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The Convergence Exposure Premium: A Risk-Adjusted Model for Industrial Digital Transformation and IT/OT Connectivity

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Abstract

Industrial digital transformation is frequently justified through expected productivity, visibility, and analytics gains, yet investment cases often omit outright failure, value-destructive underperformance, lifecycle support, cyber exposure, and connectivity debt. This paper develops the Convergence Exposure Premium (CEP) and Risk-Adjusted Industrial Transformation Value (RAITV) framework for evaluating industrial digital transformation and information technology/operational technology (IT/OT) connectivity. Unlike conventional risk-adjusted net present value, expected-loss, cybersecurity-investment, and real-options approaches, the framework isolates the incremental cyber loss attributable to a proposed connectivity architecture and combines it with maturity-adjusted success, underperformance, and failure branches. An integrative evidence synthesis and model-based sensitivity analysis were used. All monetary inputs were defined as five-year discounted present values, using an illustrative 8% discount rate, and normalized to base-year annual revenue of 100 units. Under the stated triangular assumptions, a fixed-seed Monte Carlo analysis of 20,000 runs produced a median RAITV of −0.040 and 51.6% negative runs; these values describe model behavior rather than an industry failure rate. Scenario results show that broad convergence can be negative-value when benefits are modest and exposure is high, while selective digitalization on mature operations can remain positive. The contribution is an architecture-sensitive, reproducible investment framework that treats non-connection, read-only exchange, and bidirectional convergence as explicit alternatives rather than assuming convergence is inevitable.

Keywords

Digital Transformation, IT/OT Convergence, Industrial Management, Cyber Risk, Risk-Adjusted Investment

1. Introduction

Industrial firms are increasingly encouraged to connect operational technology (OT) to enterprise information technology (IT), cloud platforms, analytics environments, vendor services, and artificial intelligence workflows. The stated rationale is familiar: connected operations promise better visibility, predictive maintenance, energy optimization, quality control, supply chain coordination, and faster management decisions. These benefits are real in some settings, but the investment narrative often treats connectivity as a modernization default rather than as a risk-bearing economic decision.

This paper takes a different position. In industrial environments, the decision to connect OT systems should be evaluated like any other investment that changes a firm's risk profile. A connection that exposes a control environment to enterprise systems is not only a data pathway. It can also become an operational dependency, a cyberattack pathway, a support burden, and a source of technical debt. The relevant investment question is therefore not simply whether digital transformation can produce value. The question is whether the expected value remains positive after accounting for implementation failure, operating burden, connectivity debt, and increased cyber losses.

The literature supports this more cautious framing. Meta-analytic evidence indicates that digital technologies produce a positive but moderate effect on firm performance, with financial performance effects smaller than innovation and operational efficiency effects (Oduro et al., 2023). Related operations research shows that lean manufacturing and digitalization can complement one another, but it also warns that digital tools yield stronger results when built on mature operational practices rather than used as substitutes for them (Buer et al., 2021; Tortorella et al., 2019). Consulting and implementation research further indicates that large-scale digital programs frequently fall short of their intended objectives (Boston Consulting Group, 2020, 2024).

At the same time, OT connectivity risk is no longer only a theoretical cybersecurity concern. NIST SP 800-82 Revision 3 defines OT as systems and devices that monitor or control physical processes and emphasizes that OT security must account for performance, reliability, and safety requirements (Stouffer et al., 2023). Joint secure-connectivity guidance from CISA and international partners similarly treats connectivity into OT environments as something that must be deliberately designed, limited, monitored, and isolated when needed (Cybersecurity and Infrastructure Security Agency [CISA] et al., 2026).

The purpose of this paper is to develop a risk-adjusted model that evaluates industrial digital transformation and IT/OT convergence within a single decision structure. The mathematical components draw on established expected-value and present-value logic. The theoretical novelty is the industrial architecture decomposition: the Convergence Exposure Premium measures differential expected cyber loss between a proposed converged architecture and a less-exposed counterfactual, while RAITV combines that exposure with lifecycle present-value costs,

connectivity debt, operational-maturity effects, and explicit success, underperformance, and failure branches. This makes non-connection and limited-connectivity architectures comparable investment alternatives rather than treating full convergence as the default.

2. Literature and Motivation

The model developed in this paper is built on five bodies of literature: digital transformation value, operational maturity and lean production, transformation execution failure, cyber risk arising from IT/OT convergence, and investment valuation under uncertainty. These literatures are often discussed separately. Industrial investment decisions, however, require them to be evaluated together. **Table 1** summarizes how each evidence stream is incorporated into the model.

2.1. Digital Transformation Value Is Positive but Conditional

The empirical literature does not support the claim that industrial digital transformation is worthless. It also does not support the stronger marketing claim that digitalization produces automatic or large-scale returns. Oduro et al. (2023) conducted a meta-analytic review of digital technologies and firm performance and found a positive but moderate overall relationship, with the strongest effects appearing in innovation performance, followed by operational efficiency, and then financial performance. This ordering matters because investment decisions are ultimately judged against cost, risk, and cash-flow consequences rather than technological novelty alone.

The broader IT-productivity literature reaches a similar conclusion: some firms benefit from IT investment while others do not, and observed returns may be delayed or obscured by adjustment lags, measurement problems, exaggerated expectations, and management failures (Hajli et al., 2015; Schweikl & Obermaier, 2020).

Industry 4.0 studies provide further evidence of that heterogeneity. Studies of Industry 4.0 adoption show that returns vary by technology type, firm capability, and implementation context. Bettiol et al. (2019), using data from 1,149 Italian firms, found positive performance effects among adopters, particularly for robotics and laser cutting, but no cumulative benefit from adopting more than one or two Industry 4.0 technologies. Recent meta-analytic work on lean and Industry 4.0 synergy also suggests that the combined effect is positive but weaker and more contradictory than optimistic transformation narratives imply (Biondo et al., 2024). The practical implication is that broad transformation portfolios may not compound value simply because more technologies are adopted.

