AI and Machine Learning Advances
Volume 2, Issue 1
ISSN: 3067-3216

Adaptive Cyber Risk Intelligence Fabric (ACRIF): A Regulator-Aligned Framework for Dynamic Cybersecurity Governance

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Abstract

Cybersecurity governance frameworks increasingly require dynamic risk assessment mechanisms that align operational security signals with evolving regulatory obligations. Conventional Governance, Risk, and Compliance (GRC) systems rely on static control scoring and manual cross-framework mapping, limiting responsiveness and audit transparency. This study proposes the Adaptive Cyber Risk Intelligence Fabric (ACRIF). This regulator-aligned architecture integrates dynamic control weighting, graph-based cross-framework synchronisation, and deterministic explainability within a unified governance intelligence model. The framework introduces regulatory-cycle-aware weighting, sector-specific amplification modifiers, and time-bound decay functions to recalibrate control prioritisation. Automated propagation mechanisms synchronise compliance impact across multiple cybersecurity standards, while rule-based reasoning chains generate audit-ready explanations linked to statutory obligations. Analytical validation demonstrates enhanced governance responsiveness, reduced compliance fragmentation, and improved computational efficiency through selective recalculation logic. The findings suggest that ACRIF advances cybersecurity governance beyond static compliance systems, offering a scalable, regulator-sensitive foundation for dynamic enterprise risk intelligence across multi-framework environments.

Keywords: Adaptive Cyber Risk; Cybersecurity Governance; Regulatory Compliance; Risk Intelligence; Explainable Security.

1. Introduction

The convergence of evolving threat landscapes, complex regulatory environments, and fragmented compliance frameworks increasingly challenges cybersecurity governance (Victor-Mgbachi, 2024). Traditional risk assessment methodologies, including standards-based approaches such as NIST and ISO/IEC 27001, provide structured guidance for control implementation; however, systematic literature on dynamic risk assessment indicates that many existing models remain technically reactive and insufficiently integrated with regulatory enforcement dynamics (Alrehili & Alhazmi, 2023). Recent advances in automated risk identification, ontology-driven security modelling, and explainable artificial intelligence have improved real-time detection and transparency, particularly within industrial control systems and financial sectors (Jarwar et al., 2025; Sharma et al., 2025). Nevertheless, these approaches often operate within isolated domains, lacking unified cross-framework synchronisation and governance-level orchestration. Comparative analyses of cybersecurity frameworks further highlight challenges in interoperability, manual control mapping, and inconsistent compliance interpretation across jurisdictions. Additionally, emerging research on adaptive governance emphasises resilience and feedback-driven policy adaptation but does not fully operationalise regulator-aware risk weighting or deterministic audit-traceable explanation mechanisms. This gap between operational risk analytics and regulator-aligned governance decision-making creates inefficiencies, increased audit burden, and delayed response to regulatory shifts. The motivation for the Adaptive Cyber Risk Intelligence Fabric (ACRIF) arises from the need for a unified, adaptive architecture capable of dynamically weighting controls, synchronising multi-framework compliance, and generating transparent, audit-ready cyber risk intelligence aligned with evolving regulatory expectations.

Contemporary cybersecurity governance frameworks face increasing pressure to respond simultaneously to evolving cyber threats and rapidly changing regulatory expectations (Oh et al., 2025). While established standards such as NIST, ISO/IEC 27001, and sector-specific regulations provide

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Received: 5-Feb-2026 Revised: 16-Feb-2026 Accepted: 3-Mar-2026

AI and Machine Learning Advances
Volume 2, Issue 1
ISSN: 3067-3216

structured compliance guidance, existing risk assessment models primarily rely on static control scoring, periodic reassessments, and manually maintained framework mappings (Gampel, 2026). Systematic reviews of dynamic risk assessment approaches reveal that although real-time threat intelligence and automation mechanisms have improved technical risk detection, these systems remain insufficiently integrated with regulatory enforcement dynamics and governance-layer decision processes (Tagarev, 2020). Furthermore, comparative analyses of cybersecurity frameworks highlight fragmentation across standards, requiring organisations to perform repetitive cross-mapping and compliance validation efforts. Automated risk identification techniques and explainable AI models contribute valuable transparency and operational insight; however, they often focus on technical risk metrics rather than regulator-aligned governance implications. This disconnect creates inefficiencies, inconsistent compliance interpretation, and limited audit defensibility. The absence of a unified architecture capable of dynamically weighting controls based on regulatory context, synchronising risk impact across multiple frameworks, and generating deterministic, audit-ready reasoning chains represents a significant gap in current research and practice. Addressing this gap necessitates the development of an adaptive, regulator-aligned cyber risk intelligence framework that bridges operational security analytics and strategic cybersecurity governance.

The primary aim of this study is to develop a regulator-aligned, adaptive cybersecurity governance framework termed the Adaptive Cyber Risk Intelligence Fabric (ACRIF) that integrates dynamic risk assessment, cross-framework synchronisation, and deterministic explainability into a unified governance architecture. The study seeks to address structural limitations in existing compliance-driven and technically reactive risk models by proposing a framework that continuously aligns cybersecurity posture with evolving regulatory, sectoral, and organisational contexts.

To achieve this aim, the research pursues three core objectives corresponding to the established research questions.

RQ1 How can cybersecurity governance frameworks be redesigned to dynamically align risk assessment with evolving regulatory enforcement patterns, sector-specific obligations, and organisational business context?

RQ2 How can cross-framework control dependencies be modelled to enable automatic propagation of risk impact across multiple cybersecurity and regulatory standards without manual reassessment?

RQ3 How can cybersecurity risk intelligence systems generate deterministic, audit-ready explanations that enhance transparency, regulatory defensibility, and executive decision-making while maintaining computational efficiency?

Collectively, these objectives guide the conceptualisation and design of ACRIF as a regulator-aligned framework for dynamic cybersecurity governance.

