RT&A, No 4 (89)
Volume 20, December 2025

RELIABILITY-CENTERED INNOVATION PLANNING FOR COMPLEX INDUSTRIAL SYSTEMS

[1]Saadat Zeynalova, [2]Rana Mammadova, [3]Leyla Rahimova

•

Azerbaijan State Oil and Industry University, Baku, Azerbaijan
[1]saadat.zeynalova@asoiu.edu.az, [2]rana.mammadova@asoiu.edu.az,
[3]leyla.rahimova@asoiu.edu.az

Abstract

Ensuring the operational reliability of industrial systems is a critical requirement in the context of technical modernization and increasing system complexity. This paper proposes a reliability-centered methodology for evaluating and enhancing the performance of manufacturing assets during innovation-driven transformation. The approach integrates quantitative reliability metrics, including Mean Time Between Failures (MTBF), Mean Time To Repair (MTTR), and operational availability (Ao), into all phases of technical planning and implementation. Statistical modeling based on exponential and Weibull distributions is applied to failure datasets from mechanical engineering systems to estimate degradation rates and failure probabilities. A case study involving digital twins, CMMS integration, and scenario-based failure modeling demonstrates the effectiveness of predictive maintenance and real-time monitoring tools in reducing system downtime. The proposed framework contributes to the unification of reliability analysis and innovation strategy, offering practical tools for minimizing operational risks and optimizing life cycle costs (LCC) in industrial environments.

Keywords: reliability engineering, MTBF, operational availability, failure modeling, life cycle cost

I. Introduction

The increasing complexity and digitalization of industrial systems have made reliability a foundational criterion for sustainable production and operational excellence. In high-risk sectors such as energy, petrochemicals, mechanical engineering, and transportation, even short-term equipment failures can trigger cascading effects—causing significant economic losses, safety hazards, and reputational damage. Consequently, the ability to accurately model, predict, and improve system reliability has become a priority in both research and practice.

In traditional innovation planning and technical modernization processes, the focus is often placed on performance metrics such as output capacity, energy efficiency, or initial investment costs. While these indicators are essential, they do not reflect the long-term operational behavior of complex technical systems under varying loads, maintenance regimes, and environmental conditions. As a result, many enterprises face a growing gap between designed performance and real-world reliability, especially when upgrading legacy infrastructure [1].

The stochastic nature of failure processes, driven by wear, aging, material fatigue, software errors, and external disturbances, requires the use of probabilistic models and reliability estimation techniques. Common methods include exponential and Weibull failure distributions, Markov chains, reliability block diagrams (RBD), and failure trees. These tools enable engineers to assess metrics such as:

DOI: https://doi.org/10.24412/1932-2321-2025-489-471-478

- Mean Time Between Failures (MTBF) — for estimating average uptime,
- Mean Time To Repair (MTTR) — for evaluating maintainability,
- Availability (A) and Operational Availability (Ao) — to determine actual production readiness,
- Failure Rate Functions ($\lambda(t)$) — to describe dynamic degradation patterns.

However, despite the availability of advanced reliability engineering tools, they are rarely integrated into strategic planning stages of innovation cycles [2, 3]. This disconnect leads to suboptimal decisions, such as introducing new technologies incompatible with existing failure-prone components, or underestimating lifecycle maintenance costs and risks.

In response to these challenges, this study proposes a reliability-oriented framework for industrial innovation planning, designed to embed technical risk assessment and predictive reliability modeling into every phase of the modernization lifecycle. The approach is based on the following principles:

1. Quantitative reliability modeling using failure data and degradation trends;
2. System-level diagnostics supported by Computerized Maintenance Management Systems (CMMS);
3. Integration of digital twins and simulation environments to emulate system performance under variable conditions;
4. Scenario-based risk analysis for evaluating the impact of critical failures;
5. Life Cycle Cost (LCC) modeling incorporating downtime, maintenance, and recovery costs.

To validate the proposed approach, we examine a multi-unit case study at a mechanical engineering enterprise undergoing partial automation and digital transformation. Each unit faced different reliability bottlenecks—including aging heat-treatment equipment, sensor malfunctions in CNC machines, and insufficient failure monitoring on assembly lines [4]. By collecting real-world CMMS data, applying failure probability models, and simulating various degradation paths, we demonstrate how reliability-centered decision-making improves operational stability and reduces the payback period for technical investments.