2.2. Operational Maturity and Lean as Prerequisites

A second literature stream emphasizes operational maturity. Lean production has a stronger and more mature evidence base than many digital-transformation narratives. Abreu-Ledón et al. (2018) found a positive relationship between lean production and business performance, while Buer et al. (2021) found that lean man-

ufacturing and factory digitalization can both improve operational performance. Crucially, their interpretation is not that lean is obsolete. Rather, lean practices remain important because they help firms realize the benefits of emerging digital technologies.

Tortorella et al. (2019) reached a similar practical conclusion from a different angle: purely technological adoption is insufficient, and Industry 4.0 can even moderate lean effects negatively when organizational practices are weak. Črešnar et al. (2022) further argued that technological and non-technological factors must be considered together, as productivity effects are mediated by business model, structure, culture, and strategy. This body of work supports an ordering principle: operational maturity should precede broad convergence. A plant that lacks process discipline, ownership, data quality, maintenance discipline, and workforce capability is unlikely to transform safely or profitably by adding more connectivity.

2.3. Execution Failure and Underperformance

A third literature stream addresses program execution. Digital transformation is not a single tool purchase. It is usually a multi-year program involving systems integration, business process redesign, data governance, workforce change, vendor dependencies, and ongoing support. BCG's digital transformation research reports that a large share of digital transformations fall short of their objectives, and its 2024 technology-program research emphasizes delivery problems involving time, budget, and scope (Boston Consulting Group, 2020, 2024). Even where exact failure-rate estimates vary by definition, the direction of the finding is stable: underperformance is common enough that it belongs in the investment model.

This matters because standard project justification often places projected benefits in the numerator while treating the failure branch as a footnote. A risk-adjusted model should instead assign value to multiple outcome branches: full success, partial success, failure, and value-destructive underperformance. A program with a large potential benefit but a low probability of success may be economically inferior to a smaller, more selective investment with higher implementation confidence and lower exposure.

2.4. Cyber Risk and IT/OT Convergence Exposure

The fourth literature stream concerns cyber exposure. Successful cyberattacks can impose firm-level financial consequences beyond immediate restoration costs. Kamiya et al. (2021) found that successful cyberattacks are associated with negative market reactions and changes in firm risk management and investment behavior. IBM's 2025 breach-cost research reports a global average breach cost of USD 4.44 million, noting that costs vary by geography, industry, containment time, and governance (IBM, 2025). Industrial firms may face additional costs when cyber events disrupt production, logistics, safety-critical operations, or customer delivery.

OT convergence intensifies this issue because operational technology supports

physical processes. Direct access from enterprise systems into control networks, persistent vendor tunnels, remote engineering paths, production historian access, cloud dashboards, and unmanaged edge gateways can change both the likelihood and the consequences. The Colonial Pipeline ransomware incident illustrates the coupling problem: the pipeline system was proactively shut down in response to a ransomware attack, even though public accounts emphasize the role of business and billing systems in the operational disruption (U.S. Department of Energy, 2021). Dragos's 2026 OT cybersecurity reporting also indicates that ransomware continues to affect industrial organizations at scale, with manufacturing heavily represented (Dragos, 2026).

These sources do not imply that every connection is irrational. They do imply that IT/OT convergence is not a free enabler of data value. It creates an exposure premium that should be included in the investment calculation.

Table 1. Evidence base and use in the risk-adjusted model.

Evidence stream	Use in the model
Digital transformation value	Oduro et al. (2023), Biondo et al. (2024), and Perrier et al. (2026) support treating benefits as positive but heterogeneous and often modest.
Operational maturity and lean	Abreu-Ledón et al. (2018), Buer et al. (2021), Tortorella et al. (2019), and Črešnar et al. (2022) support sequencing digitalization after process maturity.
Execution risk	Boston Consulting Group (2020, 2024) and de Waal (2026) support explicit probability-weighted treatment of underperformance and failure.
Cyber and convergence exposure	Stouffer et al. (2023), Cybersecurity and Infrastructure Security Agency et al. (2026), Kamiya et al. (2021), IBM (2025), and Dragos (2026) support inclusion of cyber loss and connectivity exposure.
Investment and risk valuation	National Institute of Standards and Technology (2012), Gordon and Loeb (2002), Benaroch and Kauffman (1999), and Schwartz and Zozaya-Gorostiza (2003) position the model relative to expected-loss, cybersecurity-investment, discounted-cash-flow, and real-options approaches.

2.5. Theoretical Positioning and Novelty

Conventional risk-adjusted net present value discounts expected project cash flows and may reflect risk through scenario cash flows or the discount rate. Expected-loss methods estimate risk from likelihood and impact (National Institute of Standards and Technology, 2012). The Gordon-Loeb model evaluates the economically rational level of information-security investment relative to vulnerability and expected loss (Gordon & Loeb, 2002). Real-options models value the flexibility to defer, stage, expand, contract, or abandon information-technology investments under uncertainty (Benaroch & Kauffman, 1999; Schwartz & Zozaya-Gorostiza, 2003). These approaches are useful, but they answer different questions.

Related value-based work on digital-twinning opportunities in infrastructure as-

set management likewise emphasizes evaluating individual digital investments rather than assuming that technological potential itself demonstrates value, although it addresses a different asset-management decision context (Vieira et al., 2024).

CEP and RAITV do not claim new expected-value algebra. Their novelty is a domain-specific decomposition for IT/OT convergence: an explicit, less-exposed architecture counterfactual; a separately visible connectivity-debt term; maturity-mediated outcome probabilities and payoffs; and an incremental cyber-loss term attributable to the selected connectivity state. Table 2 compares the approaches. The CEP-RAITV framework can be used as a transparent pre-screen or as an input to a full net-present-value or real-options analysis when timing and managerial flexibility must also be valued.

Table 2. Positioning of CEP and RAITV relative to established valuation approaches.