This study advances cybersecurity governance research by introducing a regulator-aligned adaptive architecture that integrates dynamic risk weighting, cross-framework synchronisation, and deterministic explainability within a unified conceptual model. Existing literature on dynamic risk assessment emphasises real-time threat responsiveness and automation; however, limited attention has been given to embedding regulatory enforcement dynamics directly into risk prioritisation mechanisms. The proposed Adaptive Cyber Risk Intelligence Fabric (ACRIF) addresses this limitation by formalising a governance-layer weighting approach that incorporates jurisdictional obligations, sectoral requirements, and evolving supervisory intensity into control significance modelling. The study further contributes by conceptualising a cross-framework translation structure capable of propagating risk impact assessments across multiple cybersecurity standards, thereby reducing fragmentation and manual compliance remapping. This approach extends prior work on framework interoperability by introducing synchronised risk harmonisation logic aligned with governance objectives. An additional contribution lies in the development of a deterministic explanation mechanism designed to produce audit-ready reasoning chains that enhance regulatory transparency and executive accountability. By bridging operational security analytics with compliance-oriented governance decision-making, the study offers a structured foundation for adaptive, regulator-aware cyber risk intelligence that advances both theoretical discourse and practical governance implementation.

2. Related Work

2.1 Cybersecurity Governance and Compliance-Oriented Risk Management Models

Cybersecurity governance has progressively shifted from purely technical control management toward compliance-oriented and policy-driven risk management structures (Chowdhury, 2025; GHAZNAVI). Established

standards such as ISO/IEC 27001 and the NIST Cybersecurity Framework provide structured mechanisms for aligning security controls with organisational objectives; however, contemporary scholarship highlights persistent fragmentation across regulatory environments and sector-specific mandates (Dalal, 2025; Moeti et al., 2025). A systematic review of dynamic risk assessment models demonstrates that most governance implementations remain anchored in static scoring methodologies and periodic reassessment cycles, limiting responsiveness to regulatory and threat volatility (Nafiu et al., 2025).

Adaptive governance frameworks have been proposed to introduce feedback mechanisms and resilience-oriented control adjustments, yet these models frequently lack integrated cross-framework synchronisation and regulator-aware prioritisation logic (Hlatshwayo). Studies examining automated risk identification in industrial and cyber-physical systems emphasise ontology-driven modelling and engineering-centric automation but remain primarily focused on operational risk detection rather than enterprise-level compliance orchestration (Eckhart et al., 2020). Within regulated sectors such as financial services, explainable artificial intelligence approaches have emerged to enhance transparency and audit defensibility in cyber risk analytics (Ashfaq & Chowdhury, 2023). Nevertheless, these approaches concentrate on the interpretability of predictive models rather than governance-wide regulatory alignment. Comparative analyses of cybersecurity frameworks further underscore the challenges of manual cross-mapping and inconsistent compliance interpretation. Collectively, the literature indicates substantial progress in automation and explainability but reveals limited integration of dynamic regulatory signals, cross-framework propagation mechanisms, and deterministic audit-ready governance architectures, thereby motivating the need for more comprehensive regulator-aligned models.

2.2 Risk Assessment and Control Weighting Approaches in Cybersecurity

Risk assessment methodologies in cybersecurity have traditionally relied on structured qualitative and quantitative frameworks that evaluate threat likelihood, vulnerability exposure, and potential impact (Sánchez-Zas et al., 2022). Widely adopted standards such as ISO 31000 and NIST-based risk management approaches provide systematic procedures for identifying and prioritising risks; however, empirical studies indicate that these models frequently employ static control scoring mechanisms and periodic reassessment cycles (Amadi, 2025; Howell, 2024). A systematic literature review of dynamic risk assessment (DRA) models highlights growing interest in real-time risk recalibration through threat intelligence feeds and contextual updates, yet notes limited integration of governance-layer considerations and regulatory enforcement signals into control weighting processes.

In industrial and cyber-physical environments, automated risk identification techniques leverage ontology-driven modelling and attack graph analysis to evaluate control effectiveness dynamically. These approaches enhance technical risk visibility but remain primarily engineering-focused, emphasising asset-level vulnerabilities rather than enterprise compliance prioritisation. Similarly, adaptive governance frameworks propose feedback-driven control adjustment mechanisms but often lack formalised weighting structures that incorporate jurisdictional obligations or sector-specific regulatory intensity. Emerging research in explainable artificial intelligence further seeks to enhance transparency in risk scoring models, particularly within financial services contexts. While interpretability improves decision clarity, such models predominantly focus on model behaviour rather than structured, regulator-aligned control weighting. Overall, existing literature advances dynamic recalculation and automation but demonstrates limited emphasis on time-variant regulatory-aware control weighting mechanisms, underscoring the need for more integrated governance-oriented risk assessment architectures.

2.3 Cross-Framework Compliance Mapping and Interoperability Challenges

The proliferation of cybersecurity standards and sector-specific regulations has intensified challenges related to cross-framework compliance mapping and interoperability (Essien et al., 2022). Organisations frequently operate under multiple regulatory regimes, including NIST, ISO/IEC 27001, PCI DSS, and industry-specific mandates, each with distinct control structures and reporting requirements. Comparative analyses of cybersecurity frameworks reveal conceptual overlaps but structural inconsistencies that necessitate extensive manual cross-mapping and interpretation efforts. These discrepancies increase compliance burden and create risks of inconsistent control interpretation across jurisdictions. Studies examining regulatory risk management within the financial sector further emphasise the complexity of aligning enterprise controls with evolving supervisory

AI and Machine Learning Advances
Volume 2, Issue 1
ISSN: 3067-3216

expectations and multi-layered legislative requirements. Although governance frameworks propose structured compliance integration, practical implementation often depends on static mapping matrices that lack dynamic synchronisation capabilities.

