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## PREDICTIVE ARCHITECTURE FOR RISKS MANAGEMENT OF MONEY LAUNDERING IN CUSTOMS CONTROL

*This article develops a comprehensive predictive architecture for managing money-laundering risks in customs control, grounded in the integration of artificial intelligence (AI), machine learning, and advanced data-driven methodologies. The study addresses the systemic limitations of traditional rule-based anti-money laundering approaches, which remain reactive, fragmented, and inefficient in the context of increasing digitalization, global trade expansion, and the growing complexity of illicit financial schemes, including trade-based money laundering and cross-border shadow flows. The research proposes a multi-layered, cloud-native architectural framework that combines federated deep learning, explainable artificial intelligence, and predictive analytics to enable real-time anomaly detection, probabilistic risk scoring, and proactive identification of suspicious transactions and trade operations. The architecture incorporates key functional modules, including AI-driven single-window systems, anomaly detection engines, behavioral profiling tools, and automated cargo-screening mechanisms, ensuring comprehensive coverage of financial, customs, and logistics data streams. The integration of explainable AI ensures transparency, interpretability, and auditability of algorithmic decisions, supporting regulatory compliance and strengthening trust in AI-driven supervision systems. The study further formalizes key implementation parameters, including data quality and interoperability, model performance and adaptability, cloud-native infrastructure, cybersecurity resilience, and governance frameworks that define accountability and institutional coordination. The findings confirm that the integration of predictive analytics, federated intelligence, and explainable compliance systems enables a transition from reactive rule-matching to proactive risk intelligence, strengthening customs oversight, improving detection of shadow financial flows, and supporting the resilience and transparency of global trade and financial systems.*

*Key words: artificial intelligence, predictive architecture, risk hedging, banking innovations, fintech, customs control, compliance.*

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## ПРЕДИКТИВНА АРХІТЕКТУРА ДЛЯ УПРАВЛІННЯ РИЗИКАМИ ВІДМИВАННЯ КОШТІВ У МИТНОМУ КОНТРОЛІ

*У цій статті розроблено комплексну предиктивну архітектуру для управління ризиками відмивання грошей у митному контролі, що ґрунтується на інтеграції штучного інтелекту (ШІ), машинного навчання та data-driven методології. Дослідження розглядає системні обмеження традиційних підходів до боротьби з відмиванням грошей, заснованих на правилах, які залишаються реактивними, фрагментованими та неефективними в контексті зростаючої цифровізації, розширення світової торгівлі та ускладнення практик незаконних фінансових схем, включаючи відмивання грошей на основі торгівлі та транскордонних тіньових потоків. У дослідженні пропонується багаторівнева хмарна архітектурна структура, яка поєднує федеративне глибоке навчання, інтерпретований ШІ та прогнозу аналітику, щоб забезпечити виявлення аномалій у режимі реального часу, ймовірнісну оцінку ризиків та проактивну ідентифікацію підозрілих транзакцій та торговельних операцій. Архітектура включає ключові функціональні модулі, включаючи системи єдиного вікна на основі ШІ, механізми виявлення аномалій, інструменти поведінкового профілювання та автоматизовані механізми перевірки вантажів, що забезпечують повне охоплення потоків фінансових, митних та логістичних даних. Інтеграція поясненого ШІ забезпечує прозорість, інтерпретованість та аудиторність алгоритмічних рішень, підтримуючи дотримання нормативних вимог та зміцнюючи довіру до систем нагляду на основі ШІ. У дослідженні також формалізовано ключові параметри впровадження, включаючи якість даних та сумісність, продуктивність та адаптивність моделі, хмарну інфраструктуру, стійкість до кібербезпеки та рамки управління, що визначають підзвітність та інституційну координацію. Результати підтверджують, що інтеграція прогнозу аналітики, федеративного ШІ та інтерпретованих систем відповідності дозволяє перейти від реактивного зіставлення правил до проактивного аналізу ризиків, посилюючи митний нагляд, покращуючи виявлення тіньових фінансових потоків та підтримуючи стійкість та прозорість світових торговельних та фінансових систем.*

*Ключові слова: штучний інтелект, предиктивна архітектура, хеджування ризиків, банківські інновації, фінтех, митний контроль, комплаєнс.*

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### STATEMENT OF THE PROBLEM IN GENERAL AND ITS RELATIONSHIP WITH IMPORTANT SCIENTIFIC OR PRACTICAL TASKS

The increasing volume of global trade, coupled with the sophisticated methodologies employed in shadow financial flows, necessitates advanced predictive architectures for robust customs control [1; 2]. Traditional rule-based systems are increasingly insufficient in detecting and preventing financial crimes, highlighting the critical need for

adaptive and intelligent solutions [3]. This urgency is further amplified by the rapid pace of financial globalization and digitalization [4], rendering conventional techniques inadequate for frequent detection and prevention of illicit financial activities [5].

