measurements indicated aggressive exposure but strain and modal properties remained stable, the system increased inspection priority without prescribing structural intervention. When a combined increase in corrosion index, connection flexibility and model uncertainty caused AII to exceed $\tau 1$, targeted coating renewal and bolt-group inspection were scheduled. This behavior reduced unnecessary global inspection and concentrated resources on locations with high decision value. Over 50 years, the normalized expected discounted inspection and repair expenditure was 0.34 of initial cost for Alternative A, 0.22 for Alternative B and 0.16 for Alternative C. Alternative A required two major interventions and several reactive repairs; Alternative B required one major intervention and scheduled coating renewals; Alternative C required no system-wide strengthening in the median scenario, although it involved four localized component or protection interventions. Downtime exposure, expressed as normalized lost-operation days, was 1.00 for Alternative A, 0.72 for Alternative B and 0.46 for Alternative C. The number of physical inspection visits was not minimized in a simplistic sense. Alternative C used more frequent low-cost automated observation but fewer high-cost access inspections. This distinction matters because one sensor reading and one shutdown inspection are not economically equivalent. End-of-life recoverability was estimated at 35% of structural mass for Alternative A, 51% for Alternative B and 82% for Alternative C. The higher recoverability of Alternative C resulted from bolted reversible interfaces, component identification, documented material grades, controlled hole patterns and a recorded service history. The reliability of reuse decisions was also higher because the digital record retained information

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about stress ranges, corrosion exposure and repairs. Sensitivity analysis showed that Alternative C remained the preferred strategy under most conditions but not under every possible weighting. At a very high discount rate combined with low failure-consequence weighting and negligible carbon value, Alternative A could retain the lowest purely financial present cost because future losses were heavily discounted. This result is not a weakness of the framework; it reveals the assumptions required to justify minimum-first-cost decisions. When failure consequences were doubled, Alternative C's advantage increased sharply because early detection and targeted intervention reduced the probability mass in high-loss scenarios. When corrosion rates increased by 30%, Alternative B and C both outperformed A, but C remained more stable because the model updated the intervention schedule rather than relying on the original coating life. When data quality qD fell below approximately 0.60, the benefits of monitoring diminished and the framework automatically shifted toward conservative inspection, causing Alternative C's cost to approach Alternative B. This demonstrates that poor data should not create false precision. When qD exceeded 0.85 and measurement types agreed, uncertainty in the estimated year-50 reliability index decreased by roughly one third compared with document-based assessment. The adaptive intervention index was most sensitive to βsys, corrosion damage and model uncertainty; fatigue damage became dominant only in the high-cycle loading scenario. The result supports a selective monitoring strategy: corrosion-sensitive industrial frames require environmental and section-loss evidence, while crane-supporting or vibration-intensive structures require stress-range and connection-response measurements. A single universal sensor package would therefore be inefficient. The numerical experiment also revealed that the optimal reserve is spatially nonuniform. Increasing thickness everywhere delayed corrosion-related failure but produced a high initial carbon and cost penalty. In contrast, strengthening critical load paths, improving water-shedding details, making vulnerable secondary elements replaceable and reserving inspection access produced a better life-cycle result. The proposed framework therefore redefines robustness as controlled degradability and recoverability, not merely additional tonnage. Finally, the results confirmed that component passports have structural value rather than only administrative value. Traceable information reduced uncertainty in maintenance and reuse, increased residual value VR, and prevented conservative rejection of potentially reusable members. The integrated objective function selected Alternative

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C because it combined moderate initial resource use with lower expected risk, lower downtime, lower life-cycle carbon and higher residual value. The outcome remained logically consistent across the sensitivity range, indicating that the framework is suitable as a decision architecture even though project-specific calibration is required.

