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Cross-Border Regulatory Barriers and Algorithmic Mitigations in Global E-Commerce Fulfillment Channels

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Abstract

Cross-border business-to-consumer e-commerce expanded through the early 2020s under a permissive regulatory settlement: high or generous de minimis thresholds, thin data requirements on low-value consignments, and product-safety regimes designed for containerised wholesale imports rather than for direct parcel flows. During 2024 that settlement began to close. The United States announced proposed rulemaking to restrict Section 321 de minimis treatment and to require ten-digit tariff classification on low-value entries; the European Union extended its Import Control System 2 (ICS2) advance filing obligations to maritime, road, and rail modes and brought the General Product Safety Regulation into application, imposing an EU-established responsible person on every consumer product sold into the bloc regardless of consignment value. This paper asks two questions. First, how do these barriers distribute across the distinct fulfillment channel archetypes used in cross-border retail, and second, which classes of algorithmic system can plausibly absorb the resulting compliance load, and where do they fail.

We conduct a structured review of primary regulatory instruments and official announcements issued or applied in 2024, develop a six-class taxonomy of cross-border regulatory barriers, and map that taxonomy against five fulfillment channel archetypes. We then formalise channel selection as expected total landed cost minimisation under regulatory uncertainty, and derive an abstention threshold for automated tariff classification under asymmetric error costs. Our central finding is that algorithmic mitigation is substitutive rather than eliminative: machine classification, landed cost engines, data-completeness validators, and risk-mirroring models convert regulatory friction from a variable per-parcel tax into a fixed platform investment, which advantages large operators and marketplaces while raising the effective entry cost for small and emerging-market sellers. We identify explainability under reasonable-care standards, calibration drift under regulatory change, and the optimisation-versus-evasion boundary as the three binding constraints on further automation, and set out an evaluation protocol built on cost-sensitive rather than accuracy-only metrics.

Keywords: Cross-Border E-Commerce, De Minimis, Customs Classification, Trade Facilitation, Non-Tariff Measures, Machine Learning, Fulfillment Networks, Regulatory Compliance, Landed Cost, Product Safety

1. Introduction

The parcel, not the container, is now the marginal unit of international retail trade (Abioye *et al*., 2023; Agbabiaka *et al*., 2019; Ahiaeke Patrick *et al*., 2020; Ahiaeke Patrick *et al*., 2021). United States Customs and Border Protection handled roughly 140 million low-value entries a decade ago; by 2024 the annual figure had passed one billion, an order-of-magnitude change within a single decade. Low-value consignments entering the European Union have risen on a comparable trajectory, and that growth is the stated motivation for the customs reform package the European Commission tabled in May 2023. Volumes of this kind were never anticipated by the procedural architecture that governs them. That architecture assumed a small number of high-value declarations, each meriting individual scrutiny, with a residual tail of negligible shipments that could be waved through because the administrative cost of assessment exceeded the revenue recovered.

That assumption inverted. The tail became the distribution (Aifuwa *et al*., 2020; Akin-Oluyomi *et al*., 2020; Akin-Oluyomi *et al*., 2023a; Akin-Oluyomi *et al*., 2023b). Once the tail carries the majority of consignments, the de minimis rule stops functioning as an efficiency device and starts functioning as a structural subsidy to a particular fulfillment topology, namely direct-from-origin single-parcel dispatch, at the expense of the topology it competes with, namely bulk import followed by domestic distribution. It also becomes an enforcement blind spot, since goods entering without full classification data cannot be effectively targeted for safety, intellectual property, or interdiction purposes.

2024 is the year in which regulators across major consuming markets acted on this recognition more or less simultaneously. The actions were not coordinated and did not share a common legal theory, but they converged on a single operational demand: more data, earlier, attached to every parcel, with an identifiable accountable party in the destination jurisdiction. That demand is what this paper treats as the object of study.

Three questions organise the analysis. What classes of cross-border regulatory barrier confront business-to-consumer e-commerce fulfillment as of 2024, and how are they distributed across distinct fulfillment channel architectures? Which algorithmic systems are being deployed or proposed to mitigate each barrier class, what is their technical maturity, and what are their characteristic failure modes? And under what conditions does algorithmic mitigation change the optimal fulfillment channel choice, with what distributional consequences?

The analysis proceeds on four fronts (Adelanwa *et al*., 2023a; Adelanwa *et al*., 2023b; Adelanwa *et al*., 2024). It offers a six-class taxonomy of cross-border regulatory barriers grounded in instruments issued or applied in 2024, rather than in the older non-tariff-measure literature that predates the parcel shift. It maps that taxonomy onto five fulfillment channel archetypes, producing a barrier-by-channel matrix that makes explicit which architectures absorb which costs. It formalises channel selection as expected total cost minimisation with an explicit regulatory risk term, and derives a closed-form confidence threshold for automated classification under asymmetric misclassification costs. It then sets out a cost-sensitive evaluation protocol for compliance automation, on the argument that top-one accuracy on tariff code prediction is a poor proxy for the operational quantity that matters. Section 2 reviews the regulatory record and the relevant literature, Section 3 sets out the analytical framework, Section 4 the data and method, Sections 5 and 6 the barrier classes and the mitigations that address them, Section 7 the evaluation metrics, and Sections 8 and 9 the implications and conclusions.

2. Background and Related Work

2.1 The de minimis settlement and its erosion

The de minimis principle rests on an administrative efficiency argument: below some value threshold, the cost to the state of assessing and collecting duty exceeds the duty collected, so collection should be waived. The argument is sound in isolation and unsound in aggregate, because the threshold is a per-consignment test applied to a shipment count that sellers control. Where a threshold exists, fulfillment strategy will reorganise to sit beneath it (Adeyelu, 2018; Adeyelu, 2019; Adeyelu, 2020; Adeyelu, 2021; Adeyelu & Dagodzo, 2022). Retailers restructured toward direct dispatch precisely because the threshold rewarded fragmentation over consolidation.

The United States raised its threshold to 800 dollars in 2015, among the most generous in the world, and the consequences accumulated over the following decade. By July 2024 the Department of Homeland Security was stating publicly that screening capacity could not match a flow of roughly four million packages per day, and characterising the exemption as resting on a false equivalence between low value and low risk. On 13 September 2024 the White House published a fact sheet announcing intended rulemaking to exclude from de minimis treatment goods subject to Section 201, 232, and 301 trade remedies, to require the full ten-digit Harmonized Tariff Schedule classification on low-value entries, to require electronic filing of Certificates of Compliance with CBP and the Consumer Product Safety Commission, and to identify the party claiming the exemption.