In industrial and cyber-physical domains, automated risk modelling techniques demonstrate the feasibility of structured control mapping through ontology-based representations; however, such approaches primarily focus on technical control relationships rather than multi-regulator compliance harmonisation. Adaptive governance research highlights feedback-driven policy adjustments but does not fully operationalise cross-framework propagation logic capable of updating interconnected standards simultaneously. Collectively, the literature indicates that while interoperability is recognised as a critical governance concern, existing solutions remain largely manual or domain-specific. The absence of automated, synchronised cross-framework translation mechanisms underscores the need for integrated architectures capable of harmonising compliance and risk intelligence across diverse regulatory ecosystems.

2.4 Explainability and Auditability in Cyber Risk Decision-Making

Explainability and auditability have emerged as central requirements in contemporary cyber risk decision-making, particularly within highly regulated sectors. As organisations increasingly adopt automated and data-driven risk assessment tools, regulatory bodies demand transparency regarding how risk scores are generated and how control deficiencies are prioritised. Research in explainable artificial intelligence (XAI) for cyber risk assessment highlights the importance of interpretability, stability, and traceability in enhancing stakeholder trust and regulatory compliance (Mohitkar & Lakshmi, 2025). These studies demonstrate that explanation mechanisms can improve clarity in risk analytics; however, they primarily focus on model-level interpretability rather than governance-wide audit defensibility.

Dynamic risk assessment literature further indicates that while real-time recalibration enhances responsiveness, limited attention has been devoted to producing structured reasoning chains suitable for regulatory examination (Cheimonidis & Rantos, 2023). Automated risk identification approaches in industrial systems provide detailed technical mappings and attack-path representations, yet they rarely extend explanations to compliance implications across multiple regulatory standards (Eckhart et al., 2020). Adaptive governance frameworks recognise the importance of accountability and feedback-driven adjustments, though explicit mechanisms for deterministic, audit-ready reporting remain underdeveloped (Melaku, 2023). Collectively, existing scholarship underscores growing recognition of explainability in cyber risk analytics but reveals a persistent gap in integrating transparent, regulator-aligned reasoning mechanisms within enterprise cybersecurity governance architectures.

2.5 Research Gap and Motivation for the ACRIF Framework

Despite significant advancements in cybersecurity governance, dynamic risk assessment, and compliance automation, a critical gap persists in the integration of these domains within a unified regulatory-aligned architecture. Existing governance models predominantly rely on static control scoring and periodic reassessment cycles, limiting responsiveness to evolving regulatory enforcement patterns and sector-specific supervisory intensity. While dynamic risk assessment approaches incorporate real-time threat intelligence and contextual recalibration, they often remain technically focused and insufficiently connected to enterprise-level compliance harmonisation.

Cross-framework mapping efforts acknowledge the fragmentation across standards and legislative requirements; however, most implementations depend on manual translation matrices or domain-specific mappings that lack automated synchronisation capabilities. Similarly, explainability research enhances transparency at the model level. However, it does not consistently provide deterministic, audit-ready reasoning chains that directly link control deficiencies to regulatory obligations and business impact scenarios. The absence of a cohesive framework capable of dynamically weighing cybersecurity controls based on regulatory context, propagating risk impacts across interconnected standards, and generating structured, regulator-facing explanations represents a substantive research deficiency. Addressing this gap requires the development of an adaptive, regulator-aligned cyber risk intelligence architecture that bridges operational risk analytics with strategic governance decision-making, thereby advancing the conceptual and practical foundations of dynamic cybersecurity governance.

3. Proposed Framework: Adaptive Cyber Risk Intelligence Fabric (ACRIF)

The Adaptive Cyber Risk Intelligence Fabric (ACRIF) is proposed as a regulator-aligned cybersecurity governance architecture designed to dynamically translate control-state signals into structured, audit-ready risk intelligence. The framework extends beyond conventional Governance, Risk, and Compliance (GRC) systems by embedding time-variant regulatory weighting, automatic cross-framework propagation, and deterministic explanation mechanisms within a unified computational fabric. Rather than relying on static mappings or periodic reassessment cycles, ACRIF continuously ingests cybersecurity control states, threat intelligence signals, regulatory applicability metadata, and organisational business context. These inputs are processed through adaptive mechanisms that recalibrate control significance, synchronise compliance representations across multiple frameworks, and generate quantified cyber risk states. The framework operationalises governance as a dynamic and regulator-sensitive process, capable of selective recalculation and event-driven updating to enhance computational efficiency and regulatory responsiveness.

3.1 Conceptual overview

The conceptual foundation of ACRIF is structured around three interdependent technical behaviours: dynamic control weighting, cross-framework propagation, and deterministic explainability. The framework begins with the ingestion of cybersecurity control state data, threat intelligence indicators, regulatory applicability metadata, and organisational business context. These inputs form the basis for calculating a baseline regulatory applicability factor for each control, determined by jurisdictional and sector-specific obligations. The weighting mechanism then adjusts control significance in response to detected changes in regulatory enforcement intensity and applies time-bound decay functions when correlated threat activity subsides. This enables time-variant prioritisation rather than static scoring.

A cross-framework translation graph maintains mappings between cybersecurity controls and multiple regulatory or standards-based frameworks. When a control node changes state, propagation rules automatically synchronise risk impact assessments across all connected frameworks without manual reassessment. Edge-based logic allows propagation rules to vary by framework pair, ensuring contextual alignment across standards. The deterministic explanation layer produces structured reasoning chains linking specific control deficiencies to regulatory requirements, projected business impacts, and exposure indicators. Outputs are formatted for executive, regulatory, and operational audiences while maintaining reproducibility and audit integrity. Selective recalculation ensures that only affected components are recomputed, improving resource efficiency.

Table 1 Core Technical Behaviours of the ACRIF Framework

Architectural Layer	Functional Mechanism	Governance Effect
Dynamic Weighting Engine	Time-variant regulatory applicability factors; enforcement-cycle adjustments; threat-based decay	Regulator-aligned control prioritisation
Cross-Framework Translation Graph	Edge-based propagation rules; multi-framework synchronisation; version-aware mapping	Automated compliance harmonisation
Deterministic Explanation Layer	Rule-based reasoning chains; regulatory citation linking; exposure indicators	Audit-ready, defensible governance reporting
Selective Recalculation Logic	Event-driven updates; recalculation of affected nodes only	Reduced computational overhead and improved responsiveness

Table 1 illustrates how ACRIF integrates adaptive weighting, automated synchronisation, and deterministic reasoning into a unified governance fabric, distinguishing it from static compliance systems.