Approach	Core logic and variables	Typical scope or limitation for IT/OT
Risk-adjusted NPV/discounted cash flow	Discounted expected cash flows; risk reflected through scenarios or discount rate	General capital budgeting; architecture-specific cyber exposure may be embedded rather than visible
Expected-loss risk assessment	Likelihood multiplied by impact, commonly by threat-event category	Risk prioritization; does not ordinarily include transformation benefit, lifecycle cost, or program failure
Gordon-Loeb cybersecurity investment	Vulnerability, expected loss, and effectiveness of security spending	Optimizes security spending rather than valuing a digital-transformation connectivity choice
Real-options valuation of IT	Values flexibility to defer, stage, expand, contract, or abandon	Strong for timing and flexibility; does not inherently isolate OT connectivity exposure
CEP/RAITV	Outcome probabilities and payoffs, lifecycle costs, maturity, connectivity debt, and differential cyber loss	Industrial digital transformation and IT/OT connectivity over a defined horizon

Note. CEP and RAITV are intended to complement rather than replace established financial and cy-bersecurity-risk methods. NPV = net present value.

3. Materials and Methods

This paper uses integrative evidence synthesis and model-based sensitivity analysis. It does not collect new human-subject data, private organizational data, or operational telemetry. The study is intended to develop a decision model for industrial and business management rather than to estimate a universal ROI value for digital transformation.

3.1. Evidence Selection and Synthesis

Searches were conducted from 30 June through 8 July 2026 and refreshed on 20 July 2026. The primary discovery interface was Elicit, whose academic search corpus includes Semantic Scholar and OpenAlex (Elicit, 2026). Targeted verification and update searches were conducted in ScienceDirect, SpringerLink, Taylor & Francis Online, Emerald Insight, IEEE Xplore, and INFORMS PubsOnLine, together with official websites maintained by NIST, CISA, the U.S. Department of Energy, IBM, Boston Consulting Group, and Dragos. Five query blocks were used: (1) "digital transformation" AND (firm performance OR productivity OR ROI OR return on investment) AND (manufacturing OR industrial OR Industry 4.0); (2) ("lean manufacturing" OR "operational maturity") AND (digitalization OR Industry 4.0) AND performance; (3) ("digital transformation" OR "technology program") AND (failure OR underperformance OR delay OR budget); (4) ("IT/OT convergence" OR "operational technology connectivity") AND (cyber risk OR ransomware OR incident cost OR exposure); and (5) ("risk-adjusted net present value" OR "expected loss" OR "cybersecurity investment" OR "real options") AND (information technology OR digital transformation OR cybersecurity).

The primary publication window was 1 January 2015 through 20 July 2026. Pre-2015 sources were retained only when they were foundational to cybersecurity investment, risk assessment, real-options valuation, or information-technology productivity research. Eligible sources were English-language peer-reviewed meta-analyses, systematic reviews, empirical firm- or plant-level studies, foundational valuation studies, and official guidance or reports providing current risk, incident, cost, or connectivity evidence. Records were deduplicated by title, screened at title and abstract, and then reviewed in full text or through an authoritative publication record when directly relevant. Duplicate records, unsupported marketing case studies, opinion pieces without identifiable evidence, and sources without direct relevance to industrial performance, transformation execution, operational maturity, IT/OT exposure, or investment valuation were excluded. The three exported Elicit source sets contained 46 records and 44 unique titles. Twenty-one substantive sources were retained after the original verification, and three additional foundational valuation and risk-assessment sources were retained after the Reviewer 2 search, producing a final synthesis of 24 sources.

3.2. Model Development Procedure

The model was developed in four stages. First, recurring benefit and cost categories were extracted from the literature. Second, established valuation families were compared to identify which conventional net-present-value, expected-loss, cybersecurity-investment, and real-options methods already capture and which remain specific to IT/OT convergence. Third, the retained categories were converted into variables that a firm can estimate before investment approval. Fourth, the variables were combined into a normalized risk-adjusted value equation and evaluated through deterministic scenarios and Monte Carlo sensitivity analysis. The output

is not a predictive model for a particular company. It is a decision structure that makes the architecture-specific downside branches visible rather than burying them in a discount rate or narrative risk register.

3.3. Evaluation Horizon, Units, and Discounting

The illustrative model uses a five-year evaluation horizon (H = 5) and an 8% annual discount rate (r = 0.08). All monetary benefits, costs, debt, and losses are converted to time-zero present values and then normalized so that base-year annual revenue (R_0) equals 100 units. A normalized value of 1.0, therefore, represents a five-year present value equal to 1% of base-year annual revenue. Implementation cost is treated as a one-time, time-zero amount. Operating/support cost is the discounted present value of recurring annual licensing, staffing, monitoring, and support. Branch payoffs, connectivity debt, and incident loss are also five-year discounted present values. Outcome and incident probabilities are cumulative over the same five-year horizon, while maturity and exposure multipliers are dimensionless.

The five-year horizon and 8% discount rate are transparent analytical defaults rather than universal industry parameters. A firm applying the framework should substitute its approved capital-planning horizon and discount rate and recompute every present-value input before calculating CEP or RAITV. The simulation inputs supplied with this paper are already-discounted lifecycle present values; the reproduction code performs no hidden discounting. Table 3 defines the variables, units, and evaluation periods used throughout the model.

Table 3. Variable definitions, units, and evaluation periods.