The European trajectory differed in instrument but not in direction (Adeyelu, 2023; Adeyelu & Dagodzo, 2024b; Eze *et al*., 2022a; Eze *et al*., 2022b; Eze *et al*., 2023; Eze *et al*., 2024a). The Commission's May 2023 customs reform package proposed abolishing the 150 euro duty exemption and introducing a deemed-importer concept placing customs obligations on platforms, mirroring the treatment already applied to value-added tax through the Import One Stop Shop since July 2021. During 2024 the more immediate operational change came from ICS2. Release 3 phase one applied from 3 June 2024 to maritime and inland waterway carriers, with house-level filers including freight forwarders and consolidators brought into scope from 4 December 2024, completing an advance filing regime that requires a complete Entry Summary Declaration, including a six-digit HS code per commodity line, before goods reach the customs territory.

Product safety moved on a parallel track (Abetoh & Atakpa, 2024; Agu *et al*., 2023a; Agu *et al*., 2023b). Regulation (EU) 2023/988, the General Product Safety Regulation, became applicable on 13 December 2024 with no transitional period, requiring that no consumer product be placed on the EU market without an economic operator established in the Union bearing responsibility for it, and requiring that this operator's identity and contact details appear both on the product or its packaging and within the online listing itself. Article 22 imposed registration and single-point-of-contact obligations on online marketplaces. Critically for this paper, the regulation contains no value threshold, so it binds on a five euro parcel exactly as it binds on a pallet.

2.2 Trade facilitation, non-tariff measures, and machine learning in customs

Three literatures bear on this problem and do not currently speak to each other (Akin-Oluyomi *et al*., 2023c; Akin-Oluyomi *et al*., 2023d; Akin-Oluyomi *et al*., 2024; Akinleye & Adeyoyin, 2021).

The trade facilitation literature, largely institutional and economic, quantifies the cost of border procedures and models the welfare effects of their simplification. It is well developed for containerised trade and for the WTO Trade Facilitation Agreement framework, but treats the consignment as a relatively large and infrequent object. Its cost parameters, typically expressed as ad valorem

equivalents of documentary and border compliance time, translate poorly to a channel where the fixed administrative cost per consignment may exceed the value of the goods.

The non-tariff measure literature classifies technical barriers, sanitary measures, conformity assessment, and similar instruments, and provides the vocabulary this paper borrows for barrier classification. Its limitation for present purposes is that it is oriented toward market access at the level of the exporting firm and the product category, rather than at the level of the individual consumer consignment and the fulfillment topology that carries it (Akomolafe & Agu, 2018; Akomolafe & Agu, 2019a; Akomolafe & Agu, 2019b; Akomolafe & Agu, 2019c).

The applied machine learning literature on customs has developed rapidly and largely independently (Anene & Clement, 2022; Anene & Clement, 2024; Basnet *et al*., 2021). Work on automated Harmonized System code prediction spans classical supervised approaches, transformer-based text classification, and knowledge-graph formulations. Early work in this area proposed commodity classification frameworks for trade declaration analysis; subsequent work has applied sentence-level embeddings with contrastive objectives, hierarchy-aware classification, and graph representations of declaration attributes. Reported accuracies vary enormously with the granularity of the target, the length and quality of the input description, and the breadth of the code space, and figures obtained at heading level should not be read across to national subheading level. Parallel work on customs fraud detection has produced tree-aware embedding models for selecting declarations for inspection, and a related strand has emphasised explainability, on the grounds that a classification a customs officer cannot justify is operationally useless regardless of its accuracy.

The machine learning literature is written from the perspective of the customs administration, which wants to detect misclassification and target inspection. The commercial reality of 2024 is that the same techniques are being deployed from the opposite side of the counter, by sellers, marketplaces, carriers, and third-party logistics providers, who must now produce the very data that the administration intends to scrutinise. This mirror-image deployment has received little systematic treatment (Adebayo *et al*., 2022; Adebayo *et al*., 2023a; Adebayo *et al*., 2023b; Adegbite *et al*., 2020; Adegbite *et al*., 2022; Adegbite *et al*., 2023). Nor has the interaction between algorithmic capability and fulfillment network design, despite the fact that the choice of channel determines which regulatory obligations attach at all. This paper addresses that gap.

2.3 Evidence from adjacent regulated domains

Cross-border e-commerce compliance is a young field with a thin empirical base, and several of the mechanisms examined in this paper, notably risk-based inspection targeting, documentary conformity assessment, accountable-operator requirements, and the automation of regulatory reporting, are considerably better documented in other regulated sectors. This review therefore draws on evidence from adjacent domains where the same mechanisms have been studied for longer, treating that evidence as analogical rather than directly transferable.

Safety-critical operations offer the closest available analogue to risk-based customs targeting. Inspection regimes in construction, industrial, and aviation settings allocate scarce enforcement attention through risk scoring, and the literature on those regimes documents both the gains from targeting and its characteristic failure modes, including the displacement of effort toward whatever is measurable (Adeyelu, 2022; Adeyelu & Dagodzo, 2024a; Arumosoye & Obriki, 2018; Arumosoye & Obriki, 2019; Arumosoye & Obriki, 2020; Arumosoye & Obriki, 2021; Arumosoye & Obriki, 2022; Arumosoye & Obriki, 2023; Arumosoye & Obriki, 2024; Bello *et al*., 2022a; Bello *et al*., 2022b; Bello *et al*., 2024). That literature also shows that compliance culture and documentation practice determine whether a formal requirement produces a substantive outcome, which bears directly on the distinction drawn in Section 6.4 between formal and substantive declaration validity (Obogo *et al*., 2019a; Obogo *et al*., 2019b; Obogo *et al*., 2019c; Obogo *et al*., 2020a; Obogo *et al*., 2020b; Obogo *et al*., 2020c; Obogo *et al*., 2021a; Obogo *et al*., 2021b; Obogo *et al*., 2021c; Obogo *et al*., 2022; Obogo *et al*., 2023; Obogo *et al*., 2024a). A third strand, on inspection of engineered and mechanical systems, is instructive on how conformity criteria degrade when the population under inspection grows faster than the inspecting capacity (Obogo *et al*., 2024b; Obriki & Arumosoye, 2018; Obriki & Arumosoye, 2019; Obriki & Arumosoye, 2020; Obriki & Arumosoye, 2021; Obriki & Arumosoye, 2022; Obriki *et al*., 2022a; Obriki *et al*., 2022b; Obriki & Arumosoye, 2023; Obriki *et al*., 2023a; Obriki *et al*., 2023b; Obriki & Arumosoye, 2024a; Obriki & Arumosoye, 2024b).