Sophisticated data-driven architectures that leverage machine learning and systemic analytics are indispensable for enhancing the resilience and efficacy of financial threat detection and mitigation within customs operations [6]. Artificial intelligence-driven predictive modeling architectures are vital for automating the generation of risk signals from transaction and operational data across various time horizons, thereby extending coverage into data-sparse regions for comprehensive risk management, detection, and mitigation [7; 8]. These architectures move beyond static analysis to incorporate dynamic, real-time assessment capabilities, which are crucial for identifying evolving patterns of illicit financial activities such as trade-based money laundering [9].

The integration of explainable artificial intelligence within these architectures is critical not only to identify illicit financial risks but also to articulate the underlying drivers of those risks, ensuring regulatory compliance and supervisory review [10]. This paper proposes a predictive architectural framework specifically tailored to bolster customs control against shadow financial flows, integrating advanced analytics and machine learning to achieve global scalability and enhanced risk detection [11]. The framework leverages federated deep learning for collaborative risk assessment across international banking institutions while preserving data privacy, alongside AI-driven single-window systems to integrate trade data for improved anomaly detection and decision-making processes [12].

The core innovation of this approach lies in its ability to transcend the limitations of traditional centralized risk assessment, which often struggles with regulatory constraints on cross-border data sharing, by enabling collaborative model training without compromising data locality [13]. This distributed learning paradigm is particularly beneficial for addressing complex layering schemes and multi-jurisdictional illicit financial activities, where insights from diverse datasets are crucial for comprehensive threat identification and mitigation [14]. Such an architecture facilitates the proactive identification of emerging typologies of financial crime, moving beyond reactive detection to preemptive disruption of shadow financial networks [15].

This necessitates the development of intelligent compliance frameworks that leverage explainable AI and cloud-native architectures to transform anti-money laundering from reactive rule-matching to proactive risk intelligence [16]. This shift is crucial given that current anti-money laundering regimes are largely failing, with only a small fraction of illicit financial activity being detected despite substantial compliance expenditures [17].

The present study is devoted to the design and validation of a predictive architectural framework for customs control, integrating federated deep learning, explainable AI, and cloud-native compliance systems. The research task encompasses: (1) mapping limitations of existing rule-based and centralized risk assessment models; (2) constructing a distributed learning paradigm for multi-jurisdictional financial crime detection; (3) evaluating scalability and compliance of AI-driven single-window systems for trade data integration. By addressing these objectives, the study contributes to both theory and practice in the modernization of customs risk management, offering a replicable model for global application in combating shadow financial flows.

## ANALYSIS OF LATEST RESEARCH AND PUBLICATIONS

Recent scholarship underscores the imperative of integrating machine learning (ML) and deep learning (DL) technologies into Anti-Money Laundering (AML) strategies to strengthen detection and mitigation capabilities against increasingly sophisticated financial crimes [18]. These computational approaches enable the processing of vast, heterogeneous datasets to uncover subtle patterns indicative of illicit financial activities, thereby overcoming the limitations of traditional rule-based systems that are easily circumvented by evolving criminal methodologies [19; 20].

Artificial intelligence (AI), ML, and DL techniques are particularly critical for developing robust, data-driven compliance systems capable of addressing challenges of flexibility, scalability, and unstructured data management inherent in conventional approaches [21]. Cloud-native AI frameworks exemplify this transformation by employing graph neural networks and temporal convolutional networks to integrate dynamic transaction-graph learning, temporal anomaly detection, and probabilistic risk scoring [22]. Such systems significantly enhance the identification of complex financial crime typologies - including cryptocurrency-related laundering and cross-border transactions - through the analysis of intricate relational structures and behavioral anomalies across large-scale datasets [16].

This paradigm shift enables a proactive rather than reactive stance against financial crime, reducing false positives while simultaneously improving the detection of high-risk events [23]. The growing complexity and scale of international financial flows necessitate intelligent and adaptive AML systems capable of countering increasingly sophisticated laundering techniques [24]. AI-driven anomaly detection models demonstrate transformative potential by adapting to evolving criminal methodologies in real time, thereby overcoming the static limitations of rule-based systems [25, p. 1898].

Moreover, the integration of predictive analytics facilitates the timely identification of suspicious activities, enhancing the overall effectiveness of AML programs [26, p. 272]. AI-based systems, particularly when combined with ML and predictive modeling, significantly improve the recognition of suspicious patterns, anomalies, and fraudulent transactions in real time, thereby reinforcing both AML initiatives and regulatory compliance [27, p. 383]. These models not only achieve higher predictive accuracy compared to traditional detection approaches but also

process larger data volumes more efficiently, uncovering previously unknown laundering schemes [28, p. 7].