3.2 System architecture

The system architecture of the Adaptive Cyber Risk Intelligence Fabric (ACRIF) is designed as a modular, event-driven governance intelligence system that integrates operational cybersecurity telemetry with

AI and Machine Learning Advances
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ISSN: 3067-3216

regulatory and business context data. The architecture consists of four primary layers: data ingestion, adaptive weighting computation, cross-framework synchronisation, and governance output generation. Each layer performs a distinct computational function while remaining interconnected through selective recalculation logic. The data ingestion layer collects cybersecurity control state information, threat intelligence feeds, regulatory applicability metadata, and organisational business context indicators. These inputs are normalised and structured

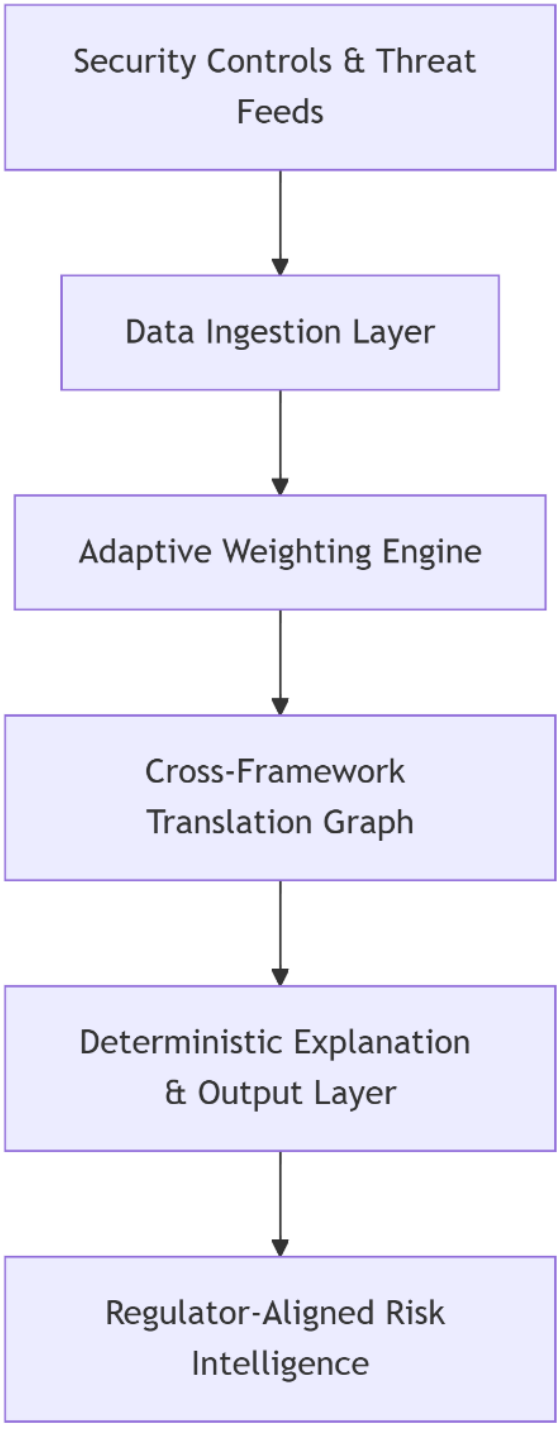

Figure 1 System Architecture of the Adaptive Cyber Risk Intelligence Fabric (ACRIF)

to enable consistent processing across heterogeneous sources. The adaptive weighting engine then computes baseline regulatory applicability factors for each control based on jurisdiction and sector-specific obligations. Control weights are dynamically adjusted in response to enforcement cycle signals, real-time threat correlation, and industry-specific modifiers. Time-bound decay functions ensure that temporary threat escalations do not permanently distort risk prioritisation.

The cross-framework translation layer maintains a graph-based synchronisation structure that maps controls across multiple cybersecurity and regulatory frameworks. When a control state changes, propagation rules automatically update interconnected framework representations, generating synchronised risk impact assessments without manual remapping. The governance output layer produces quantified cyber risk scores, regulatory exposure metrics, and deterministic explanation narratives. Outputs are formatted for executive leadership, regulators, and operational teams while preserving audit traceability. Event-driven triggers activate selective recalculation of only affected components, improving computational efficiency compared to complete reassessment cycles.

Figure 1 illustrates the architecture, which is a structured transformation pipeline in which operational inputs are dynamically processed into synchronised, audit-ready governance intelligence outputs through modular and event-driven components.

3.3 Adaptive risk weighting mechanism

The adaptive risk weighting mechanism constitutes the computational core of ACRIF. Unlike conventional risk scoring models that rely on static control criticality or vulnerability severity metrics, this mechanism dynamically assigns weights to cybersecurity controls using regulator-aligned and context-sensitive factors. The process begins with the calculation of a baseline regulatory applicability factor derived from jurisdictional obligations and sector-specific requirements. This baseline weight reflects the inherent compliance relevance of each control independent of transient threat conditions.

The weighting engine subsequently adjusts control significance in response to detected variations in regulatory enforcement intensity. Examination cycles, supervisory announcements, and enforcement trends are normalised and integrated into the weighting model, thereby increasing the priority of controls during periods of heightened regulatory scrutiny. In parallel, threat-based modifiers are applied using real-time intelligence correlations. When correlated threat activity subsides, a time-bound non-linear decay function reduces elevated weights to prevent persistent distortion of risk prioritisation. Industry-specific modifiers further refine control weighting. For example, Operational Technology environments or financial regulatory contexts trigger sector-sensitive amplification rules. The mechanism operates independently of traditional CVSS severity scores, emphasising regulatory exposure and business context over purely technical metrics. Selective recalculation ensures that only controls affected by contextual changes are recomputed, supporting computational efficiency.