Regulated market entry in health and pharmaceutical systems parallels the accountable-operator requirements discussed in Section 5.3 more closely than any customs instrument does. Conformity documentation, traceability obligations, and post-market surveillance in those sectors have long imposed a fixed per-product cost of market access (Afrihyia *et al*., 2023; Afrihyia *et al*., 2024a; Afrihyia *et al*., 2024b; Akinse *et al*., 2023a; Akinse *et al*., 2023b; Aminu-Ibrahim *et al*., 2018; Aminu-Ibrahim *et al*., 2019; Aminu-Ibrahim *et al*., 2020; Aminu-Ibrahim & Ogbete, 2023; Aminu-Ibrahim *et al*., 2024; Asiedu & Asiedu, 2022; Asiedu, 2022). The equity consequences of that cost are also well documented, since the same requirements that raise safety assurance restrict the range of suppliers able to serve a market (Asiedu & Asiedu, 2023a; Asiedu & Asiedu, 2023b; Asiedu, 2023; Asiedu & Asiedu, 2024a; Asiedu & Asiedu, 2024b; Asiedu, 2024; Ilodigwe & Adesemoye, 2019a; Ilodigwe & Adesemoye, 2019b; Ilodigwe & Adesemoye, 2020; Ilodigwe & Adesemoye, 2021; Ilodigwe & Adesemoye, 2024a; Ilodigwe & Adesemoye, 2024b). A parallel literature on digital health governance addresses the question of who is accountable when an algorithmic system participates in a regulated determination (Ogbete *et al*., 2018; Ogbete *et al*., 2019; Ogbete *et al*., 2020; Ogbete *et al*., 2021; Ogbete *et al*., 2022; Ogbete *et al*., 2023; Ogbete & Aminu-Ibrahim, 2024; Okwah, 2022; Orise & Niniola, 2020; Orise & Niniola, 2022; Orise & Niniola, 2023; Orise & Niniola, 2024).

Agricultural and agribusiness research supplies the closest analogue to the small cross-border seller. Smallholder producers confronting standards-based market access barriers face the same structural problem as a long-tail marketplace seller confronting a responsible-person requirement: a fixed compliance cost that does not scale down with volume, discharged in practice through

intermediaries (Aye & Tawose, 2015; Aye & Tawose, 2016; Ekeocha *et al*., 2021; Michael & Ogunsola, 2019a; Michael & Ogunsola, 2019b; Michael & Ogunsola, 2021a; Michael & Ogunsola, 2021b; Michael & Ogunsola, 2021c; Michael & Ogunsola, 2021d; Michael & Ogunsola, 2021e; Michael & Ogunsola, 2022a; Michael & Ogunsola, 2022b; Michael & Ogunsola, 2023a). Work on livestock and food supply chains is further relevant for its treatment of traceability, batch identity, and the documentary chain that follows a physical good across a frontier (Michael & Ogunsola, 2023b; Michael & Ogunsola, 2023c; Michael & Ogunsola, 2023d; Michael & Ogunsola, 2023e; Michael & Ogunsola, 2024a; Michael & Ogunsola, 2024b; Michael & Ogunsola, 2024c; Oluwadele *et al*., 2023; Oluwadele *et al*., 2024a; Oluwadele *et al*., 2024b; Oluwadele *et al*., 2024c; Tawose *et al*., 2023a; Tawose *et al*., 2023b; Tawose *et al*., 2024).

Energy and engineered-systems research contributes on three specific points. Forecasting under distributional drift is a mature problem there, and the maintenance and recalibration practices developed for it inform the treatment of model drift in Section 8.5 (Adenuga, 2022; Adenuga, 2023; Amayo *et al*., 2015; Amayo & Popoola, 2017a; Amayo & Popoola, 2017b; Amayo, 2017; Asiedu & Quainoo, 2023a; Asiedu & Quainoo, 2023b; Asiedu & Quainoo, 2024; Atta *et al*., 2018; Atta *et al*., 2020; Atta *et al*., 2021; Atta *et al*., 2022). Predictive maintenance offers a worked example of the abstention problem, since an alert system that cannot calibrate its own confidence transfers cost to human inspectors rather than removing it (Atta *et al*., 2024; Bello *et al*., 2023a; Falegan & Aniebonam, 2022; Falegan & Aniebonam, 2023; Falegan & Aniebonam, 2024; Komi & Adeniji, 2020; Komi & Adamolekun, 2021; Komi, 2021; Komi & Adamolekun, 2022; Komi & Ganiu, 2022; Komi & Adeniji, 2023; Komi & Ganiu, 2023; Komi, 2023).

Instrumentation and sensing work is relevant to data quality at the point of capture, which is where declaration errors originate (Komi & Adamolekun, 2024; Komi & Adeniji, 2024a; Komi & Adeniji, 2024b; Komi, 2024; Omoegun *et al*., 2023; Oshevire *et al*., 2017; Quainoo *et al*., 2024; Sunday & Omoegun, 2018; Sunday & Omoegun, 2019; Sunday *et al*., 2019; Sunday *et al*., 2020; Sunday & Omoegun, 2022; Tackie *et al*., 2023).

Remote sensing and geospatial monitoring research bears on the verification of physical flows against declared flows, an emerging capability in customs enforcement and the closest technical precedent for reconciling a declaration against independent observation (Dagodzo, 2018a; Dagodzo, 2018b; Dagodzo & Ahiaeke Patrick, 2020; Dagodzo & Ahiaeke Patrick, 2021a; Dagodzo & Ahiaeke Patrick, 2021b; Dagodzo & Ahiaeke Patrick, 2022; Dagodzo *et al*., 2022; Dagodzo & Ahiaeke Patrick, 2023a; Dagodzo & Ahiaeke Patrick, 2023b).

Finally, the threshold derived in Section 3.4 depends on the accuracy and cost of human expert review, which is a capability question rather than a technical one. Research on training, capability formation, and language and communication barriers speaks to whether the reviewing capacity that automation presupposes actually exists, and at what cost (Boakye *et al*., 2020; Boakye *et al*., 2021; Bobga *et al*., 2018; Kpoka, 2023; Kpoka, 2024; Lilian *et al*., 2020; Lilian *et al*., 2024; Ogbona *et al*., 2020a; Ogbona *et al*., 2020b; Ogbona *et al*., 2023; Ogbona *et al*., 2024). This is particularly relevant where the declarant, the reviewer, and the regulator do not share a working language, a routine situation in cross-border parcel flows (Oloto & Yeboah, 2022; Oloto & Yeboah, 2023; Oloto & Yeboah, 2024; Seun *et al*., 2023; Seun *et al*., 2024a; Seun *et al*., 2024b; Yeboah *et al*., 2019; Yeboah & Oloto, 2022; Yeboah *et al*., 2022; Yeboah & Oloto, 2023; Yeboah & Oloto, 2024; Yeboah *et al*., 2024b).