This work contributes to the ongoing effort to align engineering reliability theory with practical needs of technical modernization, and to enable decision-makers to incorporate risk-based logic and lifecycle performance into industrial innovation strategies. Ultimately, it underscores the necessity of treating reliability not as a reactive maintenance task, but as a strategic design variable that governs system robustness, adaptability, and sustainability.

II. Formulation of the problem

Technical modernization of industrial enterprises, especially in asset-intensive sectors such as mechanical engineering, metallurgy, and process industries, is increasingly challenged by the need to balance innovation with system reliability. While the implementation of new technologies—such as robotic systems, advanced automation platforms, and sensor-based diagnostics—promises operational improvements, it also introduces new failure modes and amplifies the complexity of reliability assurance.

A fundamental problem lies in the absence of structured reliability diagnostics and probabilistic failure modeling at the strategic planning stage. In many industrial facilities, critical assets continue to operate well beyond their designed service life, exhibiting nonlinear degradation behaviors due to aging, thermal cycling, corrosion, and cyclic mechanical loads. These failure mechanisms often follow stochastic patterns that cannot be accurately predicted without appropriate reliability models, such as Weibull or exponential distributions.

In practice, however, planning decisions for modernization are often made based on economic feasibility and expected productivity gains, with insufficient attention paid to metrics such as:

- Failure rate functions $\lambda(t)$,
- Mean Time Between Failures (MTBF),
- Mean Time To Repair (MTTR),
- System availability (A) and operational readiness (Ao),
- Residual life estimation under varying stress profiles.

This results in a disconnect between the planned technical capabilities of newly introduced systems and the real-world performance under industrial operating conditions [5].

The lack of integration between innovation planning and reliability engineering leads to a range of systemic challenges that compromise the effectiveness of modernization efforts:

Aging equipment and infrastructure often contain latent defects and exhibit erratic failure behavior, which traditional deterministic models fail to capture. The absence of diagnostic audits or degradation modeling leads to underestimation of operational risks.

*Low system redundanc*y and inflexible architectures increase the likelihood of cascading failures. A single point of failure in interconnected production chains may result in complete production halts and safety hazards.

Inadequate monitoring mechanisms, such as the absence of condition-based maintenance (CBM) systems or digital twins, impede early failure detection and predictive maintenance scheduling.

Fragmented responsibility for innovation and maintenance creates organizational silos. Technical planners may overlook failure histories, while reliability engineers are not engaged in early-stage decision-making.

Insufficient use of reliability modeling tools, such as Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and Reliability Block Diagrams (RBD), limits the ability to forecast and mitigate failure risks.

A synthesis of these systemic issues and their impact on modernization efforts is presented in Table 1, which links each phase of innovation planning with relevant reliability factors and outlines possible consequences of neglecting reliability considerations.

Table 1 : *Relationship between reliability factors and stages of innovation planning*

Innovation Planning Stage	Key Reliability Factors	Potential Consequences	Response Measures
Current State Analysis	Equipment aging, hidden defects	Underestimation of modernization risks	Diagnostics, technical audits
Goal and Priority Setting	Ignoring reliability metrics	Unrealistic technical objectives	Inclusion of reliability criteria
Technology and Investment Selection	No evaluation of operational costs	Inappropriate technology choices	LCC analysis, failure forecasting
Design and Implementation	Unprepared production base	Failures, accidents, inconsistencies	Staff training, systems adaptation
Operation and Monitoring	Lack of monitoring and feedback mechanisms	Increased costs and downtimes	Implementation of CMMS, digital twins

This table provides a conceptual basis for embedding reliability engineering into industrial development workflows by identifying key intervention points for risk assessment and diagnostics.

These challenges are not merely theoretical. For instance, at a mechanical engineering plant, an attempt to integrate a robotic assembly line resulted in repeated shutdowns and reduced system availability during the first six months of operation. Root cause analysis revealed:

- Software incompatibility between new robotic modules and legacy conveyor systems;
- Electrical noise disrupting sensor feedback loops;
- Lack of pre-installation stress testing under nominal load conditions.

This case underscores the critical importance of evaluating technical compatibility, failure interactions, and degradation risks during the early design stages [6, 7]. The failure to do so not only delayed the realization of innovation benefits but also increased the total cost of ownership due to unplanned retrofitting and downtime.