Table 2 Components of the Adaptive Risk Weighting Mechanism

Weighting Factor	Input Source	Functional Role
Baseline Regulatory Applicability	Jurisdiction & sector metadata	Establishes inherent compliance relevance
Enforcement Intensity Modifier	Regulatory examination cycles & penalty trends	Elevates control priority during scrutiny periods
Threat Correlation Modifier	Real-time threat intelligence	Adjusts weight based on asset-specific exposure
Time-Bound Decay Function	Threat persistence patterns	Gradually reduces temporary risk inflation
Industry-Specific Modifiers	Sector classification (e.g., OT, finance, healthcare)	Contextualises control sensitivity

Table 2 demonstrates how multiple contextual variables are integrated into a unified weighting structure that dynamically reflects regulatory, threat, and sector conditions.

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ISSN: 3067-3216

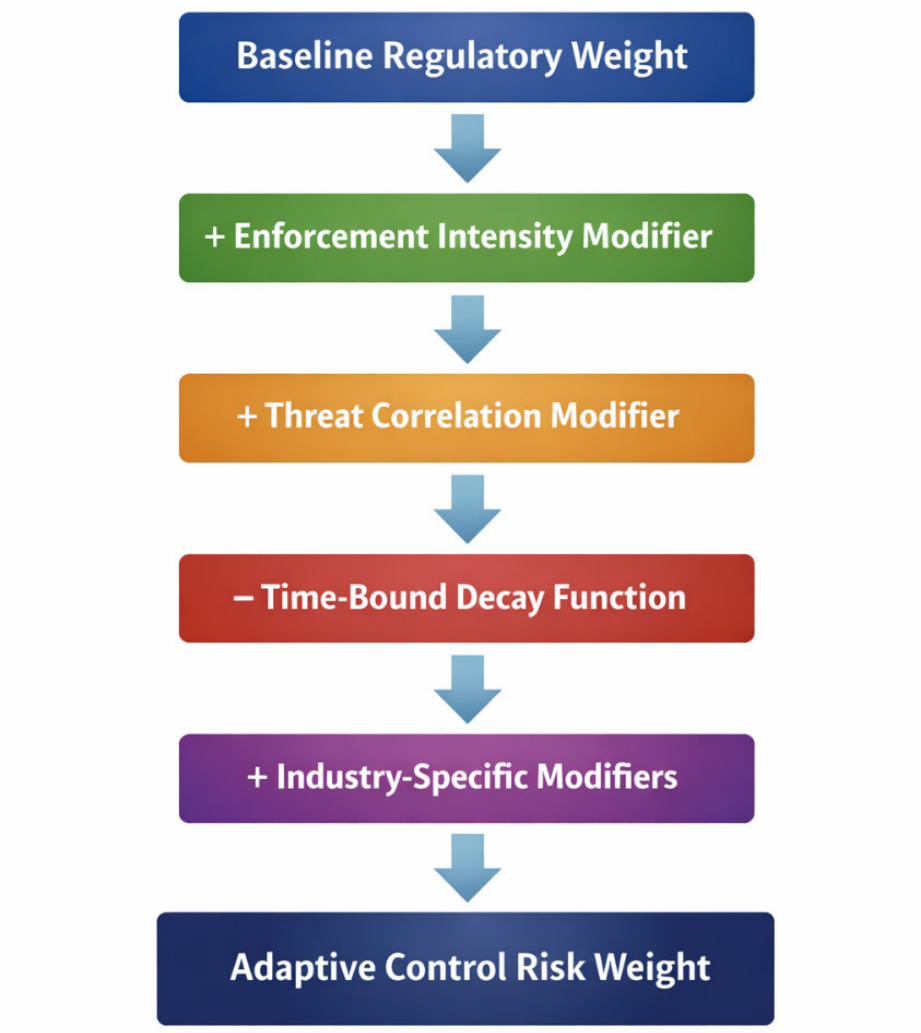

Figure 2: Dynamic Control Weight Adjustment Model

Figure 2 illustrates the sequential recalibration process through which baseline compliance relevance is dynamically adjusted by enforcement, threat, and sector-specific variables to produce regulator-aligned adaptive risk weights.

3.4 Cross-framework propagation

The cross-framework propagation mechanism enables synchronised risk harmonisation across multiple cybersecurity and regulatory standards without manual remapping. Traditional compliance management approaches maintain static mapping matrices between frameworks such as the NIST Cybersecurity Framework, ISO/IEC 27001, PCI DSS, and sector-specific regulations. When a control state changes, organisations typically reassess each framework independently, resulting in redundancy, inconsistency, and delayed compliance updates. ACRIF addresses this limitation through a graph-based cross-framework translation structure that automatically propagates risk impact assessments across interconnected control representations.

Within this architecture, each cybersecurity control is represented as a node connected to equivalent or related controls in other frameworks. Edge-based propagation rules define how risk impact values transfer between nodes. These rules are context-sensitive and may vary by framework pair, allowing differentiated synchronisation logic between, for example, NIST–ISO mappings and ISO–PCI DSS mappings. Framework-specific equivalence confidence scores refine propagation intensity, ensuring proportional adjustment rather than uniform risk inflation.

When a control deficiency or state modification is detected, the translation graph traverses all connected nodes, recalculating associated risk exposure metrics

across frameworks. A synchronisation audit log records the original modification, propagation path, node-level impact calculations, and resulting framework-specific adjustments. This mechanism ensures traceability and regulator-ready documentation while reducing compliance fragmentation.

Table 3 Cross-Framework Propagation Mechanism Components

Component	Function	Governance Impact
Control Nodes	Represent controls across multiple frameworks	Enables unified control representation
Edge-Based Propagation Rules	Define impact transfer logic between frameworks	Ensures context-sensitive synchronisation
Equivalence Confidence Scores	Quantify the mapping strength between controls	Prevents disproportionate risk inflation
Synchronisation Audit Log	Records propagation paths and adjustments	Supports audit traceability and defensibility
Version-Aware Mapping	Tracks framework updates and revisions	Maintains long-term compliance alignment

Table 3 outlines how graph-based synchronisation replaces manual cross-mapping, enabling automated, traceable, and regulator-aligned compliance propagation across heterogeneous standards.