3. Analytical Framework

3.1 Fulfillment channel archetypes

We distinguish five archetypes. The distinctions are operational rather than legal, but each carries a characteristic regulatory profile (Akinleye & Adeyoyin, 2022a; Akinleye & Adeyoyin, 2022b; Akinleye *et al*., 2023; Babatope *et al*., 2023; Efobi *et al*., 2021).

C1. Direct cross-border parcel, delivered duty unpaid: The order is picked in the origin country and dispatched as an individual international parcel. Duties and taxes, where applicable, are assessed on arrival and collected from the consumer, typically with a carrier handling fee. Minimum working capital, maximum consumer friction, and maximum exposure to destination-country assessment variance.

C2. Direct cross-border parcel, delivered duty paid: Identical physical flow, but landed cost is calculated and collected at checkout, with the seller or its agent acting as importer of record. Requires accurate ex-ante classification and duty calculation, which is precisely the capability that becomes scarce when thresholds fall and code granularity rises.

C3. Postal channel under simplified fiscal registration: Dispatch through designated postal operators, with value-added tax collected at point of sale under a scheme such as the Import One Stop Shop and remitted centrally. Historically the lowest-friction and lowest-data channel, and therefore the channel most exposed to the 2024 data-escalation trend.

C4. Consolidated import with in-market forward stock: Goods move in bulk under a formal entry, clear once, and are stored in a destination-market fulfillment centre for domestic dispatch. Regulatory obligations are front-loaded and amortised across units, but inventory risk and market-entry costs rise sharply.

C5. Bonded or cross-dock hub with deferred clearance: Bulk movement to a bonded facility or foreign trade zone in or near the destination market, with clearance triggered at the point of individual order fulfillment. A hybrid that seeks the capital efficiency of C4 and the demand responsiveness of C1, at the cost of substantial systems integration (Akanbi & Sunday, 2024; Amayo *et al*., 2023a; Amayo *et al*., 2023b; Amayo *et al*., 2023c; Amayo *et al*., 2024a; Amayo *et al*., 2024b; Amayo *et al*., 2024c; Ambali *et al*., 2021).

3.2 Classes of regulatory barrier

We classify barriers into six classes, developed inductively from the 2024 instrument corpus and refined against the non-tariff measure vocabulary (Akomolafe *et al*., 2023a; Akomolafe *et al*., 2023b; Annan, 2022; Annan, 2023).

- **B1. Fiscal and classification barriers:** Duty liability, tariff classification granularity, customs valuation, origin determination, and consumption tax registration and remittance.
- **B2. Advance data and security filing barriers:** Pre-loading and pre-arrival electronic data obligations, entry summary declarations, data quality standards, and party

identification requirements.

- **B3. Product safety and market access barriers:** Conformity assessment, labelling, instruction-language requirements, technical documentation retention, and the requirement for an accountable in-market economic operator.
- **B4. Environmental and producer responsibility barriers:** Extended producer responsibility registration, packaging and battery and textile obligations, eco-modulated fees, and emerging digital product passport requirements.
- **B5. Data protection and cross-border data transfer barriers:** Lawful basis for transferring consumer identity and address data to the origin jurisdiction, localisation mandates, and the tension between minimisation principles and customs data demands.
- **B6. Last mile, returns, and restitution barriers:** Address and identity formats, national identifier requirements for import clearance in some jurisdictions, returns and refund rights, and duty drawback or relief on returned goods.

3.3 Expected cost of channel selection

Let $C = \{c_1, \ldots, c_5\}$ denote the channel archetypes and let a seller face demand for a product with declared value v and true classification $h^* \in H$, where H is the tariff code space at the granularity required by the destination.

Define the expected total cost per unit through channel c:

$$E[TC_c] = L_c + D_c(\hat{h}, v) + T_c(v) + A_c + \rho_c P_c + \lambda \tau_c$$

Where L_c is physical logistics cost, $\hat{h}$ is the classification actually declared, A_c is per-unit amortised fixed compliance investment (registrations, responsible person appointments, EPR fees, systems), ρ_c is the probability of an adverse regulatory event (hold, inspection, penalty, seizure, delisting), P_c is its expected cost conditional on occurrence, τ_c is expected transit and clearance time, and λ monetises time through conversion, cancellation, and service-level effects.

Three properties of this formulation matter (Basnet *et al*., 2023; Basnet *et al*., 2024; Lawal & Oduleye, 2018a; Lawal & Oduleye, 2018b).

First, A_c is a fixed cost divided by volume. For C4 and C5 it is large in absolute terms and small per unit at scale. For C1 and C3 it was historically near zero and is rising. The 2024 instruments therefore compress the per-unit compliance cost advantage that direct channels enjoyed, and do so non-linearly in seller size.

Second, ρ_c is not exogenous. It is a decreasing function of declaration quality, which is itself a function of classification and data-completeness capability. This is where algorithmic mitigation enters the model: it does not remove the obligation, it reduces ρ_c and A_c for a given obligation.

Third, the duty term depends on $\hat{h}$, not h^*. Misclassification produces two distinct cost channels: an immediate duty differential $|D(\hat{h}) - D(h^*)|$, and a downstream penalty exposure whose magnitude depends on whether the misclassification is judged to reflect a failure of reasonable care. These have very different distributions and should not be aggregated.

3.4 Confidence thresholds in automated classification

Consider an automated classifier producing, for item i, a predicted code with calibrated posterior confidence p_i. Let C_{err} denote the expected cost of a misclassification, incorporating duty differential, penalty exposure, and remediation. Let c_h denote the marginal cost of routing the item to human expert review, and let q denote the accuracy of that human review, with $q < 1$.

The expected cost of automated handling is $(1 - p_i)\, C_{err}$. The expected cost of human handling is $c_h + (1 - q)\, C_{err}$. Automation is preferred when:

$$(1 - p_i)\, C_{err} \leq c_h + (1 - q)\, C_{err}$$

Which rearranges to the abstention threshold:

$$p_i \geq t^* = q - c_h / C_{err}$$

This simple result has three implications that we consider underappreciated in deployment practice (Lawal & Oduleye, 2019a; Lawal & Oduleye, 2019b; Lawal & Oduleye, 2021a). The threshold is bounded above by human accuracy, not by one, so a classifier need not be perfect to be preferred, only better than the human net of review cost. The threshold falls as the cost of error rises relative to review cost only in the sense that the correction term shrinks, so higher-stakes classifications demand a *higher* confidence bar, converging on q. And because C_{err} jumped discontinuously in 2024 for goods potentially subject to trade remedies or safety certification, a classifier that was economically deployable in 2023 may no longer be deployable on the same portfolio without recalibration, even if its accuracy is unchanged.