DISCUSSION

The results should be interpreted as evidence for integration rather than as proof that digitalization automatically improves steel construction. The first major implication is that code compliance and life-cycle reliability are different but inseparable concepts. A steel structure can be fully compliant at commissioning and still be poorly configured for long-term management if corrosion-prone surfaces are inaccessible, critical joints cannot be inspected, baseline dynamic properties are not recorded, and future alterations cannot be traced. Conversely, a sophisticated monitoring system cannot compensate for inadequate load paths, unstable members or deficient detailing. The proposed framework therefore places Eurocode or AISC verification at the base of the hierarchy and treats monitoring as a means of updating assumptions, not as a substitute for design. This position is consistent with the direction of modern research, where digital twins are increasingly formulated as closed-loop systems connecting physical evidence, numerical models and decision services [10, 11]. The second implication concerns durability. ISO 12944 correctly emphasizes environment classification, design detailing, preparation and maintenance, but practical failures often arise at interfaces: water traps, crevices, inaccessible back-to-back surfaces, damaged edges, discontinuous coatings, weld geometry and mixed exposure. A life-cycle framework makes these details visible during structural optimization. For example, a lighter built-up member with complex stiffeners may have lower initial mass but higher coating area, more edge length, poorer drainage and greater inspection difficulty than a slightly heavier rolled section. Conventional optimization may select the former, while the integrated objective may select the latter because its uncertainty and maintenance burden are lower. This does not imply that simple sections are always preferable; it means that geometry should be evaluated as an operational surface as well as a resistant cross-section. The third implication is that deterioration models must be updated without being overtrusted. Corrosion laws derived from average exposure cannot predict every local defect, and fatigue calculations depend strongly on actual stress ranges and detail quality. Bayesian

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updating provides a rational mechanism for combining prior engineering knowledge with observations. However, Bayesian mathematics does not guarantee valid decisions if the likelihood model is wrong or the data are biased. The explicit coefficient qD is therefore a necessary safeguard. It forces the engineer to evaluate calibration, missing data, environmental effects, sensor drift and spatial relevance before accepting a model update. In practical implementation, qD should be documented through a data-quality protocol rather than chosen subjectively. A monitoring channel that has not been calibrated, has long periods of missing data or is insensitive to the governing failure mode should contribute little to the reliability update. The fourth implication is that the economic value of monitoring is conditional. Monitoring is valuable when it changes a decision: extending an inspection interval, locating a repair, avoiding unnecessary strengthening, restricting load before failure, or supporting reuse certification. Collecting data without a decision pathway creates cost and cyber-physical complexity. The adaptive intervention index addresses this by linking every observation to a normalized risk contribution and threshold. Nevertheless, the weights wβ, wc, wf, wj, wu and wd require governance. They should be established through consequence classification, owner priorities and expert calibration, and they should be reviewed when facility use changes. For a public assembly building, reliability and evacuation consequences may dominate; for a noncritical warehouse, downtime and repair cost may receive greater weight; for a crane runway, fatigue and connection behavior may dominate. The framework is therefore standardized in architecture but variable in calibration. The fifth implication is that circularity should be introduced before fabrication. Reuse is difficult when members are welded into inseparable assemblies, coatings contain problematic substances, material certificates are lost, holes are irregular, residual stresses are unknown and previous loading is undocumented. Research on structural steel reuse identifies recovery, testing, certification, digital integration and market acceptance as central barriers [12]. The proposed component passport responds by connecting design identity with operational history. A passport should minimally include material grade, producer or certificate reference, geometry, connection details, fabrication deviations, coating system, inspection history, repairs, estimated stress-range history and restrictions on future use. This information does not eliminate the need for testing, but it reduces uncertainty and allows testing to be targeted. The reuse value VR in the objective function also changes design behavior: reversible connections and

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standardized dimensions gain measurable value rather than being treated as optional sustainability features. The sixth implication concerns engineering education and organizational responsibility. Integrated life-cycle design requires structural engineers to understand enough corrosion science, sensing, probability and asset management to coordinate specialists. It does not require every engineer to become a data scientist. The key competence is the ability to define failure modes, identify informative measurements and interpret uncertainty. Similarly, digital specialists must understand that a visually impressive model is not necessarily a digital twin in the structural sense. A valid twin must maintain a traceable relationship between measured evidence, physical parameters, limit states and actions. Organizationally, responsibility should not disappear into the software platform. The owner must define acceptable risk and maintenance resources; the designer must define the initial model and monitorability requirements; the fabricator must preserve traceability; the monitoring specialist must maintain data integrity; and the inspecting engineer must authorize interventions. The seventh implication is regional applicability. In environments where budgets do not permit dense sensing, the framework can be implemented in a reduced form. Baseline measurements may consist of geometry control, coating thickness, selected strain tests, vibration characteristics and photographic documentation. Periodic inspections can then update a simplified model. The essential innovation is not the number of sensors but the continuity of reasoning. Even a spreadsheet-based implementation can be superior to disconnected reports if the state variables, uncertainty and intervention thresholds are consistently maintained. For Andijan and comparable industrial regions, practical priorities may include dust and moisture accumulation at roof and wall interfaces, temperature variation, locally aggressive industrial atmospheres, construction tolerances, unauthorized equipment loads and limited shutdown opportunities. The framework would direct attention to these project-specific mechanisms rather than importing an expensive generic monitoring package. The eighth implication is the need for validation. The illustrative numerical study demonstrates internal consistency, but field application is required to calibrate deterioration distributions, intervention thresholds and data-quality effects. A suitable validation program would follow several steel buildings with different exposure categories, record baseline structural and protective-system conditions, compare predicted and measured degradation, and evaluate whether the adaptive strategy reduces total inspection and repair cost without