Finally, advanced AI and ML techniques empower financial institutions to move beyond simple transaction monitoring by incorporating behavioral profiling and network analysis. This reduces false positives and enhances the efficiency of AML investigations, marking a decisive step toward intelligent, adaptive, and globally scalable compliance systems [29].

The rapid evolution of financial crime methodologies has prompted scholars to explore advanced computational approaches for Anti-Money Laundering (AML). Recent studies emphasize the transformative role of artificial intelligence, machine learning, and deep learning in overcoming the limitations of static, rule-based systems. These technologies enable dynamic anomaly detection, behavioral profiling, and network analysis, thereby enhancing the resilience and adaptability of compliance frameworks.

To synthesize the latest research directions, Table 1 presents a structured overview of technological approaches, their applications in AML, and their documented impacts. This comparative mapping highlights how AI-driven architectures are reshaping the detection, prevention, and mitigation of shadow financial flows across diverse contexts.

Table 1

**Integration of AI/ML in Anti-Money Laundering (AML) Research**

Technology / Approach	Application in AML	Impact / Contribution	Representative Sources
Machine Learning (ML) & Deep Learning (DL)	Large-scale data analysis; detection of subtle illicit patterns	Moves beyond static rule-based systems; adapts to evolving criminal methodologies	Amoako et al., 2025 [18]; Alli et al., 2023 [19]; Bhoyar, 2025 [20]; Dumanska, 2026 [2]
Cloud-native AI frameworks	Graph neural networks; temporal convolutional networks	Dynamic transaction-graph learning; temporal anomaly detection; probabilistic risk scoring	Abbas et al., 2024 [21]; Idowu et al., 2025 [22]
Cryptocurrency & cross-border transaction analysis	Behavioral anomaly detection across diverse datasets	Identifies complex typologies of financial crime; enhances global scalability	Sunday et al., 2025 [16]
Predictive analytics & anomaly detection	Real-time monitoring of suspicious activities	Proactive stance; reduced false positives; improved detection of high-risk events	Gelle, 2025 [23]; Qian et al., 2024 [24]; Eghaghe et al., 2024 [25]
Behavioral profiling & network analysis	Beyond transaction monitoring; relational mapping	Higher predictive accuracy; uncovering unknown laundering schemes; efficiency in investigations	Lokanan, 2023 [28]; Ghimire, 2025 [29]

The comparative analysis of recent publications reveals several key findings:

1. Shift from rule-based to adaptive systems: AI/ML approaches consistently outperform static detection models, enabling systems to adapt to evolving laundering methodologies.
2. Integration of advanced architectures: Cloud-native frameworks and federated learning models provide scalable solutions for cross-border and cryptocurrency-related typologies.
3. Enhanced accuracy and efficiency: Predictive analytics and behavioral profiling reduce false positives, improve investigative efficiency, and uncover previously unknown laundering schemes.
4. Global applicability: The research demonstrates that distributed and explainable AI systems can overcome regulatory barriers, offering replicable models for multi-jurisdictional AML compliance.

Collectively, these findings highlight that AI-driven predictive architectures are not only reshaping AML strategies but also laying the foundation for proactive, globally scalable risk management frameworks in customs and financial regulation.

### **HIGHLIGHTING THE PREVIOUSLY UNSOLVED PARTS OF THE GENERAL PROBLEM TO WHICH THE ARTICLE IS DEDICATED**

Despite significant progress in the digital transformation of banking and customs systems, several critical aspects of the general problem remain unresolved. The integration of artificial intelligence into risk-hedging frameworks is still fragmented, with applications concentrated in isolated domains such as fraud detection or transaction monitoring, while customs oversight and cross-border regulation remain insufficiently addressed. This fragmentation prevents the creation of comprehensive systems capable of managing the full spectrum of risks associated with shadow financial flows. At the same time, the diversification of fintech applications in customs control is limited, as current solutions focus predominantly on payments and duty collection, leaving predictive analytics, automated cargo screening, and intelligent dispute resolution underdeveloped. The deployment of AI-driven customs systems also continues to face technical, financial, and regulatory barriers, including infrastructure readiness, investment constraints, and the absence of harmonized international legal frameworks, which collectively hinder scalability and interoperability across jurisdictions. Furthermore, existing anti-money laundering regimes remain largely reactive and rule-based, detecting only a fraction of illicit financial activity despite substantial compliance expenditures, and failing to anticipate the evolving typologies of financial crime such as trade-based money laundering and cryptocurrency-enabled flows.