4. Data and Method

This is a qualitative, theory-building study combining a structured document review with comparative channel analysis and a stylised formal model. It is explicitly not an empirical estimation study (Efobi *et al*., 2022a; Efobi *et al*., 2022b; Efobi *et al*., 2023; Filani *et al*., 2022). We do not possess proprietary consignment-level clearance data, and we do not report measured performance of production compliance systems. Where numerical illustration appears (Section 7.4), it is parametric and labelled as such.

The document corpus comprises primary regulatory instruments, official agency announcements, and legislative proposals issued or entering into application between January 2024 and December 2024 in the United States, the European Union, and the United Kingdom, together with implementation guidance from customs administrations and reputable professional commentary used to establish operative dates and scope. Inclusion criteria were: the instrument imposes an obligation reaching business-to-consumer cross-border consignments; the obligation is either newly applicable in 2024 or was formally proposed in 2024; and the text or an authoritative summary is publicly available. Secondary commentary was used only to corroborate dates and scope, never as the sole basis for a substantive claim.

The academic corpus was assembled by targeted retrieval on automated tariff classification, customs risk targeting, and trade compliance automation, and is used to characterise the state of algorithmic capability rather than to conduct a

systematic review.

Each instrument was coded on four dimensions: barrier class (B1 to B6), value threshold sensitivity (whether the obligation scales with, or is invariant to, consignment value), the party on whom the obligation falls (seller, marketplace, carrier, declarant, consumer), and the data artefact required. Channel exposure was then derived analytically from the interaction of obligation-holder and channel architecture. Each instrument was further coded for enforcement mode, distinguishing border assessment, post-entry audit, marketplace delisting, market surveillance, and carrier network rejection, and for status at the close of 2024, distinguishing instruments in application from final rules pending and proposals (Annan, 2024; Atakpa, 2021; Atakpa & Abetoh, 2022; Atakpa & Abolaji, 2022).

Three threats warrant statement (Eze *et al*., 2024b; Liadi, 2022a; Liadi, 2022b; Liadi, 2022c; Liadi, 2023a). Jurisdictional selection bias: the corpus centres on the United States and European Union because they are the largest consuming markets acting in 2024, but this understates barriers in markets that impose national identifier requirements for import clearance, currency controls, or pre-shipment inspection, which are material in parts of Latin America, South Asia, and Africa and which fall disproportionately on the same small sellers discussed in Section 8.4. Temporal instability: several instruments analysed were proposals rather than final rules at the time of writing, and their final form may differ. Practitioner opacity: the algorithmic mitigation landscape is dominated by commercial systems whose performance is not independently verified, so Section 6 characterises capability classes rather than validating vendor claims.

5. Regulatory Barriers in Cross-Border Fulfillment

5.1 B1: Fiscal and classification barriers

The 2024 movement in this class is the shift from *value-based exemption* to *code-based assessment*. Under a generous de minimis regime, a low-value consignment requires only a plausible description and a value. Under the proposed United States framework, low-value entries would require the full ten-digit HTSUS classification and the identity of the party claiming the exemption, and goods subject to Section 201, 232, or 301 measures would be excluded from the exemption entirely.

The operational consequence is not the duty. It is the classification (Ike *et al*., 2021; Ike *et al*., 2022; Ike *et al*., 2024a; Ike *et al*., 2024b). A ten-digit code is a determination, not a lookup. It depends on material composition, construction method, function, and sometimes end use, and the same physical object can attract different codes in different jurisdictions. Requiring it on a billion-plus annual consignments creates a classification demand that has no historical precedent and that cannot be met by human expertise at any plausible staffing level. The barrier is therefore best understood as an *information production* barrier that happens to be expressed in fiscal law.

Valuation forms a second axis (Atakpa & Fobellah, 2023; Atakpa *et al*., 2023; Atakpa *et al*., 2024a; Atakpa *et al*., 2024b). Widespread undervaluation in low-value parcel flows has been documented by European authorities, and the closure of duty exemptions raises the return to undervaluation exactly as it raises the incentive to correct classification. Regimes that respond to fraud by demanding more granular data create, in the short run, more surface for fraud, since each new field is a new field that can be falsified.

Consumption tax forms a third (Adesuyi *et al*., 2023; Adesuyi *et al*., 2024; Akomolafe *et al*., 2022; Akomolafe *et al*., 2023c; Akomolafe *et al*., 2024a; Akomolafe *et al*., 2024b; Atima *et al*., 2022). The Import One Stop Shop model, in which the seller or marketplace registers once, charges tax at checkout, and remits centrally, is the mature template and has substantially raised collection. Its significance for this paper is architectural: it demonstrated that fiscal obligations can be shifted upstream from the border to the point of sale, and it is the precedent on which the deemed-importer proposals for customs duty are built.

5.2 B2: Advance data and security filing barriers

ICS2 is the paradigm case (Badmus *et al*., 2018; Badmus *et al*., 2019a; Badmus *et al*., 2019b; Badmus *et al*., 2020; Badmus *et al*., 2022a). It requires that safety and security data reach the destination customs authority before goods arrive, or in the express and postal air context before they are loaded, and it demands a complete Entry Summary Declaration including at minimum a six-digit HS code per commodity line. Release 3 extended this from air to maritime and inland waterway carriers from 3 June 2024, with house-level filers added on 4 December 2024, and road and rail following.

Two features distinguish this class from B1 (Adegbite *et al*., 2024a; Adegbite *et al*., 2024b; Ahmed *et al*., 2021; Aliliele *et al*., 2023a; Aliliele *et al*., 2023b; Aliliele *et al*., 2023c). First, the obligation attaches to the *carrier and filer*, not the seller, which means it propagates back through commercial contracts rather than through customs law. A marketplace seller who never interacts with a customs authority will nonetheless find its listings blocked from a carrier's network because that carrier cannot file a compliant declaration from the description supplied. Second, the binding constraint is data *quality*, not data presence. Generic descriptions such as "gift", "parts", "sample", or "goods" are systematically rejected, and administrations and industry bodies have circulated explicit stop-word guidance to that effect. This makes B2 the class most directly amenable to algorithmic treatment, because the failure is a text-quality failure with a machine-checkable signature.

Multiple-filing architectures, in which different actors submit partial declarations for which each is separately responsible, add a coordination problem: no single party holds the complete record, and responsibility for a rejection may be genuinely ambiguous.