To illustrate this conceptually, Figure 1 presents an extended innovation project lifecycle augmented with reliability checkpoints at each phase. The model emphasizes the iterative nature of reliability assessment, ensuring that system robustness, maintainability, and risk mitigation are evaluated continuously—from early-stage planning to long-term operation.

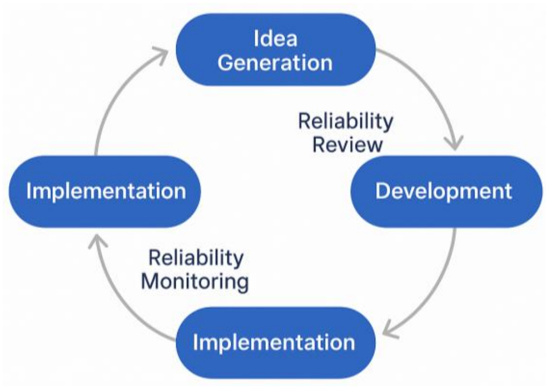

Figure 1: *Innovation project lifecycle with reliability assessments*

This model builds upon the PDCA (Plan–Do–Check–Act) framework, embedding reliability analysis into a cyclical improvement process. By incorporating feedback from operational monitoring (e.g., CMMS data, failure logs), enterprises can refine both technical designs and maintenance strategies over successive innovation cycles.

The innovation lifecycle presented in Figure 1 reflects the iterative nature of modern production development, where reliability is not treated as a static requirement but rather as a dynamic, continuously monitored parameter. Conceptually, this model draws upon the PDCA (Plan–Do–Check–Act) cycle, enabling a structured approach to innovation planning. At each phase — from initial idea formation to implementation and feedback — reliability assessments act as checkpoints that ensure not only the feasibility of proposed solutions but also their compatibility with existing infrastructure and long-term operational stability [8]. This cyclical integration fosters continuous improvement, allowing enterprises to refine their technical strategies based on real-world performance data and evolving risk profiles.

At the Idea Generation stage, strategic goals are formulated, and preliminary risk factors are identified. As the project advances to the Development phase, a Reliability Review is conducted to assess the compatibility of proposed innovations with the existing technical infrastructure, taking into account failure rates, readiness of production systems, and critical operational risks.

Taken together, the outlined technical challenges, empirical examples, and modeling gaps form a strong motivation for developing a reliability-based modernization framework. Such a framework should:

- Integrate quantitative reliability metrics into technical and economic evaluation criteria;
- Employ scenario modeling to simulate equipment behavior under variable operating conditions and failure probabilities;
- Include economic justification methods that account for reliability-driven savings, such as reduced downtime and optimized maintenance intervals.

The goal is to enable industrial enterprises to shift from reactive problem-solving toward proactive reliability assurance, where innovation becomes not just a source of performance gains, but a structured pathway to improved system dependability and operational resilience.

In the next section, a methodological framework is introduced that incorporates these principles into a unified reliability planning model for industrial modernization.

III. Problem solution

To address the reliability-related shortcomings identified in industrial modernization strategies, this study proposes an integrated framework that combines digital diagnostics, reliability modeling, and lifecycle risk analysis into the planning and execution phases of technical upgrades. The proposed approach enables the quantification of degradation effects and failure risks, allowing decision-makers to optimize investments not only for performance but also for long-term system dependability.

The core of the solution lies in embedding reliability and risk indicators into all key stages of the modernization project lifecycle. This is achieved through the following architectural elements:

1. Technical Audit and Risk Mapping: Assessment of existing equipment and infrastructure to identify critical failure modes, using tools such as FMEA and Root Cause Analysis (RCA).
2. Digital Reliability Twin: A digital replica of key assets, constructed using real-time monitoring data (e.g., temperature, load, cycle count), enabling the tracking of condition degradation over time.
3. Failure Modeling Engine: Application of statistical methods (Weibull, exponential, log-normal) to model time-to-failure distributions and predict residual life.
4. Reliability-Based Investment Justification (RBIJ): Economic analysis that includes expected cost of downtime, failure probabilities, and repair logistics in the evaluation of modernization options.
5. Lifecycle Monitoring System: Post-implementation tracking of reliability indicators and feedback into planning for continuous improvement.