These unresolved issues form the central challenges to which this article is dedicated. By addressing the fragmentation of AI integration, the narrow scope of fintech applications, the persistent deployment barriers, and the inadequacies of current compliance regimes, the study underscores the necessity of comprehensive AI-driven risk-hedging models, expanded fintech innovations, and deeper institutional reforms. The research aims to contribute to the development of resilient, transparent, and globally scalable customs and banking systems capable of proactively disrupting shadow financial networks and ensuring compliance in an increasingly complex international environment.

### **FORMULATING THE PURPOSE OF THE ARTICLE**

The primary purpose of this research article is to critically investigate the design and application of predictive architectures for managing risks associated with shadow financial flows in customs control. The study seeks to examine how artificial intelligence, machine learning, and deep learning can be systematically integrated into risk-hedging frameworks to strengthen detection, prevention, and mitigation of illicit financial activities. Particular emphasis is placed on the interplay between AI-driven predictive analytics, explainable compliance systems, federated learning models, and cloud-native customs platforms, with the aim of enhancing resilience against complex, multi-jurisdictional financial crimes.

### **PRESENTATION OF THE MAIN MATERIAL**

The conceptual basis of predictive architectures in customs control lies in the recognition that shadow financial flows represent systemic risks requiring advanced, adaptive mechanisms of oversight. Traditional rule-based systems, while foundational in early anti-money laundering (AML) regimes, have proven increasingly inadequate in addressing the complexity and dynamism of illicit financial activities. Their reliance on static thresholds and predefined rules generates high volumes of false positives, diverts investigative resources, and fails to anticipate evolving typologies of financial crime. This limitation underscores the necessity of integrating artificial intelligence, machine learning, and deep learning into risk-hedging frameworks, situating these technologies as transformative tools for resilience, compliance, and systemic analytics.

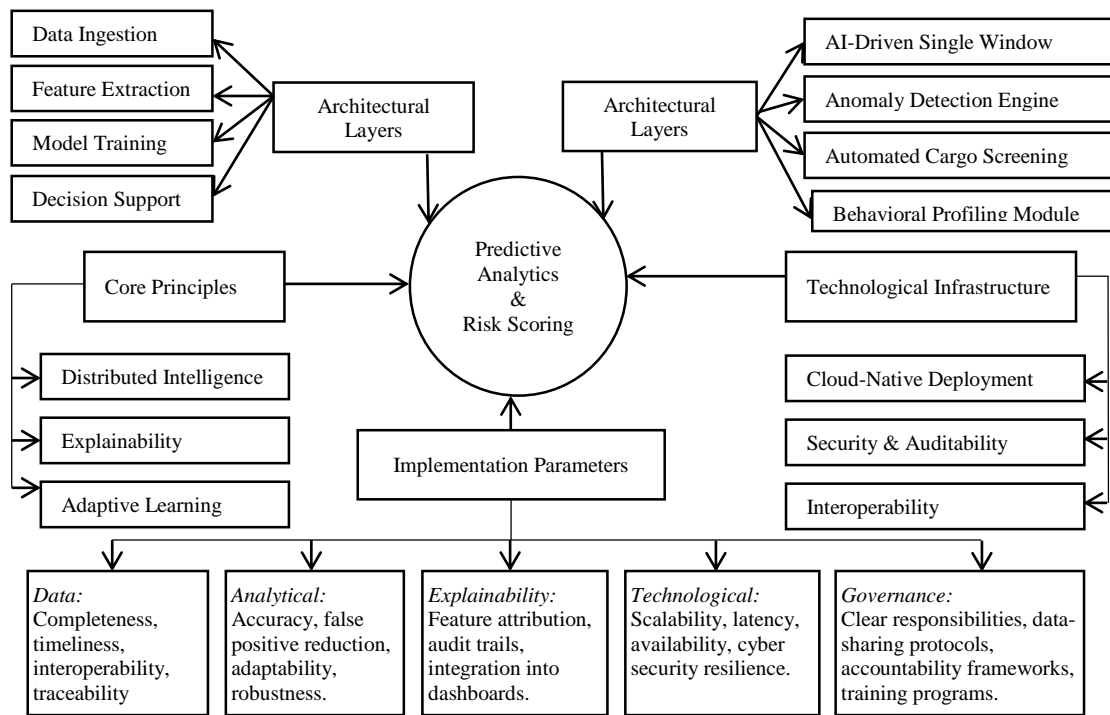
The efficacy of advanced computational methods in combating illicit financial activities has been empirically substantiated across recent studies, which demonstrate significant improvements in predictive accuracy and substantial reductions in false positives compared to conventional approaches [9]. AI algorithms - including deep learning, machine learning, and natural language processing - have been shown to construct robust fraud detection frameworks capable of identifying, analyzing, and preventing fraudulent transactions in real time [30, p. 602]. Within transaction monitoring, machine learning represents a decisive shift in the banking sector, driven by regulatory support for innovative approaches to strengthen AML programs [31]. By scanning vast volumes of transactional data, these systems identify anomalies and trends that would be impossible to detect manually [28].