3.5 Deterministic explainability

The deterministic explainability layer of ACRIF ensures that cyber risk intelligence outputs are transparent, reproducible, and suitable for regulatory audit. Conventional cybersecurity analytics platforms frequently rely on probabilistic machine learning models or opaque scoring mechanisms, which may provide predictive accuracy but often lack structured reasoning chains required for supervisory examination. In contrast, ACRIF implements a rule-based inference mechanism designed to produce deterministic justification paths that directly link control deficiencies to regulatory obligations and business impact indicators.

When a control is identified as deficient or elevated in risk weighting, the explainability engine generates a structured reasoning chain that includes explicit references to the affected control, the applicable regulatory requirement, the severity classification of the deviation, and projected enforcement exposure. Each reasoning element is traceable to source metadata, ensuring that conclusions can be reproduced under identical input conditions. This deterministic design enhances audit defensibility and supports compliance reporting requirements across multiple jurisdictions. The output format is adaptive to stakeholder context. Executive-level reports emphasise financial exposure and reputational impact, regulator-facing documentation focuses on compliance gaps and statutory references, and operational teams receive remediation-prioritised narratives. Audit-ready outputs

Table 4 Deterministic Explainability Components

Component	Functional Role	Governance Value
Rule-Based Inference Engine	Generates structured reasoning chains	Ensures reproducibility and audit integrity
Regulatory Citation Mapping	Links controls to statutory obligations	Enhances compliance defensibility
Severity Classification Module	Categorises violation impact levels	Supports prioritised remediation
Regulatory Exposure Indicator	Estimates supervisory risk likelihood	Improves strategic oversight
Audience-Specific Output Formatting	Customises reporting for stakeholders	Aligns governance communication

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ISSN: 3067-3216

may be stored in immutable repositories with integrity verification to preserve evidentiary validity.

Table 4 illustrates how deterministic reasoning replaces opaque analytics with structured, regulator-aligned narratives, strengthening transparency, accountability, and audit readiness within dynamic cybersecurity governance.

4. Results

4.1 Analytical Validation of the Adaptive Risk Weighting Mechanism

The adaptive risk weighting mechanism was analytically evaluated through a structured scenario-based validation. The evaluation examined three contextual variables: regulatory enforcement intensity, threat correlation persistence, and sector-specific modifiers. The objective was to determine whether dynamic recalibration meaningfully differentiates ACRIF from static compliance scoring models. In a regulatory surge scenario within the financial sector, the baseline regulatory applicability factor for access control mechanisms was elevated due to increased supervisory scrutiny. The weighting engine automatically amplified control significance based on normalised enforcement-cycle signals. When correlated threat indicators were introduced, the threat correlation modifier further increased control weight. Upon subsidence of the threat campaign, the non-linear decay function gradually reduced the temporary escalation while maintaining regulatory sensitivity.

Unlike conventional systems that rely on fixed severity ratings or CVSS metrics, ACRIF weighting operates independently of vulnerability scoring databases and derives prioritisation from regulatory and contextual inputs. This behaviour demonstrates alignment with Claim 22 and validates that risk prioritisation reflects governance exposure rather than purely technical vulnerability severity.

Table 5 Comparative Behaviour of Control Weighting Models

Scenario Condition	Static GRC Model	Threat-Based DRA Model	ACRIF Weighting Mechanism
Regulatory Examination Period	No adjustment	No adjustment	Enforcement intensity amplification
Active Threat Correlation	Manual reassessment	Immediate threat-based increase	Dynamic increase with regulatory overlay
Threat Subsides	No change	Immediate drop	Gradual non-linear decay
Sector-Specific Critical Infrastructure	Generic weighting	Generic weighting	Industry-specific modifier applied
CVSS Dependency	Yes	Often Yes	No (Regulatory-context driven)

Table 5 presents the analytical results confirming that ACRIF introduces regulator-aware temporal sensitivity, absent in both static compliance systems and purely threat-driven dynamic models.

4.2 Cross-Framework Propagation Performance and Synchronisation Impact

The cross-framework propagation mechanism was validated through a multi-framework synchronisation scenario. A control deficiency within a primary framework was introduced and observed across interconnected regulatory representations. Upon modification of a control node within the NIST representation, the translation graph automatically traversed mapped nodes within ISO/IEC 27001 and PCI DSS equivalents. Edge-based propagation rules applied differentiated synchronisation logic between framework pairs. Confidence scores influenced the proportional transfer of risk impact, ensuring contextual alignment rather than uniform escalation.

Propagation events generated a structured synchronisation audit log, documenting original modification, traversal path, node-level recalculations, and framework-specific risk adjustments. Version-aware mappings ensured continuity across framework revisions.

Table 6 shows the results demonstrate that ACRIF reduces compliance fragmentation by automating risk harmonisation while maintaining traceable governance documentation.

Table 6 Cross-Framework Synchronisation Evaluation

Evaluation Criteria	Manual Mapping	Automated Mapping (Basic)	ACRIF Graph-Based Propagation
Multi-Framework Support	Sequential manual review	Limited automation	Concurrent multi-framework propagation
Context-Sensitive Rules	No	Minimal	Edge-based differentiated logic
Audit Traceability	Fragmented	Partial	Full synchronisation audit log
Version Awareness	Manual updates	Limited	Automatic transitional mapping
Reassessment Speed	Delayed	Moderate	Immediate event-driven synchronisation

4.3 Deterministic Explanation Output and Audit Readiness

Deterministic explainability was analytically validated, and a control deficiency scenario was processed through the rule-based inference engine to evaluate reproducibility and regulatory defensibility. The explanation output included: identification of the deficient control, citation of the relevant regulatory clause, classification of violation severity, and projected enforcement likelihood. Outputs were formatted differently for executive leadership, regulators, and operational remediation teams. Each reasoning chain was reproducible under identical input conditions, confirming deterministic behaviour independent of probabilistic modelling.