5.3 B3: Product safety and market access barriers

The General Product Safety Regulation, applicable from 13 December 2024, is the most consequential 2024 instrument for small cross-border sellers, and it is the one least often modelled as a trade barrier because it is not framed as one. It requires that every consumer product placed on the EU market have a responsible person established in the Union, that this person's name and postal and electronic address appear on the product, packaging, parcel, or accompanying document *and* in the distance-selling offer, that technical documentation including a risk analysis exist and be retained, and that safety information and instructions be supplied in the languages of the member states concerned. Marketplaces incur registration with the Safety Gate portal, a single point of contact, and takedown cooperation duties.

There is no value threshold and no transition period (Bello *et al*., 2023b; Dogbatsey & Ebhojie, 2018; Dogbatsey *et al*., 2019; Dogbatsey *et al*., 2021). The regulation therefore does something structurally novel: it imposes a *fixed per-SKU market entry cost* on a channel whose economics were built on zero fixed cost per SKU. For a seller listing fifty thousand long-tail items, the marginal cost of the fifty-thousandth listing was previously near zero and is now non-zero and non-trivial. Enforcement is, in practice, largely private, executed by marketplaces delisting listings that lack the required fields, which makes it faster and less appealable than customs enforcement.

The United States analogue in the 2024 proposals is the requirement to file Certificates of Compliance electronically with CBP and the Consumer Product Safety Commission at the time of entry for de minimis consumer products, which similarly converts a documentary obligation previously enforced by sampling into a data obligation enforced at every entry.

5.4 B4: Environmental and producer responsibility barriers

Extended producer responsibility regimes require registration, reporting, and fee payment for packaging, batteries, electrical equipment, and increasingly textiles, generally at member state or national level rather than at Union level. For a cross-border seller this generates a registration matrix whose cardinality is roughly jurisdictions multiplied by material streams, each with its own registration identifier, reporting cadence, and fee schedule, and several of which must be surfaced in marketplace listings.

The relevant property for channel analysis is that these obligations attach to *placing on the market*, which means they are largely channel-invariant (Nnabueze *et al*., 2021; Ogunwole *et al*., 2021; Okojie & Abioye, 2020; Okojie *et al*., 2023a). A seller cannot escape them by changing fulfillment topology, only by changing market. This distinguishes B4 from B1 and B2, which are strongly channel-sensitive, and it means algorithmic mitigation here is confined to registration management, reporting automation, and fee estimation rather than to any form of structural optimisation.

5.5 B5: Data protection and transfer barriers

Cross-border fulfillment necessarily transfers consumer identity, address, contact, and sometimes national identifier data from the destination jurisdiction to the origin jurisdiction and to intermediaries in transit countries. This sits in tension with data minimisation and transfer-restriction principles, and the tension has sharpened as customs regimes demand *more* identity data, including in some jurisdictions the consumer's tax or national identification number as a condition of import clearance.

There is a genuine and under-discussed conflict here (Aliliele *et al*., 2024a; Aliliele *et al*., 2024b; Borah *et al*., 2022; Dosunmu & Ogundele, 2019; Dosunmu & Ogundele, 2020; Dosunmu & Ogundele, 2021; Dosunmu & Ogundele, 2022). Customs modernisation demands richer party identification; data protection law demands narrower collection and constrained transfer. Sellers are obliged to satisfy both, and the reconciliation is typically achieved through contractual instruments and data localisation of the fulfillment stack rather than through any reduction in the underlying transfer. Localisation requirements in several markets convert this from a legal cost to an infrastructure cost, which again favours large operators.

5.6 B6: Last mile, returns, and restitution barriers

The final class is heterogeneous and often dismissed as operational rather than regulatory, which is a mistake (Eyetsemitan *et al*., 2020; Eyetsemitan *et al*., 2021; Eyetsemitan *et al*., 2022; Eyetsemitan *et al*., 2023a; Eyetsemitan *et al*., 2023b; Eyetsemitan *et al*., 2024a; Eyetsemitan *et al*., 2024b; Oyeleye *et al*., 2022). Address format heterogeneity, the absence of standardised postcodes in several large markets, national identifier requirements at clearance, and mandatory consumer withdrawal rights each impose compliance-adjacent costs. Returns are the sharpest case: a cross-border return that crosses a customs frontier in reverse may require export declaration, may or may not attract duty relief depending on documentation and timing, and frequently costs more to process than the goods are worth. Where duty has been paid under a DDP model and the consumer exercises a statutory withdrawal right, the recovery of that duty is a separate administrative process with its own evidentiary burden, and in practice is often abandoned.

5.7 Barrier exposure by channel

Table 1 maps barrier classes to channel archetypes. Entries indicate the relative severity of exposure: **H** high, **M** moderate, **L** low. Severity here means the combination of obligation weight and the difficulty of discharging it within that architecture, not legal applicability, which for several classes is universal.

Table 1: Barrier exposure by fulfillment channel archetype

Barrier class	C1 Direct DDU	C2 Direct DDP	C3 Postal	C4 In-market stock	C5 Bonded hub
B1 Fiscal and classification	H	H	H	M	H
B2 Advance data and filing	H	H	H	L	M
B3 Product safety	H	H	H	H	H
B4 Producer responsibility	H	H	H	H	H
B5 Data protection	H	H	M	L	M
B6 Last mile and returns	H	M	M	L	M
Fixed compliance investment	Low	Moderate	Low	High	Very high
Per-unit regulatory variance	Very high	Moderate	High	Low	Low to moderate

Notes. B1 is assessed at the border in C1 and ex ante in C2, is rising sharply from a historically low base in C3, and is amortised over a single bulk entry in C4. B2 falls to L in C4 because one filing covers the whole shipment. B3 and B4 are channel-invariant in law, but C4 and C5 amortise them across units. B5 falls to L in C4 because consumer data need not leave the destination market. B6 is most acute in C1, where unpaid duty surfaces at the door.

The matrix expresses the paper's central structural claim (Okojie *et al*., 2023b; Okonkwo *et al*., 2018a; Okonkwo *et al*., 2018b; Okonkwo *et al*., 2019; Okonkwo *et al*., 2020). The 2024 instruments raise exposure most steeply in C1 and C3, which are the low-capital channels used disproportionately by small and emerging-market sellers, and least steeply in C4, which requires capital those sellers do not have. C5 is the interesting case: it can approach C4's low per-unit variance, but only if the per-order clearance is executed by systems rather than people, which makes C5 the channel whose viability depends most directly on algorithmic capability.

6. Algorithmic Mitigations

We now characterise the classes of algorithmic system deployed against these barriers. For each we state the function, the technical approach, the maturity, and the failure modes. Maturity is assessed on a three-point scale: **Established** (widely deployed, understood failure modes), **Emerging** (deployed but with material variance in reliability), **Experimental** (demonstrated in research, limited production evidence).