The application of natural language processing further extends predictive architectures by enabling the analysis of unstructured data sources such as emails and social media, thereby complementing structured data analysis with contextual insights into suspicious behaviors [32]. Collectively, these methodologies refine risk scoring mechanisms and optimize resource allocation for investigations, enhancing the overall effectiveness of financial crime detection and prevention [3; 5]. The integration of supervised and unsupervised learning algorithms has proven particularly effective in improving detection accuracy and reducing false positives in AML systems [16; 18; 20]. This advancement is crucial given that rule-based systems frequently generate alerts requiring extensive manual review, thereby diverting attention from genuine illicit activities [26].

Empirical evidence indicates that AI-powered AML systems can reduce false positives by up to 60% while simultaneously increasing the detection of true positives by 50% [29]. Such improvements mark a paradigm shift toward proactive, predictive intelligence frameworks that enhance financial resilience and regulatory compliance. The growing adoption of AI in risk mitigation across financial institutions reflects this transformation, as advanced analytics and anomaly detection dramatically improve fraud detection accuracy by uncovering complex transactional patterns often missed by traditional systems [30; 31]. These AI-driven approaches are pivotal for transforming AML and compliance procedures, enabling the identification of sophisticated financial crimes that conventional systems, with their high false positive rates, frequently fail to detect [29-31].

The methodological design of the proposed predictive architecture is grounded in the integration of federated deep learning, explainable artificial intelligence (XAI), and cloud-native systems to enhance customs oversight and financial risk management. This framework reflects a convergence of computational intelligence, regulatory compliance, and systemic analytics, enabling proactive identification and mitigation of shadow financial flows. The methodological approach combines theoretical modeling with applied system design, emphasizing interoperability, scalability, and transparency across multi-jurisdictional environments (Figure 1).

Figure 1 presents the integrated framework, combining federated deep learning, explainable artificial intelligence, and cloud-native systems to strengthen customs oversight and advance financial risk management. The architecture is structured around distributed intelligence, explainability, and adaptive learning, with applied modules including single-window platforms, anomaly detection engines, automated cargo screening, and behavioral profiling. Together, these components address fragmentation, scalability, and regulatory barriers, enabling proactive identification and mitigation of shadow financial flows.



**Fig. 1. Methodological Design of Predictive Architecture for Risk Management in Customs Control against Money Laundering\***  
 \* formed by the author based on [16-20, 29-31]

**Architectural Design Principles.** The predictive architecture is structured around three core principles: distributed intelligence, explainability, and adaptive learning. Distributed intelligence is achieved through federated deep learning, which allows multiple institutions - such as customs authorities, financial regulators, and banking systems - to collaboratively train models without sharing sensitive data. This approach preserves data locality and privacy while enabling global risk assessment through shared model parameters [13]. Explainability ensures that AI-driven decisions are transparent and interpretable, addressing regulatory concerns about algorithmic opacity and accountability [10]. Adaptive learning, meanwhile, enables continuous model refinement based on new data inputs, ensuring responsiveness to emerging typologies of illicit financial activity.

The architecture employs a multi-layered design, integrating data ingestion, feature extraction, model training, and decision-support modules. Data sources include transactional records, customs declarations, trade documentation, and external intelligence feeds. These inputs are processed through machine learning pipelines that perform anomaly detection, behavioral profiling, and probabilistic risk scoring. The system’s modularity allows for integration with existing customs and AML infrastructures, facilitating interoperability across national and international platforms.

**Federated Deep Learning for Cross-Border Risk Assessment.** Federated deep learning constitutes the methodological backbone of the proposed architecture. Unlike centralized models that require data aggregation, federated learning enables decentralized training across multiple nodes, each representing a participating institution. This design mitigates regulatory barriers related to cross-border data sharing while enhancing the collective intelligence of the system [11]. Each node trains local models on its proprietary data and shares only model updates - such as gradients or weights - with a central aggregator. The aggregator synthesizes these updates to refine a global model, which is then redistributed to all nodes for further training.

Empirical studies have demonstrated that federated learning improves detection accuracy in multi-institutional AML contexts by leveraging diverse datasets without compromising confidentiality [14]. In customs control, this approach enables collaborative identification of suspicious trade patterns, such as under-invoicing, over-valuation, or circular trade flows indicative of money laundering. The distributed nature of federated learning also enhances resilience against data breaches and ensures compliance with data protection regulations such as the EU’s General Data Protection Regulation (GDPR) [15].