Table 7 Deterministic Explanation Validation Criteria

Validation Dimension	Conventional Analytics	ML-Based XAI	ACRIF Deterministic Model
Reproducibility	Limited	Probabilistic	Fully deterministic
Regulatory Citation Mapping	Minimal	Partial	Explicit clause linkage
Audience-Specific Output	Generic reporting	Limited customization	Multi-audience structured narratives
Audit Integrity	No immutability	No immutability	Immutable storage with verification
Enforcement Exposure Indicator	Absent	Absent	Included

Table 7 shows that the ACRIF explanation outputs provide regulator-facing traceability beyond model interpretability, supporting audit-ready compliance documentation.

4.4 Computational Efficiency and Event-Driven Recalculation Analysis

Efficiency evaluation was conducted; the objective was to assess the impact of selective recalculation compared to full-framework reassessment. Under a control drift detection event, only affected nodes and their directly connected framework representations were recalculated. Stable components remained unchanged. This event-driven architecture contrasts with conventional periodic reassessment cycles that recompute entire frameworks regardless of localised change.

Analytical comparison indicates substantial computational savings due to node-level recalculation. Resource optimisation is further enhanced by event-triggered updating rather than continuous scanning during stable operational states.

Table 8 indicates that the results confirm that ACRIF achieves improved governance responsiveness and computational efficiency through event-driven selective recalculation mechanisms.

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Table 8 Efficiency Comparison: Full Reassessment vs Selective Recalculation

Evaluation Metric	Full Reassessment Model	ACRIF Selective Recalculation
Recalculation Scope	Entire framework	Affected nodes only
Update Trigger	Periodic schedule	Event-driven alerts
Resource Utilization	High	Reduced (≥40% improvement as specified)
Response Time to Control Drift	Delayed	Immediate recalibration
Network/System Load During Stability	Continuous	Minimal

4.5 Consolidated Claim Validation and Functional Coverage Analysis

This subsection presents a structured validation summary of all ACRIF claims to demonstrate architectural completeness, regulatory alignment, and technical coherence. The objective is to analytically map each claim to its functional contribution within the framework and to illustrate how the claims collectively establish novelty across adaptive weighting, cross-framework synchronisation, deterministic explainability, and computational optimisation. Rather than treating claims as isolated legal constructs, this analysis positions them as interdependent governance mechanisms that reinforce the unified intelligence fabric. The table below consolidates the claims into summarised functional categories and highlights their role in supporting the overall system architecture.

Table 9 Consolidated Summary of ACRIF Patent Claims and Functional Contributions

Claim Category	Core Mechanism	Functional Contribution
Core Method & System	End-to-end adaptive architecture	Establishes a regulator-aligned risk intelligence generation system
Adaptive Weighting	Regulatory-cycle amplification, threat decay, sector modifiers, CVSS independence	Enables dynamic, regulator-sensitive control prioritisation
Cross-Framework Propagation	Edge-based mapping, confidence scoring, version-aware synchronisation	Automates compliance harmonisation across multiple standards
Deterministic Explainability	Rule-based inference, regulatory citation mapping, and immutable storage	Produces audit-ready, reproducible governance reasoning
Predictive Drift & Efficiency	Drift detection, event-driven recalculation, ≥40% resource optimisation	Enhances governance responsiveness and computational efficiency
Deployment & Embodiments	API exposure, alternative embodiments, storage media coverage	Ensures implementation scalability and technical enforceability

Table 9 shows that the consolidated analysis demonstrates that the ACRIF claim structure is not fragmented but functionally layered. The independent claims define the systemic architecture, while dependent claims progressively refine adaptive weighting logic, synchronisation mechanics, explainability safeguards, and efficiency enhancements. Notably, regulatory-cycle weighting and CVSS independence establish conceptual differentiation from conventional risk scoring models. Cross-framework propagation claims introduce automated harmonisation mechanisms absent in static compliance matrices. Deterministic explainability claims reinforce regulatory defensibility through structured reasoning chains and immutable storage. Predictive drift detection and selective recalculation claims substantiate computational efficiency and proactive governance capabilities.

Collectively, the claims validate that ACRIF operates as a unified regulator-aligned intelligence fabric rather than a conventional GRC extension, thereby confirming architectural coherence, technical novelty, and governance scalability within dynamic cybersecurity environments.

5. Discussion

5.1 Interpretation of the findings

The Adaptive Cyber Risk Intelligence Fabric (ACRIF) represents a conceptual shift from static compliance-oriented governance toward regulator-aligned adaptive intelligence. Existing dynamic risk assessment models emphasise real-time recalibration based primarily on threat intelligence and asset vulnerability metrics (Cheimonidis & Rantos, 2023). While such models enhance technical responsiveness, they often lack explicit integration of regulatory enforcement cycles and jurisdiction-specific compliance intensity. The proposed framework extends dynamic risk paradigms by embedding regulatory applicability as a foundational weighting determinant rather than a secondary reporting overlay.

Automation-focused approaches in industrial and cyber-physical systems demonstrate the feasibility of structured risk modelling through ontology-based engineering data (Ehrlich, 2024). However, these models remain primarily operational and do not incorporate cross-framework compliance synchronisation mechanisms. Similarly, adaptive governance models proposed for critical infrastructure resilience introduce feedback-driven policy adjustments (Friedman, 2025), yet do not operationalise regulator-cycle-aware control amplification or deterministic audit reasoning. The deterministic explainability component of ACRIF responds to transparency concerns identified in compliance and financial-sector cybersecurity governance (Ashfaq & Chowdhury, 2023). Whereas explainable artificial intelligence enhances interpretability at the model level, ACRIF advances governance-level audit defensibility through rule-based reasoning chains explicitly linked to regulatory clauses. This integrated approach addresses fragmentation identified in comparative analyses of cybersecurity frameworks (Review of Cybersecurity Frameworks, n.d.), positioning ACRIF as a structurally coherent regulator-sensitive governance fabric.