Symbol	Definition	Unit and evaluation period
H; r; R_0	Evaluation horizon; annual discount rate; base-year revenue normalization base	5 years; 8% per year; R_0 = 100
m	Operational maturity	Dimensionless, 0 - 1
p_{s0}; p_{f0}	Baseline success and failure probabilities	Cumulative over H
p_s; p_u; p_f	Maturity-adjusted, mutually exclusive outcome probabilities	Dimensionless; sum to 1
B_s; B_u; B_f	Lifecycle payoff in success, underperformance, and failure branches	Discounted present value over H, normalized to R_0
C_i	One-time implementation and integration cost	Time zero, normalized to R_0
C_o	Recurring operating and support cost	Discounted present value over H, normalized to R_0
C_d	Deterministic connectivity-debt cost	Discounted present value over H, normalized to R_0
p_i	Baseline probability of at least one qualifying cyber incident	Cumulative over H
L	Conditional lifecycle loss from a qualifying incident	Discounted present value over H, normalized to R_0

Continued

M_c	Expected-loss ratio of converged to counterfactual architecture	Dimensionless; 1 means no increment
CEP	Incremental expected cyber loss caused by convergence	Discounted present value over H, normalized to R_0
RAITV	Risk-adjusted industrial transformation value	Discounted present value over H, normalized to R_0

Note. Subscript 0 denotes a baseline value before the operational-maturity transformation. All monetary values must use the same currency basis, horizon, discount rate, and revenue normalization.

3.4. Scenario and Sensitivity Analysis

The scenario and Monte Carlo analyses use the five-year present-value and revenue-normalization convention in Section 3.3. In the absence of universal empirical distributions for industrial-transformation inputs, bounded triangular distributions were used because they permit a transparent minimum, most-likely value, and maximum. Table 4 reports every primitive distribution, range, unit, and rationale.

The Monte Carlo experiment used 20,000 simulations generated with Python 3.13.5 and NumPy 2.3.5 default_rng (PCG64), with fixed random seed 20260520. Primitive inputs were sampled independently; no exogenous correlation matrix was imposed. Each run followed the same calculation sequence: sample the 12 primitive inputs from Table 4; apply the operational-maturity transformations in Equations (3)-(6); derive the underperformance probability as the residual outcome branch; calculate CEP with Equation (7); and calculate RAITV with Equation (1). Dependence was introduced only through the explicit maturity transformations, so the same maturity draw affected success probability, failure probability, underperformance payoff, connectivity debt, and the convergence exposure multiplier.

Table 4. Monte Carlo primitive input assumptions and rationale.

Input (symbol)	Triangular minimum/mode /maximum	Unit/ period	Rationale
Operational maturity (m)	0.20/0.60/0.95	Dimensionl ess, 0-1	Represents process stability, standard work, maintenance discipline, data ownership, workforce capability, and governance
Baseline success probability (p_{s0})	0.25/0.50/0.75	5-year probability	Allows low-confidence through strong-but-not-certain execution
Baseline failure probability (p_{f0})	0.02/0.08/0.18	5-year probability	Represents abandonment or value-destructive failure before maturity adjustment

Continued

Successful benefit (B_s)	1.00/3.50/8.00	5-year PV, normalized	Covers modest through strong lifecycle benefit without assuming a universal return
Underperformance payoff (B_{u0})	−0.50/0.75/3.00	5-year PV, normalized	Permits partial value, neutrality, or value destruction
Failure payoff (B_f)	−2.00/−0.50/0.00	5-year PV, normalized	Captures write-off, abandonment, disruption, or recovery beyond common costs
Implementation cost (C_i)	0.50/1.30/3.00	Time-zero, normalized	One-time acquisition, engineering, integration, validation, and deployment burden
Operating/support cost (C_o)	0.10/0.40/1.00	5-year PV, normalized	Discounted recurring licensing, staffing, monitoring, and support
Connectivity debt (C_{d0})	0.02/0.20/0.75	5-year PV, normalized	Deterministic lifecycle burden from interfaces, identities, patching, vendor support, and obsolescence
Incident probability (p_i)	0.003/0.025/0.080	Cumulative 5-year probability	At least one qualifying event under the less-exposed counterfactual
Conditional incident loss (L)	1.00/3.50/12.00	5-year PV, normalized	Discounted business loss conditional on a qualifying event
Convergence multiplier (M_{c0})	1.03/1.50/3.00	Dimensionl ess ratio	Converged expected cyber loss relative to the less-exposed counterfactual before maturity adjustment

Note. Triangular distributions are parameterized as minimum, mode, and maximum. PV = present value. Monetary values are already-discounted five-year lifecycle values normalized to base-year annual revenue of 100. Seed = 20260520; N = 20,000; primitive inputs sampled independently.

Scenario values were assigned deterministically rather than sampled. Appendix A reports every baseline input, maturity-adjusted input, branch probability, branch payoff, common lifecycle cost, expected branch value, CEP value, and RAITV outcome for all five scenarios. The same values are provided in Supplementary Table A1. The ranges in Table 4 and the scenario values are literature-informed analytical assumptions, not estimates of universal industry parameters.

3.5. Reproducibility and Sensitivity Statistics

The complete Python script, software versions, variable dictionary, model-comparison table, assumption register, 20,000-row input/output file, scenario input/output file, and sensitivity output are supplied with the manuscript. Univariate sensitivity was reported as the Pearson product-moment correlation between each modeled input and RAITV. Two-sided 95% confidence intervals were calculated with Fisher's z transformation. Spearman rank correlations were calculated as a robustness check and are reported in Supplementary Table A2. These correlations describe association within the stated simulation design; they are not causal coefficients or a variance-decomposition measure.

4. Risk-Adjusted Industrial Transformation Value Model

The Risk-Adjusted Industrial Transformation Value model places expected digital benefits, lifecycle costs, connectivity debt, and incremental convergence exposure into the same five-year present-value decision equation. It is deliberately transparent so executives, plant leaders, finance teams, and cyber-risk personnel can inspect each assumption rather than allowing architecture risk to disappear inside a discount rate.