This framework is illustrated conceptually in Figure 2, which shows the interaction between engineering systems, diagnostic data, reliability models, and decision modules [9, 10].

The framework promotes a closed-loop strategy, where reliability data informs both preventive maintenance and strategic decisions on system upgrades and replacements.

At the heart of the solution is the quantitative modeling of system reliability, which enables the estimation of future failure probabilities and degradation-driven risk. The approach is based on classical reliability engineering equations, adapted to real-world industrial systems with variable operational conditions.

For components with constant failure rate (memoryless process), the exponential distribution is used:

$$R(t) = e^{-\lambda t} \tag{1}$$

where λ is the failure rate (1/h).

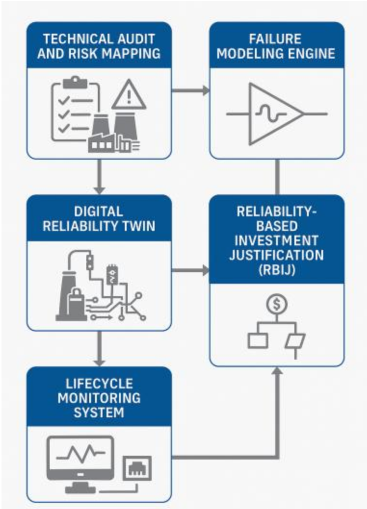

Figure 2: *Architecture of a reliability-integrated innovation planning system*

For wear-out dominated components, the 2-parameter Weibull distribution is more suitable:

$$R(t) = e^{-(t/\eta)^{\beta}}, \quad \beta > 1 \ \eta \, is \, the \, characteristic \, life$$

where: R(t)— reliability function, β— shape parameter (indicates failure pattern), η— scale parameter (characteristic life), t — operation time.

These models allow the calculation of key indicators such as Mean Time Between Failures (MTBF), system availability A, and unavailability Q=1−A.

In complex systems, where multiple components are connected in series or parallel, system-level reliability can be derived using Reliability Block Diagrams (RBDs):

For series systems:

$$R_{sys}(t) = \prod_{i=1}^{n} R_i(t) \tag{2}$$

For parallel systems (with redundancy):

$$R_{sys}(t) = 1 - \prod_{i=1}^{n} [1 - R_i(t)] \tag{3}$$

A comparative analysis of two modernization scenarios is presented in Table 2, where failure probability, MTBF, expected downtime, and total lifecycle cost are calculated for:

- Option A: Standard upgrade without diagnostic integration,
- Option B: Upgrade with digital twin and predictive maintenance tools.

The analysis demonstrates that although Option B requires higher initial investment, its total lifecycle cost is significantly reduced due to fewer failures, lower downtime, and optimized maintenance scheduling.

To validate the proposed framework, a case study was conducted on the modernization of a DC auxiliary power supply system in an industrial plant. The existing system, composed of two battery banks and a single charger unit, was prone to faults due to overloads and charger degradation.

Using field failure data and environmental load profiles, a reliability model was built using Weibull parameters (β=2.1, η=36 months). Simulation of 5-year operation using Monte Carlo methods revealed:

- Predicted failure rate reduction: 43%,
- Increase in system availability: from 89.2% to 96.5%,

- ROI achieved in 2.7 years due to reduced unscheduled downtimes.

The implementation of real-time monitoring and integration of predictive diagnostics enabled timely interventions and avoided catastrophic failures.

Table 2: *Comparative analysis: traditional vs. reliability-centered modernization approaches*

Aspect	Traditional Modernization	Reliability-Centered Modernization (RCM)
Planning Driver	Performance and cost priorities	Risk mitigation and system lifecycle integrity
Failure Modeling	Rarely applied, based on averages	Uses probabilistic failure data and degradation laws
Asset Condition Assessment	One-time visual/technical audit	Continuous or scheduled monitoring (CBM, PdM)
Decision Criteria	ROI, CAPEX/OPEX	Reliability metrics (MTBF, availability, failure rate λ) + financial factors
System Complexity Consideration	Often simplified or overlooked	Modeled through reliability block diagrams, FMEA, FTA
Maintenance Integration	Separate from planning process	Integrated as a feedback loop (RCM principles)
Digital Tools	Spreadsheets, static databases	Digital twins, IoT-based monitoring, reliability modeling software
Resulting Reliability	May stagnate or decline post-upgrade	Improved mean time between failures, higher system availability
Risk Visibility	Low – qualitative and intuitive	High – quantitative, with scenario-based sensitivity analysis