**Explainable AI and Compliance Integration.** Explainable AI (XAI) is incorporated into the architecture to ensure interpretability of predictive outputs. In regulatory environments, transparency is essential for supervisory review and legal accountability. XAI techniques - such as SHAP (Shapley Additive Explanations) and LIME (Local Interpretable Model-agnostic Explanations) - are applied to elucidate the contribution of individual features to model predictions [9]. This allows compliance officers to understand why certain transactions or entities are flagged as high-risk, facilitating informed decision-making and reducing reliance on opaque algorithmic judgments.

The integration of XAI also supports regulatory harmonization, as explainable models can be audited and validated across jurisdictions. This feature is particularly relevant for customs control, where decisions often involve

multiple stakeholders - banks, logistics providers, and trade regulators. By providing interpretable outputs, the architecture bridges the gap between technical complexity and regulatory comprehension, fostering trust in AI-driven compliance systems.

**Cloud-Native Infrastructure and Scalability.** The architecture is deployed within a cloud-native environment to ensure scalability, flexibility, and real-time processing capabilities. Cloud-native systems leverage containerization and microservices to enable dynamic resource allocation and seamless integration with external APIs [12]. This infrastructure supports high-volume data ingestion from customs and financial networks, enabling continuous monitoring of global trade flows.

Cloud-based deployment also facilitates interoperability between national customs systems and international financial institutions. Through secure APIs and blockchain-enabled audit trails, the architecture ensures data integrity and traceability. The use of cloud-native technologies aligns with global trends in digital transformation, allowing for rapid scaling of predictive models and efficient management of computational workloads.

**Applied Components and Functional Modules.** The proposed predictive architecture comprises several functional modules that collectively enhance customs oversight:

(1) **AI-Driven Single-Window Platform:** Integrates trade, customs, and financial data into a unified interface, enabling real-time anomaly detection and risk scoring. This platform automates document verification and cross-checks trade declarations against transactional data to identify inconsistencies indicative of illicit flows.

(2) **Anomaly Detection Engine:** Utilizes unsupervised learning algorithms - such as autoencoders and clustering models - to detect deviations from normal trade patterns. These anomalies are prioritized based on probabilistic risk scores, guiding targeted investigations.

(3) **Automated Cargo Screening System:** Employs computer vision and sensor data to analyze cargo images and detect discrepancies between declared and actual contents. Integration with predictive analytics enhances the identification of high-risk shipments.

(4) **Behavioral Profiling Module:** Applies graph analytics to model relationships among entities - importers, exporters, intermediaries - and identify suspicious networks. This module supports the detection of layering and structuring schemes typical of trade-based money laundering.

Each module operates within the federated learning ecosystem, contributing to the global model while maintaining institutional autonomy. The architecture's modularity ensures adaptability to diverse regulatory contexts and technological infrastructures.

**Comparative Analysis with Existing Systems.** A comparative analysis reveals that traditional AML and customs control systems are predominantly rule-based, reactive, and siloed. They rely on static thresholds and manual reviews, resulting in inefficiencies and high false-positive rates [27]. In contrast, the proposed predictive architecture introduces dynamic, data-driven intelligence capable of learning from evolving patterns of financial crime.

Existing centralized systems also face challenges related to data fragmentation and regulatory constraints on cross-border information exchange. The federated learning approach directly addresses these issues by enabling collaborative model training without data transfer. Moreover, the integration of explainable AI enhances transparency, a feature largely absent in conventional systems. Cloud-native deployment further distinguishes the proposed framework by offering scalability and real-time responsiveness, essential for monitoring global trade flows.

Empirical evidence supports the superiority of AI-driven architectures in AML contexts. Studies indicate that machine learning models can reduce false positives by up to 60% and increase true positive detection by 50% [31]. These improvements translate directly into operational efficiency and regulatory compliance. In customs control, predictive architectures enable early identification of suspicious consignments, reducing inspection delays and optimizing resource allocation.

**Addressing Fragmentation, Scalability, and Regulatory Barriers.** The proposed framework effectively addresses the unresolved challenges identified in prior research. Fragmentation is mitigated through federated learning, which unifies analytical capabilities across institutions without compromising data sovereignty. Scalability is achieved through cloud-native deployment, allowing the system to handle increasing volumes of trade and financial data. Regulatory barriers are overcome through explainable AI and privacy-preserving model training, ensuring compliance with international data protection standards.

By integrating these methodological components, the predictive architecture establishes a foundation for proactive risk management in customs control. It transforms AML and compliance processes from reactive rule-matching to predictive intelligence, enabling early detection and disruption of shadow financial flows. The framework's adaptability ensures relevance across diverse jurisdictions, supporting global efforts toward transparency, resilience, and sustainable trade governance.