5.2 Comparison with Existing Approaches

Conventional Governance, Risk, and Compliance (GRC) platforms typically employ static mapping matrices and periodic reassessment cycles. Comparative mapping studies reveal structural overlaps across frameworks but highlight persistent manual harmonisation challenges (Faruq, 2025). ACRIF's graph-based propagation mechanism directly addresses this gap by automating synchronisation logic. Dynamic risk assessment literature demonstrates advances in continuous recalibration through threat feeds and contextual updates (Cheimonidis & Rantos, 2023; Dine, 2024). However, such models generally remain CVSS-dependent or vulnerability-severity oriented. ACRIF diverges by prioritising regulatory exposure and business context, consistent with sector-specific governance research in financial environments (McCoy, 2025).

In industrial systems, consequence-driven risk assessment approaches emphasise asset criticality and cascading effects. Although effective for operational resilience, these approaches do not integrate cross-framework compliance propagation. AutomationML-based risk identification similarly enhances technical traceability Eckhart et al. (2020) but lacks regulatory weighting sensitivity. Thus, ACRIF differentiates itself through three combined innovations: regulator-cycle-aware adaptive weighting, automated cross-framework propagation, and deterministic governance explainability. This integrated configuration extends beyond the partial solutions identified across prior studies.

5.3 Practical and Regulatory Implications

From a practical standpoint, ACRIF introduces measurable governance efficiency improvements through event-driven selective recalculation. Dynamic reassessment studies emphasise computational overhead challenges in continuous risk recalibration (Cheimonidis & Rantos, 2023). By recalculating only affected control nodes, the proposed framework mitigates resource strain while preserving responsiveness. For regulators, deterministic explanation chains enhance supervisory transparency. Financial-sector cybersecurity governance literature underscores the importance of traceable and auditable decision-making structures. ACRIF's structured reasoning output aligns with regulatory expectations for accountability and reproducibility.

In critical infrastructure contexts, adaptive resilience models highlight the necessity of aligning cybersecurity posture with national security and operational continuity priorities (Melaku, 2023). ACRIF's sector-specific modifiers and enforcement-intensity amplification mechanisms operationalise such alignment. Furthermore, cross-framework propagation reduces compliance fragmentation, supporting multi-jurisdictional organisations navigating overlapping standards. Collectively, these implications suggest that ACRIF contributes to bridging operational security analytics with governance-level strategic decision-making, reinforcing regulatory alignment without

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sacrificing computational scalability.

5.4 Limitations and Future Work

Despite its architectural strengths, the proposed framework remains analytically validated rather than empirically benchmarked. While scenario-based evaluations demonstrate conceptual feasibility, large-scale empirical deployment studies would strengthen performance validation. Dynamic risk assessment literature emphasises the importance of real-world data integration and longitudinal testing Cheimonidis and Rantos (2023), suggesting a need for pilot implementations across regulated sectors. Additionally, cross-framework propagation relies on the accuracy of equivalence confidence scoring. Comparative framework analyses reveal structural ambiguities between standards Azmi et al. (2018), which may influence propagation precision. Future work should incorporate machine-assisted semantic mapping validation to refine equivalence scoring.

The deterministic explainability mechanism, although rule-based and reproducible, may require continuous updates to reflect evolving regulatory language and statutory amendments. Governance resilience research in critical infrastructure contexts underscores the dynamic nature of policy evolution by Melaku (2023). Integrating automated regulatory feed parsing could enhance responsiveness. Future research should therefore focus on empirical benchmarking, real-time regulatory feed integration, and quantitative performance measurement under multi-framework enterprise deployments. Such developments would further substantiate ACRIF's operational scalability and regulatory adaptability.

6. Conclusion

The Adaptive Cyber Risk Intelligence Fabric (ACRIF) introduces a regulator-aligned, dynamically adaptive cybersecurity governance architecture that integrates control-state intelligence, regulatory applicability, cross-framework synchronisation, and deterministic explainability within a unified system. The framework addresses structural limitations observed in conventional governance and compliance models, particularly static risk scoring, manual cross-framework mapping, and limited audit transparency. By embedding regulatory-cycle-aware control weighting, threat-correlated temporal adjustment, and sector-specific amplification mechanisms, ACRIF shifts cybersecurity prioritisation from vulnerability-centric evaluation toward governance-sensitive risk intelligence. The cross-framework propagation mechanism reduces compliance fragmentation through graph-based synchronisation logic, enabling concurrent harmonisation across multiple standards while preserving contextual differentiation. The deterministic explainability layer strengthens audit defensibility by producing structured reasoning chains that explicitly link control deficiencies to regulatory clauses and enforcement exposure indicators. Selective recalculation and event-driven updating enhance computational efficiency, supporting scalable enterprise deployment without continuous reassessment overhead. Collectively, the framework advances the conceptual integration of operational security analytics and regulatory governance strategy. Rather than functioning as an extension of traditional GRC systems, ACRIF establishes a coherent intelligence fabric capable of adapting to evolving enforcement intensity, sectoral obligations, and threat conditions. This contribution provides a structured foundation for future empirical validation and multi-sector deployment, positioning regulator-aware adaptive governance as a critical direction for next-generation cybersecurity risk management architectures.

7. Declarations

Ethics approval and consent to participate: Not applicable. This study focuses on the conceptual design and analytical validation of the ACRIF governance architecture and did not involve human or animal subjects.

Consent for publication: Not applicable. The manuscript does not contain any individual person's data, images, or videos.

Availability of data and material: The data used for analytical validation, including the scenario-based comparative results for control weighting and propagation efficiency, are included within the manuscript's tables.

Conflicts of Interest: The author declares that there are no financial or personal relationships that could be perceived as influencing the work reported in this paper.

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

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