IV. Conclusion

Amid the accelerating pace of technological transformation in industry, it has become increasingly evident that traditional approaches to the modernization of technical systems—primarily focused on performance metrics and capital expenditures—are no longer sufficient to meet the demands of sustainability, operational safety, and reliability. The lack of systematic integration of reliability indicators at the planning stage often leads to structural vulnerabilities that manifest as frequent failures, increased maintenance costs, and inefficient resource utilization.

The reliability-centered planning (RCP) framework presented in this study offers a systemic alternative, where decision-making is guided not only by economic factors but also by quantifiable indicators of failure probability, component degradation, restoration time, downtime costs, and the cascading impact of failures on interconnected subsystems. The use of probabilistic modeling (e.g., Weibull distribution), system-level reliability analysis, integrated condition monitoring, and scenario-based failure analysis enables a more comprehensive and forward-looking strategy for modernization.

As shown in Table 2, the comparative analysis clearly demonstrates that transitioning from reactive or cost-centric planning to reliability-oriented strategies yields tangible benefits in reducing operational risks and improving long-term system efficiency. This approach is particularly critical for industries where failures have high-stakes consequences—such as energy, oil and gas, heavy manufacturing, and transportation—where reliability is not merely a technical parameter but a key determinant of safety, regulatory compliance, and economic resilience.

RT&A, No 4 (89)
Volume 20, December 2025

The successful adoption of RCP, however, requires a certain level of organizational maturity. This includes access to failure history data, the implementation of digital monitoring infrastructure, analytical expertise in reliability modeling and risk assessment, and a willingness to reassess conventional practices in asset planning and investment allocation. Despite the potentially higher initial costs, practical experience indicates that even partial implementation of reliability-centered strategies significantly enhances risk visibility, system availability, and return on investment.

In this light, RCP emerges as a vital step in the evolution of sustainable industrial development strategies. By embedding reliability principles into the early phases of technical and innovation planning, organizations can foster a more resilient, adaptive, and data-driven approach to managing complex systems. This not only leads to technically sound modernization outcomes but also ensures a balanced trade-off between innovation, lifecycle reliability, and economic viability under conditions of increasing system complexity and uncertainty.

References

[1] Trachuk, A.V., & Linder, N.V. (2021). Assessing the innovation potential of industrial enterprises. *Strategic Decisions and Risk Management*, 12(4), 292–311.

[2] Ponomarev, A.A., & Kirsanov, S.V. (2020). Equipment reliability in the context of production process digitalization. *Engineering Bulletin*, 8, 45–51.

[3] Belyaev, S.V. (2022). Managing techno-economic development in industry under resource constraints. *Economics and Management*, 10(2), 55–64.

[4] UralMet JSC internal report on rolling mill modernization (2023).

[5] Grishin, A.I., & Vasiliev, P.N. (2021). Methodology for reliability assessment in strategic innovation planning. *Problems of Forecasting*, 3, 110–118.

[6] ISO 55000:2014. *Asset management – Overview, principles and terminology*. International Organization for Standardization.

[7] Lee, J., Bagheri, B., & Kao, H.A. (2015). A cyber-physical systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3, 18–23.

[8] S. Kamble, A. Gunasekaran, and R. Sharma (2020) Modeling the blockchain-enabled traceability in agriculture supply chain, *Computers in Industry*, vol. 111, pp. 103178, 2020. doi: 10.1016/j.compind.2020.103178

[9] B. Bagheri, S. Yang, H.-A. Kao, and J. Lee, (2015) Cyber-physical systems architecture for self-aware machines in Industry 4.0 environment, *IFAC-PapersOnLine*, vol. 48, no. 3, pp. 1622–1627, 2015. doi: 10.1016/j.ifacol.2015.06.318

[10] J. Lee, B. Bagheri, and H.-A. Kao, (2015) A cyber-physical systems architecture for Industry 4.0-based manufacturing systems, *Manufacturing Letters*, vol. 3, pp. 18–23, 2015. doi: 10.1016/j.mfglet.2014.12.001