4.1. Model Variables

The model assigns mutually exclusive probabilities to success, underperformance, and outright failure, and the three probabilities sum to one. The successful-branch payoff represents the five-year present value realized when the transformation reaches target performance. The underperformance payoff may be positive, near zero, or negative when a partially implemented program destroys value. The failure payoff is constrained to be nonpositive and captures abandonment, write-off, disruption, or recovery effects beyond common project costs. Common deductions include time-zero implementation and integration cost, the present value of ongoing operating and support cost, deterministic connectivity-debt cost, and the Convergence Exposure Premium. Each term follows the unit definitions in Table 3. Equation (1) presents the notation.

$$RAITV = p_s B_s + p_u B_u + p_f B_f - C_i - C_o - C_d - CEP \tag{1}$$

$$p_s + p_u + p_f = 1 \tag{2}$$

Operational maturity is represented on a normalized scale from zero to one and reflects process stability, standard work, maintenance discipline, data ownership, workforce capability, and accountable governance. It is not inserted as a free benefit. Instead, it changes the probability and consequence structure numerically. The baseline success probability, baseline failure probability, baseline underperformance payoff, baseline connectivity-debt cost, and baseline convergence multiplier are transformed as shown in Equations (3)-(6).

$$p_s = \min\left\{0.90, \max\left[0.05, p_s^0 + 0.25\left(m - 0.50\right)\right]\right\} \tag{3}$$

$$p_f = \min\left\{0.35, \max\left[0.01, p_f^0 - 0.10(m-0.50)\right]\right\}, p_u = 1 - p_s - p_f \quad (4)$$

$$B_u = B_u^0 + 0.75(m-0.50), C_d = C_d^0(1.50-m) \quad (5)$$

$$M_c = 1 + (M_c^0 - 1)(1.50-m) \quad (6)$$

Within the Monte Carlo bounds in Table 4, Equations (3) and (4) preserve positive probabilities without post hoc renormalization. Higher maturity increases the success probability, reduces the failure probability, improves the underperformance payoff, and reduces both connectivity debt and the exposure multiplier. The coefficients are explicit sensitivity assumptions rather than empirically estimated structural effects; firms should recalibrate them when longitudinal project data are available.

A positive RAITV indicates that the investment remains economically defensible after all three outcome branches and common costs are included. A negative RAITV indicates that the project may still have strategic, regulatory, or safety value, but the stated business case is not supported by the modeled risk-adjusted economics.

4.2. Convergence Exposure Premium

The Convergence Exposure Premium is the incremental expected cyber loss created by the proposed IT/OT connectivity architecture relative to a less-exposed counterfactual over the same five-year horizon. In the scalar implementation, baseline expected cyber loss is p_i L and converged expected cyber loss is $p_i M_c$ L. Equation (7) therefore prices only the additional expected loss attributable to convergence.

$$CEP = p_i(M_c - 1)L \quad (7)$$

Equation (7) is a transparent first-order approximation. A convergence multiplier of one means that the proposed design adds no expected loss beyond the counterfactual; values above one represent added reachability, dependency, or blast radius. When internal or insurer loss data are available, the preferred estimate is the ratio of converged expected annualized or lifecycle loss to counterfactual expected loss, as shown in Equation (8). Firms should establish the counterfactual architecture first, identify common incident categories, estimate category probabilities and conditional losses from internal incidents, near misses, threat modeling, insurer data, sector evidence, and recovery exercises, and then calculate the ratio using the same horizon and discount basis.

$$M_c = EAL_c / EAL_0 \quad (8)$$

where one scalar multiplier would hide materially different event types, the generalized form in Equation (9) should be used. The index k may represent ransomware, unauthorized remote access, safety or process disruption, third-party compromise, data loss, or another decision-relevant incident category. The subscript c denotes the proposed converged architecture and 0 denotes the less-exposed counterfactual.

$$CEP = \sum_{k=1}^{K} \left[p_{c,k} L_{c,k} - p_{0,k} L_{0,k} \right] \tag{9}$$

The scalar Equation (7) assumes a common proportional exposure effect and linear expected loss. This is suitable as a transparent baseline when data are sparse, but it does not represent thresholds, correlated failures, safety cascades, recovery-time nonlinearities, or changing loss severity. Those cases should use Equation (9), an event tree, or a correlated simulation. The cost taxonomy also prevents double counting: C_i covers one-time implementation; C_o covers routine recurring operations; C_d covers deterministic lifecycle burden created by connectivity; and CEP covers contingent incident loss. If an insurance premium, incident-response retainer, outage reserve, or recovery expense is included in C_o or C_d, the same component must be excluded from L and CEP.

4.3. Connectivity Decision Tiers

The model converts the investment question into a connectivity question. Not every analytics use case requires bidirectional convergence (Figure 1). Table 5 organizes connectivity into tiers ranging from no connection to autonomous optimization. The purpose is not to argue that lower tiers are always superior, but to require the lowest-exposure architecture that satisfies the documented business use case.