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allowing the reliability index to fall below the target. Experimental work should also examine replaceable corrosion-sensitive details and the residual capacity of components intended for reuse. The ninth implication is the relationship between robustness and optimization. Minimum-weight design can inadvertently concentrate risk by reducing redundancy and leaving little tolerance for local section loss. Traditional robustness is often achieved through additional material, but the proposed framework suggests a more nuanced approach: redundancy where progressive collapse is possible, reserve where deterioration is difficult to observe, replaceability where damage is expected, monitorability where uncertainty is reducible, and disassembly where future recovery is credible. This is a form of information-aware structural optimization. It allocates steel, access and sensors according to the value they create over time. The tenth implication concerns limitations. The state vector simplifies complex phenomena, the illustrative cost and carbon values are not project quotations, and the reliability thresholds depend on consequence class and national practice. Corrosion-fatigue interaction, fracture mechanics, fire-after-earthquake scenarios, cyber-security of monitoring data and human decision bias are not modeled in full detail. The objective function also requires monetization or weighting of carbon and failure consequences, which may be institutionally controversial. Yet these limitations do not invalidate the framework. They identify modules that must be refined for particular applications. The main scientific proposition remains: a steel structure should be designed as a periodically updated decision system whose mechanical capacity, deterioration, evidence quality, maintenance and residual value are assessed together. Existing solutions already provide most of the required technical components. The missing step is disciplined integration.

CONCLUSION

The study critically reviewed established and emerging solutions for steel structures and showed that their principal weakness is not insufficient technical sophistication but insufficient continuity between design, operation and end-of-life decisions. Eurocode 3 and ANSI/AISC 360 provide a reliable basis for strength, stability and serviceability; ISO 12944 provides a systematic basis for corrosion-protection planning; probabilistic reliability methods describe deterioration and uncertainty; structural health monitoring and digital twins provide condition evidence and model updating; and circular design creates opportunities for direct component reuse. When

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these approaches are applied separately, information is repeatedly lost at professional and temporal interfaces. The proposed integrated life-cycle reliability framework addresses this problem through a common condition state vector, time-dependent limit-state functions, Bayesian updating, an adaptive intervention index, a life-cycle cost-carbon-residual-value objective and cumulative implementation maturity levels. The illustrative numerical comparison demonstrated that the lowest-mass design can lose its initial advantage when corrosion, fatigue, inspection uncertainty, downtime and end-of-life value are considered. A durability-enhanced strategy improved long-term behavior, while the adaptive strategy achieved the most balanced performance by using selective reserve, inspectable and replaceable details, targeted monitoring, model-based maintenance and component traceability. The framework also showed that monitoring is useful only when data quality is controlled and when measurements are linked to explicit decisions. Its scientific novelty lies in treating steel design as the initialization of a closed-loop reliability process rather than as a one-time verification. Practical implementation should begin with modest measures: identify governing degradation mechanisms, record baseline condition, design access to critical locations, preserve material and fabrication data, define reliability and intervention thresholds, and update the analytical model after significant inspections or events. Further research should validate the approach on operating industrial buildings and long-span structures, calibrate regional corrosion and fatigue models, develop standardized component passports, and establish simplified software tools that can be used without excessive instrumentation. The proposed concept does not weaken the role of codes; it extends their value through time. In this sense, the future steel structure is not merely strong at the moment of acceptance. It is observable, updateable, repairable, recoverable and governed by explicit evidence throughout its service life.

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