The practical implementation of a predictive architecture for managing money-laundering risks in customs control requires the formalization of functional, technological, regulatory, and organizational parameters. These parameters transform the proposed conceptual model into an operational system capable of supporting real-time risk identification, supervisory decision-making, and cross-border cooperation, as outlined in the proposed federated, explainable, and cloud-native framework.

*1. Data Parameters.* Implementation should begin with the definition of harmonized data inputs, including customs declarations, trade documents, financial transaction records, logistics data, and external risk indicators. Data

requirements include completeness, timeliness, interoperability, and traceability. Practical guidance involves the adoption of unified data models (e.g., single-window formats) and the use of automated validation rules to reduce information asymmetry and manual errors.

2. *Analytical and Model Parameters.* Predictive performance depends on a combination of supervised and unsupervised learning models. Key parameters include model accuracy, false-positive rate, adaptability to new typologies, and robustness across jurisdictions. Federated deep learning parameters should define update frequency, aggregation rules, privacy thresholds, and convergence criteria, ensuring collaborative intelligence without cross-border data leakage.

3. *Explainability and Compliance Parameters.* For regulatory acceptability, implementation must incorporate explainable AI mechanisms. Parameters include the selection of explanation techniques (e.g., feature attribution), audit trails for model decisions, and documentation standards. Practical guidance emphasizes integrating explainability outputs directly into risk dashboards used by customs officers and AML analysts, enabling justified inspections and defensible enforcement actions.

4. *Technological Infrastructure Parameters.* Cloud-native deployment parameters include scalability, latency, system availability, and cybersecurity resilience. Microservice architecture, secure APIs, and encrypted communication channels should be standardized to support real-time monitoring of high-volume trade flows. A phased rollout strategy-pilot, scale, integrate-helps mitigate operational risks and investment constraints.

5. *Institutional and Governance Parameters.* Effective implementation requires clear allocation of responsibilities among customs authorities, financial institutions, and regulators. Governance parameters include data-sharing protocols, model ownership, accountability frameworks, and continuous validation procedures. Training programs for analysts and decision-makers are essential to ensure effective human-AI interaction and to reduce resistance to algorithm-supported decisions.

In practice, the architecture should be introduced incrementally, starting with high-risk trade corridors and priority commodities. Early performance metrics-such as reduction in false positives, inspection time, and detection lag-should inform model recalibration. Continuous feedback loops between investigators and model outputs support adaptive learning and long-term sustainability.

The scheme in Figure 2 operationalizes the principles of distributed intelligence, explainability, and adaptive learning, ensuring that the predictive architecture functions as a scalable and regulator-ready system for combating money laundering in customs control.

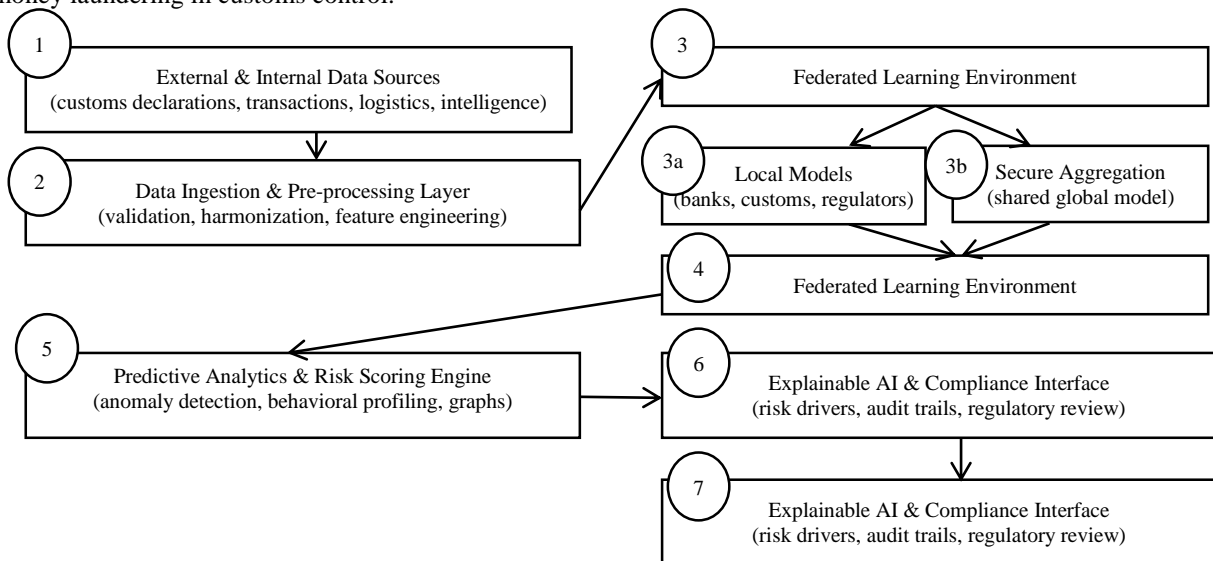


Fig. 2. Scheme of Predictive Architecture for Customs AML

\* formed by the author based on [16; 18; 20; 25; 29]