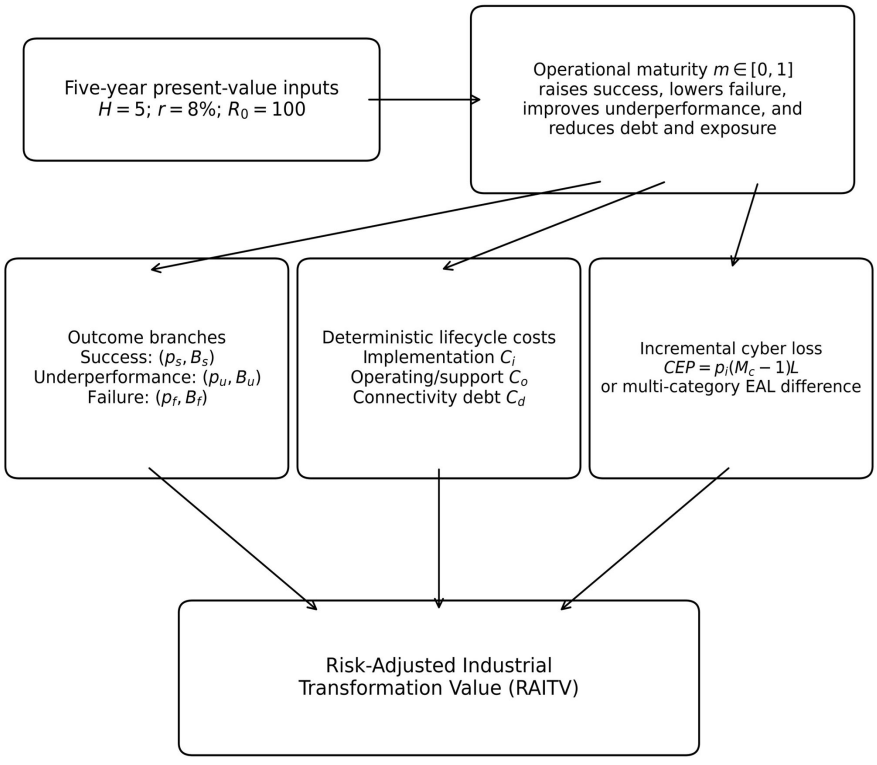

Figure 1. Revised CEP-RAITV architecture. All monetary terms are five-year discounted present values normalized to base-year annual revenue of 100. Operational maturity modifies execution probabilities, underperformance payoff, connectivity debt, and the convergence exposure multiplier before RAITV is calculated.

Table 5. Connectivity decision tiers for industrial transformation.

Tier	Connectivity pattern	Exposure discipline
0	No connection	Use when data has no proven decision value.
1	Offline export	Use for periodic reporting or compliance.
2	Delayed batch export	Use for trends, quality, and energy summaries.
3	Read-only historian replica	Use for frequent telemetry without control access.
4	Brokered telemetry	Use only with ownership, schema governance, and monitoring.
5	Bidirectional integration	Require formal risk acceptance and proof that value exceeds CEP.

5. Results

The model was evaluated through normalized scenarios and Monte Carlo sensitivity analysis. Because the analysis is not based on a proprietary plant dataset, the results should be interpreted as decision-model behavior rather than empirical estimates of a specific industry's ROI.

5.1. Scenario Results

Table 6 summarizes the five normalized scenarios. The conservative/minimal-connectivity scenario remains positive because costs, failure probability, and exposure are constrained. Broad convergence with modest benefits is negative because expected branch value is insufficient to overcome implementation, operating, connectivity-debt, and exposure costs. Broad convergence becomes positive only under stronger execution and maturity assumptions. The high-exposure scenario is strongly negative, while selective digitalization on mature operations remains positive. **Appendix A** and Supplementary Table A1 provide every baseline input, maturity-adjusted value, branch probability, branch payoff, expected branch value, common lifecycle cost, CEP value, and RAITV result used to reproduce these outcomes.

Table 6. Normalized scenario outcomes.

Scenario	CEP	RAITV	Result
Minimal connectivity	0.003	0.140	Positive
Broad/modest benefit	0.241	−2.614	Negative
Broad/strong execution	0.158	0.623	Positive
High-exposure convergence	1.312	−4.348	Negative
Selective mature operations	0.013	0.903	Positive

5.2. Monte Carlo Sensitivity

Using the exact assumptions in Table 4, 20,000 fixed-seed simulations produced a mean RAITV of 0.009, a median of −0.040 five-year present-value units, and a

standard deviation of 1.094. A total of 51.595% of runs were negative; the 5th and 95th percentiles were −1.721 and 1.892. These values describe model behavior under the specified distributions, valuation horizon, and maturity transformations; they are not an estimated industry failure rate. Figure 2 displays the distribution.

Figure 3 reports Pearson product-moment correlations between modeled inputs and RAITV with two-sided 95% confidence intervals calculated by Fisher's z transformation. Successful benefit had the largest positive association, r = 0.687, 95% CI [0.680, 0.695], while implementation cost had the largest negative association, r = −0.471, 95% CI [−0.482, −0.460]. Success probability was positively associated with RAITV, r = 0.347, and underperformance probability was negatively associated, r = −0.292. Operational maturity also had a positive association, r = 0.244, because it changed multiple downstream model inputs. Full Pearson and Spearman results are provided in Supplementary Table A2.

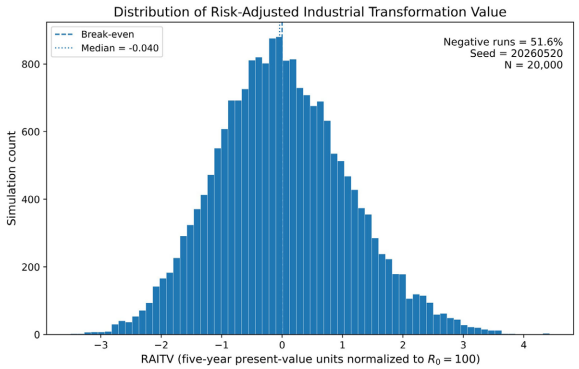

Figure 2. Distribution of RAITV across 20,000 simulations using seed 20260520 and Table 4 assumptions. Values are five-year discounted present values normalized to base-year annual revenue of 100; the distribution represents model behavior under the stated assumptions, not an empirical industry ROI distribution.

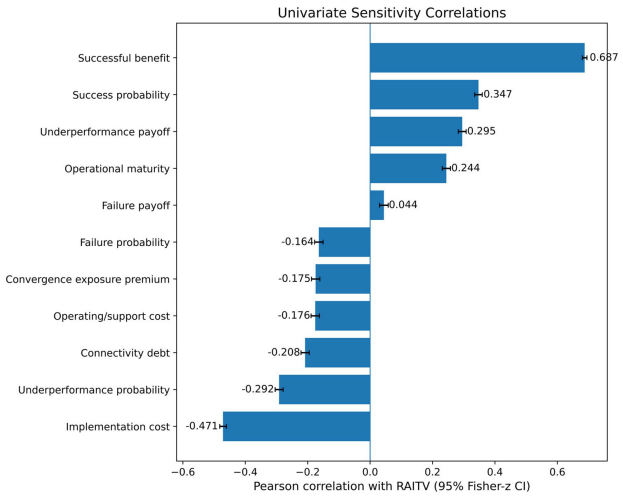

Figure 3. Pearson product-moment correlations between modeled inputs and RAITV, with two-sided 95% confidence intervals from Fisher's z transformation (N = 20,000). Primitive inputs were sampled independently; maturity created the only modeled dependence. Correlations are sensitivity indicators, not causal effects or variance shares.