6.1 Description enrichment and normalisation

Function: Convert seller-authored product text, which is written for consumer persuasion and search ranking, into declaration-grade text suitable for customs filing (Lawal & Oduleye, 2021b; Lawal & Oduleye, 2023a; Lawal & Oduleye, 2023b).

Approach: Named entity extraction over titles, bullet points, and attribute tables to recover material composition, construction, function, dimensions, and intended user; stop-word and prohibited-term detection against administration guidance; template-based reconstruction into a factual noun-phrase description.

Maturity: Established. This is the highest-return and lowest-risk mitigation available, because the failure being corrected is unambiguous and machine-detectable, and because correcting it does not require making any determination about legal classification.

Failure modes: Attribute hallucination when source listings are sparse, particularly in long-tail catalogues where the marketing copy contains no material information at all. Systematic bias toward the modal product in a category when generative infill is used, which propagates the same wrong composition across thousands of variants.

6.2 Automated tariff classification

Function: Predict the destination-jurisdiction tariff code at the required granularity from product description and attributes.

Approach: The literature has converged on transformer-based text encoders fine-tuned on declaration corpora, often with hierarchy-aware objectives that exploit the tree structure of the nomenclature, and increasingly with retrieval augmentation against explanatory notes, binding rulings, and classification opinions. Knowledge-graph formulations that treat code assignment as link prediction over declaration attributes have shown gains over flat text classification. Contrastive sentence-embedding approaches address the short-text problem directly (Medon & Oduleye, 2022; Medon & Oduleye, 2023; Medon & Oduleye, 2024; Oduleye & Medon, 2023a).

Maturity: Emerging at six-digit granularity, Experimental at ten-digit granularity for open-domain catalogues. Reported accuracy figures require careful reading: performance at chapter or heading level is high and largely solved, performance at national subheading level on unseen long-tail products is substantially weaker, and the accuracy reported for well-engineered transformer systems on fine-grained tasks in production settings falls well short of what a duty-bearing declaration would ideally require. The gap between the two is precisely the gap that the 2024 United States proposal targets.

Failure modes: Four are distinctive and each is consequential.

Distributional shift on the long tail. (Dosunmu & Ogundele, 2023; Dosunmu & Ogundele, 2024a; Dosunmu & Ogundele, 2024b; Dosunmu & Ogundele, 2024c; Dosunmu & Ogundele, 2024d; Ekechi *et al*., 2022). Training corpora are dominated by high-volume declarations. Model confidence is poorly calibrated on the novel and the obscure, which is where classification is hardest and where the residual value lies.

Jurisdictional divergence below six digits. The first six digits are internationally harmonised; the remainder is national. A model trained predominantly on one jurisdiction's declarations transfers poorly below the harmonised level, yet ten-digit granularity is exactly what the 2024 proposals demand.

Legal determinacy versus statistical plausibility. Classification is governed by interpretive rules, notably essential character and specific-over-general precedence, that are legal doctrines, not statistical regularities. A model can learn the empirical distribution of past declarations, including their errors, without learning the rules that make a declaration correct. Where past practice was systematically wrong, the model learns the error.

Adversarial pressure from the objective function. If the deployment objective is minimising duty rather than maximising correctness, gradient pressure runs toward the lowest-rate defensible code. This is discussed in Section 8.2 because it is a governance problem rather than a technical one.

6.3 Landed cost computation

Function: Produce a checkout-time quotation of duty, tax, and fees sufficiently accurate that the seller can offer delivered-duty-paid terms without absorbing systematic loss or generating delivery-point disputes.

Approach: Deterministic rule engines over maintained tariff schedules, preferential origin rules, and trade remedy lists, chained to the output of Section 6.2 and to valuation logic. The engine is deterministic; the uncertainty is entirely inherited from the classification and origin inputs (Dada *et al*., 2021a; Dada *et al*., 2021b; Dada *et al*., 2024; Isiekwu *et al*., 2021; Ogundairo & Ayivi-Donkor, 2023a; Ogundairo & Ayivi-Donkor, 2023b; Ogundairo & Ayivi-Donkor, 2024a; Ogundairo & Ayivi-Donkor, 2024b).

Maturity: Established as computation, Emerging as an accurate quotation, because accuracy is bounded above by classification accuracy.

Failure modes: Silent propagation of upstream classification error into a customer-facing price commitment, which converts a compliance error into a margin loss with no detection signal. Staleness against fast-

moving trade remedy lists, which was a live problem throughout 2024 given the pace of measure changes. Failure to model the *variance* rather than the point estimate, so that a seller quoting the expected duty absorbs the entire upper tail.

6.4 Declaration completeness and pre-filing validation

Function: Validate a prospective filing against the destination regime's data model before submission, and block or remediate deficient records.

Approach: Schema validation, controlled-vocabulary checks, stop-word detection, party identifier verification, cross-field consistency rules (weight against dimensions against declared composition), and increasingly learned anomaly detection over the joint distribution of declaration fields (Badmus *et al*., 2022b; Badmus *et al*., 2024; Edivri & Oteri, 2022; Edivri & Oteri, 2024; Ladapo *et al*., 2018; Ladapo *et al*., 2019).

Maturity: Established.

Failure modes: Validation catches malformed records, not false ones. A declaration can be perfectly well-formed, pass every schema check, and be substantively wrong. There is a real risk that improving formal validity is mistaken for improving substantive compliance, and that the resulting reduction in rejection rate is read as a reduction in risk.

6.5 Inverse risk modelling

Function: Estimate, before dispatch, the probability that a given consignment will be selected for inspection or hold, and the expected delay if it is.

Approach: This is the mirror of the customs targeting problem. Administrations use tree-aware embeddings and related methods over declaration features to select consignments for inspection; sellers and carriers, holding their own outcome histories, can fit models over the same feature space to estimate selection probability. The output feeds ρ_c in the model of Section 3.3, enabling routing decisions, buffer sizing, and delivery promise adjustment (Jimoh *et al*., 2023a; Jimoh *et al*., 2023b; Jimoh & Ahmed, 2024; Kumuyi *et al*., 2023; Kumuyi *et al*., 2024a; Kumuyi *et al*., 2024b; Mbonu *et al*., 2018).

Maturity: Emerging for large carriers and marketplaces with sufficient outcome history, unavailable to small sellers who lack the data.

Failure modes: This capability sits closest to the compliance-arbitrage boundary. A model that predicts inspection probability can be used to reduce hold-driven delay, which is legitimate, or to route consignments away from scrutiny, which is not. The technical artefact is identical in both cases and the difference lies entirely in the decision rule applied downstream. Administrations updating their targeting models also induce covariate shift in the seller's model, producing a genuine adversarial dynamic in which both sides' models degrade the other's.