Figure 2 presents the methodological design of a predictive architecture for managing money-laundering risks in customs control based on the integration of federated deep learning, explainable artificial intelligence (XAI), and cloud-native infrastructure. The architecture is structured around three core principles: distributed intelligence, explainability, and adaptive learning. It encompasses sequential layers of data ingestion from customs, financial, and logistics sources; data validation, harmonization, and feature engineering; a federated learning environment with local models operated by banks, customs authorities, and regulators; and secure aggregation mechanisms for building a shared global model without cross-border data transfer [33]. Predictive analytics and risk-scoring modules generate probabilistic risk signals, while the XAI interface provides interpretable explanations, audit trails, and supervisory support. The proposed design ensures scalability, regulatory compliance, data sovereignty, and transparency of algorithmic decision-making in customs AML systems.

## CONCLUSIONS FROM THIS RESEARCH AND PROSPECTS FOR FURTHER RESEARCH IN THIS DIRECTION

This research demonstrates that the integration of artificial intelligence-driven predictive architectures into risk-hedging systems can substantially enhance the effectiveness, transparency, and resilience of money-laundering risk management in customs control. The synthesis of recent academic literature, comparative analysis, and conceptual modeling confirms that AI-based predictive analytics, real-time monitoring, anomaly detection, and behavioral profiling significantly improve the quality of risk identification while reducing false positives and the operational costs of compliance. In contrast to traditional rule-based approaches, the proposed architecture enables a proactive, adaptive, and data-driven response to evolving typologies of trade-based money laundering and cross-border illicit financial flows.

The findings indicate that the modernization of customs control increasingly depends on the deployment of integrated, cloud-native and federated AI systems capable of combining customs, financial, and logistics data. Digital single-window platforms, automated validation of declarations, intelligent cargo screening, and AI-supported risk scoring collectively reduce information asymmetry among stakeholders and limit opportunities for shadow trade. At the same time, the study confirms that the economic and regulatory value of these technological innovations is maximized only when their implementation is accompanied by regulatory harmonization, explainable AI mechanisms, and ethical governance principles, including data privacy protection, bias control, model accountability, and auditability. This is particularly critical in multi-jurisdictional environments where cross-border coordination and trust in algorithmic decision-making are essential.

The experience of Ukraine's alignment with European digital customs practices, including the implementation of NCTS, illustrates that convergence with EU standards can serve as an effective pathway for institutional modernization. However, persistent constraints related to infrastructure readiness, investment capacity, data quality, and human capital highlight the need for coordinated long-term strategies rather than fragmented, isolated AI projects.

Prospects for further research in this direction include:

1. The development of integrated AI-based risk-hedging architectures that connect banking compliance functions (AML/CFT, fraud detection, credit risk) with customs risk management (targeting, screening, post-clearance audit) through shared data models and interoperable platforms.
2. Quantitative evaluation of the effectiveness and return on investment of AI solutions in financial and customs control, including robust methodologies for causal impact assessment of reductions in false positives, processing times, compliance costs, and improvements in revenue protection.
3. Regulatory and legal research focused on cross-border data exchange, federated learning governance, algorithmic accountability, and the alignment of AI-enabled RegTech and SupTech tools with EU legislation and international trade agreements.
4. Advancement of AI-enabled customs technologies beyond digital payments, including automated cargo screening, intelligent anomaly detection in declarations, and decision-support systems for dispute resolution, with particular attention to cyber security and operational risks.
5. Research on human capital, organizational readiness, and change management, including skill requirements, institutional learning mechanisms, and strategies to mitigate the "predictive paradox" where AI projects underperform due to talent shortages or implementation delays.
6. Analysis of the ethical and societal implications of AI deployment in customs and financial supervision, including bias risks, transparency standards, public trust, and the design of governance frameworks that ensure responsible innovation.

Overall, the conclusions of this research confirm that strengthening risk-hedging capacity in customs control and connected financial systems requires a systemic approach in which artificial intelligence and fintech tools are embedded within coherent regulatory frameworks and supported by institutional reforms. Further interdisciplinary research combining economics, data science, law, and public administration is essential to design scalable solutions, ensure compliance with international standards, and translate digital innovations into measurable gains in trade security, economic resilience, and the integrity of public revenues.

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