5.3. Break-Even Interpretation

The break-even boundary converts the model into an explicit benefit threshold. The base case assumes the five-year horizon and 8% discount rate defined in Section 3.3, operational maturity of 0.60, a baseline success probability of 0.50, a baseline failure probability of .08, a baseline underperformance payoff of 0.75, a failure payoff of −0.50, implementation cost of 1.30, operating cost of 0.40, and baseline connectivity-debt cost of 0.20. The maturity transformations produce a success probability of 0.525, an underperformance probability of 0.405, a failure probability of 0.070, an adjusted underperformance payoff of 0.825, and an adjusted connectivity-debt cost of 0.180. Solving Equation (1) for the successful-branch benefit yields Equation (10). Figure 4 varies CEP from 0 to 1.5 while holding these base values constant.

$$B_s^* = \left(C_i + C_o + C_d + CEP - p_u B_u - p_f B_f\right) \Big/ p_s \tag{10}$$

The threshold rises linearly with CEP. Firms can improve modeled value either by increasing realized operational benefit and success probability or by reducing implementation burden, connectivity debt, failure exposure, and cyber coupling.

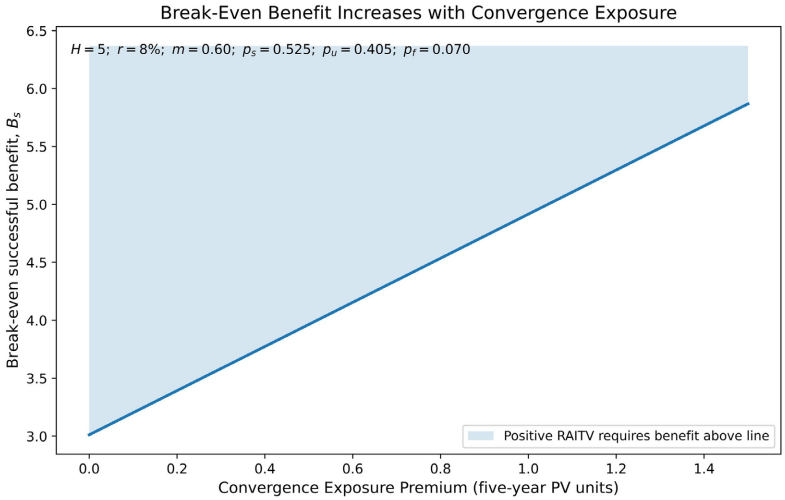

Figure 4. Break-even successful benefit as CEP increases under the stated base assumptions. The figure holds the five-year horizon, 8% discount rate, maturity-adjusted branch probabilities, branch payoffs, and common costs constant; the straight boundary is therefore conditional on varying only CEP.

6. Discussion

The results support a risk-adjusted interpretation of industrial digital transformation. The issue is not whether digital technologies can create value. They can. The issue is whether the value survives a complete accounting of execution risk and convergence exposure. Many digital transformation proposals are written as if the success branch is the expected case and the risk branch is merely a mitigation checklist. The RAITV model reverses that practice by forcing the benefit, failure, cost, and exposure branches into the same equation.

6.1. Operational Maturity First

The literature on lean and non-technological factors suggests that firms should prioritize operational maturity before broad digitalization. In the model, this recommendation is not rhetorical: higher maturity raises the modeled success probability, lowers the modeled failure probability, improves the underperformance payoff, and reduces connectivity debt and the convergence exposure multiplier through Equations (3)-(6). The positive sensitivity correlation for operational maturity in Figure 3 is therefore the combined result of these pathways. The coefficients are deliberately transparent assumptions rather than estimated causal effects, and firms should calibrate them with their own project history. Process control, workforce development, maintenance discipline, data ownership, standard work, and clear accountability remain the conditions that make digital investment more likely to pay off.

6.2. Selective Digitalization Second

Selective digitalization means connecting or digitizing only those functions that have a defined business decision, a known owner, measurable value, and an acceptable exposure level. This is not anti-technology. It is pro-investment discipline. Predictive maintenance, energy reporting, quality analytics, and production dashboards may be worthwhile when they use the least exposed data architecture that satisfies the use case. In many cases, delayed data, read-only replicas, or summary data may satisfy the business need without granting enterprise systems live access to control assets.

6.3. Convergence Last

Bidirectional IT/OT convergence should be treated as the highest scrutiny tier. It may be justified for particular operations, but it should not be the default endpoint of digital transformation. The stronger the coupling between enterprise systems and process environments, the greater the need for formal risk acceptance, business continuity planning, incident response readiness, and isolation capability. Cybersecurity and Infrastructure Security Agency et al. (2026) emphasize that OT connectivity should be deliberately designed, secured, logged, monitored, and paired with an isolation plan. This paper adds that it should also be economically justified through the convergence exposure premium.

6.4. Theoretical and Managerial Implications

The theoretical contribution is not a new form of expected-value arithmetic. It is the explicit, architecture-sensitive decomposition of industrial transformation value. The combined CEP-RAITV framework keeps the less-exposed counterfactual, connectivity debt, maturity-mediated execution branches, and incremental cyber loss visible as separate decision terms. It can therefore complement conventional NPV and real-options analysis while preventing IT/OT exposure from being hidden in an undifferentiated discount rate. For boards and executives, the

framework provides a way to challenge investment cases that present only gross benefits. For chief information officers, it supports a portfolio view that includes execution probability and ongoing support burden. For chief information security officers, it converts OT cyber exposure into an investment variable rather than a post-approval objection. For plant and engineering leaders, it requires each connection to justify its existence. For finance leaders, it creates a common language for comparing transformation benefit against cyber and operational exposure.

7. Limitations and Future Work

This paper has several limitations. First, the model is normalized and illustrative; it does not estimate universal ROI, incident probability, loss, or transformation-failure rates. Second, the five-year horizon, 8% discount rate, triangular ranges, and operational-maturity coefficients in Table 4 and Equations (3)-(6) are transparent analytical assumptions rather than parameters estimated from a multi-firm longitudinal dataset. Third, primitive Monte Carlo inputs were sampled independently. The only modeled dependence came from the shared maturity transformations, so real-world correlations among project size, benefit ambition, implementation cost, exposure, incident categories, and failure severity may be stronger or different. Fourth, Pearson sensitivity coefficients are univariate associations and should not be interpreted as causal effects or global variance contributions. Fifth, scalar Equation (7) assumes a linear common exposure multiplier. It does not fully capture nonlinear safety effects, correlated failures, recovery-time thresholds, multiple incident categories, or cascading operational disruption; Equation (9) provides a more general structure but still requires credible category inputs. Sixth, C_o, C_d, and CEP are conceptually distinct, but firms can double count costs unless they apply the accounting boundaries stated in Section 4.2. Seventh, RAITV does not itself value managerial flexibility; a real-options extension would be appropriate when deferral, staging, expansion, or abandonment options are material.

Future research should validate the framework using case data from industrial transformation projects, sector-specific cyber-loss ranges, insurance underwriting data, and plant-level connectivity inventories. Additional work should estimate M_c from paired counterfactual and converged architectures using attack-path inventories, identity and remote-access pathways, third-party dependencies, incident and near-miss data, recovery exercises, and insurer expected-loss models. Nonlinear event trees, correlated Monte Carlo inputs, safety and environmental consequence categories, and real-options treatment of staged connectivity should also be evaluated. A future extension could integrate the model with the OT Exposure Budget concept so that every proposed data flow receives a value score, exposure score, and renewal period before approval.

8. Conclusion

Industrial digital transformation should not be rejected categorically, but neither

should it be treated as inevitable. The empirical literature suggests that digital technologies can create value, but that value is conditional, heterogeneous, and execution-dependent. At the same time, IT/OT convergence can create real cyber and operational exposure. The combined CEP-RAITV framework provides a practical way to consolidate lifecycle benefits, execution branches, connectivity debt, and differential cyber loss into a single transparent investment structure.

The central conclusion is that industrial firms need a defensible reason for every connection. Operational maturity should come first, selective digitalization second, and high-exposure convergence last. Non-connection, delayed export, read-only replication, and one-way or commandless telemetry should be recognized as legitimate transformation strategies when they satisfy the business need at lower risk. The safest and most economically sound industrial transformation is not the one with the most connectivity. It is the one where each connection earns its exposure.

Data Availability

This paper uses publicly available literature and a normalized model-based sensitivity analysis. The submission package includes the complete Python reproduction script, exact software versions, fixed random seed, five-year valuation convention, Monte Carlo assumption register with rationale, 20,000-row input/output dataset, model variable dictionary, valuation-model comparison table, full scenario input/output table with intermediate calculations, simulation summary, Pearson confidence intervals, Spearman robustness statistics, and the evidence-search protocol.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Appendix A Full Normalized Scenario Inputs

Table A1 and Table A2 report the complete deterministic inputs and derived values for the five scenarios. CM = conservative/minimal connectivity; BM = broad convergence with modest benefits; BS = broad convergence with strong execution; HE = high-exposure convergence; SM = selective digitalization with mature operations. All monetary values are five-year discounted present values normalized to base-year annual revenue of 100. Table A2 now reports expected branch value and common lifecycle costs so that RAITV can be verified directly as expected branch value minus common lifecycle costs minus CEP.

Table A1. Scenario maturity, branch probabilities, and branch payoffs.

Parameter	CM	BM	BS	HE	SM
Operational maturity	0.7500	0.3500	0.7500	0.2500	0.8500
Baseline success probability	0.4500	0.3000	0.6500	0.3000	0.6000
Baseline failure probability	0.0600	0.1200	0.0500	0.1600	0.0400
Adjusted success probability	0.5125	0.2625	0.7125	0.2375	0.6875
Underperformance probability	0.4525	0.6025	0.2625	0.5775	0.3025
Adjusted failure probability	0.0350	0.1350	0.0250	0.1850	0.0100
Successful benefit	2.0000	2.0000	4.5000	2.0000	3.0000
Baseline underperformance payoff	0.5000	0.2500	1.0000	0.0000	0.8000
Adjusted underperformance payoff	0.6875	0.1375	1.1875	−0.1875	1.0625
Failure payoff	−0.5000	−1.0000	−0.5000	−1.5000	−0.2500

Table A2. Scenario costs, exposure inputs, and outcomes.

Parameter	CM	BM	BS	HE	SM
Implementation cost	0.8000	1.8000	1.8000	1.8000	1.0000
Operating/support cost	0.3000	0.7000	0.7000	0.7000	0.4000
Baseline connectivity debt	0.1000	0.3000	0.3000	0.5000	0.1000
Adjusted connectivity debt	0.0750	0.3450	0.2250	0.6250	0.0650
Incident probability	0.0150	0.0350	0.0350	0.0600	0.0200
Incident loss	3.0000	6.0000	6.0000	10.0000	4.0000
Baseline exposure multiplier	1.1000	2.0000	2.0000	2.7500	1.2500
Adjusted exposure multiplier	1.0750	2.1500	1.7500	3.1875	1.1625
Expected branch value	1.3186	0.4728	3.5055	0.0892	2.3814
Common lifecycle costs	1.1750	2.8450	2.7250	3.1250	1.4650
Convergence Exposure Premium	0.0034	0.2415	0.1575	1.3125	0.0130
RAITV	0.1402	−2.6137	0.6230	−4.3483	0.9034