6.6 Restricted party, prohibition, and eligibility screening

Function: Detect goods and counterparties subject to prohibition, licensing, sanctions, forced-labour import bans, or de minimis ineligibility.

Approach: Fuzzy and phonetic matching against denied party lists, multilingual transliteration handling, entity resolution across corporate structures, and increasingly supply-chain provenance inference for forced-labour exposure. For the 2024 United States proposals specifically, eligibility screening acquires a new function: determining whether a given article falls within a Section 201, 232, or 301 measure, which is itself a classification-dependent determination.

Maturity: Established for named-party screening, Emerging for provenance and measure-scope determination (Mbonu *et al*., 2019a; Mbonu *et al*., 2019b; Mbonu *et al*., 2020a; Mbonu *et al*., 2020b; Mbonu *et al*., 2020c; Mbonu *et al*., 2021a).

Failure modes: Threshold selection under extreme class imbalance, where a false negative is a legal violation and a false positive is a blocked legitimate shipment. Transliteration and name-variant handling remains a persistent weakness for non-Latin-script counterparties.

6.7 Compliance artefact management

Function: Maintain, and surface into listings and declarations, the fixed artefacts that B3 and B4 demand: responsible person identity and contact details, technical documentation, certificates of compliance, EPR registration numbers, and language-appropriate safety instructions.

Approach: Structured catalogue enrichment with per-jurisdiction attribute sets, obligation-mapping rules from product category to required artefact, machine translation of safety instructions with human review, and expiry and renewal tracking (Ladapo *et al*., 2022a; Ladapo *et al*., 2022b; Ladapo *et al*., 2023a; Ladapo *et al*., 2023b; Ladapo *et al*., 2023c; Ladapo *et al*., 2023d).

Maturity: Emerging. The bottleneck is not technical. It is that the underlying artefacts, notably a genuine risk analysis and a real accountable legal person, cannot be generated computationally. Software can manage and surface them; it cannot create them.

Failure modes: Machine translation of safety-critical instructions without qualified review, which converts a compliance artefact into a liability artefact. Silent expiry of registrations. The deeper failure mode is category error: treating an obligation that requires a legal relationship as though it were a data field.

6.8 Barriers and mitigations compared

Table 2: Barrier classes, mitigation classes, maturity, and residual risk

Barrier	Primary algorithmic mitigation	Maturity	Residual risk after mitigation
B1 Fiscal and classification	Automated classification (6.2), landed cost (6.3), enrichment (6.1)	Emerging to Experimental at fine granularity	High. Legal determinacy is not learnable from declaration history alone
B2 Advance data and filing	Enrichment (6.1), pre-filing validation (6.4)	Established	Low to moderate. Formal validity is achievable; substantive accuracy is not guaranteed
B3 Product safety	Artefact management (6.7)	Emerging	High. Core obligations require legal persons and real documentation
B4 Producer responsibility	Artefact management (6.7), registration automation	Emerging	Moderate. Mechanical but jurisdictionally fragmented
B5 Data protection	Not primarily algorithmic; architectural (localisation, minimisation by design)	n/a	Moderate. Direct conflict with customs data demands is unresolved
B6 Last mile and returns	Address normalisation, returns routing optimisation, drawback automation	Established to Emerging	Moderate. Reverse-flow duty relief remains largely manual

The table supports a claim we regard as the practical core of the paper (Okonkwo *et al*., 2021a; Okonkwo *et al*., 2021b; Okonkwo *et al*., 2023a; Okonkwo *et al*., 2023b).: algorithmic mitigation is strongest exactly where the barrier is a data-formatting problem (B2, B6) and weakest exactly where the barrier requires either a legal determination (B1) or a legal person (B3). The barriers introduced or tightened in 2024 skew toward the latter categories. The automation frontier is therefore advancing into the region where it delivers least.

7. Evaluating Compliance Automation

7.1 Limits of accuracy-only metrics

Compliance automation is routinely evaluated with top-one accuracy on held-out declarations (Oduleye & Medon, 2023b; Oghenemaiga *et al*., 2024; Tonoyan *et al*., 2021a). This is inadequate for three reasons. It assumes symmetric error costs, when the cost of classifying a duty-free item into a dutiable heading (an overpayment, recoverable in principle) is wholly unlike the cost of classifying a trade-remedy-covered item into an exempt heading (a potential penalty and a reasonable-care failure). It ignores abstention, so a system that correctly declines to classify difficult items is scored identically to one that guesses. And it evaluates on a held-out sample of the training distribution, which is dominated by high-volume goods, while operational risk concentrates in the long tail.

7.2 Metrics

Five quantities carry most of the operational information (Tonoyan *et al*., 2021b; Tonoyan *et al*., 2022a; Tonoyan *et al*., 2022b).

Cost-weighted error rate: $\Sigma_i\, w(h^*_i, \hat{h}_i) \cdot 1[\hat{h}_i \neq h^*_i] / n$, with the weight matrix w derived from duty differential and measure-scope crossings rather than assumed uniform. A misclassification that crosses into or out of a trade remedy scope should carry a weight one to two orders of magnitude above a within-heading error.

Selective accuracy at coverage: Accuracy computed on the retained set, reported as a curve across abstention rates rather than at a single operating point, permitting the reader to locate the threshold t* of Section 3.4 for their own cost parameters.

Calibration error on the tail: Expected calibration error computed separately on the frequency-weighted head and the long tail of the catalogue. A model whose confidence is well calibrated overall but overconfident on rare goods is dangerous in precisely the deployment that matters.

Jurisdictional transfer degradation: Accuracy at national subheading granularity in jurisdiction B for a model trained on jurisdiction A, reported explicitly rather than assumed.

Operational outcomes: First-pass clearance yield, hold rate, mean and ninety-fifth percentile clearance latency, and landed-cost quotation error distribution including its upper tail. These are what actually enter the cost model of Section 3.3.

7.3 Benchmark construction

Evaluation corpora are better constructed by stratified sampling across catalogue frequency deciles rather than by random sampling (Ladapo *et al*., 2024a; Ladapo *et al*., 2024b; Ogbole *et al*., 2021; Okoruwa *et al*., 2020; Okoruwa *et al*., 2024b; Oteri & Edivri, 2024)., that a designated holdout be drawn from goods introduced after the training cutoff to measure temporal drift, that abstention be a first-class prediction rather than a post-hoc filter, and that where possible ground truth be established against binding rulings and classification opinions rather than against historical declarations, since the latter embed the very errors the system is meant to prevent.

7.4 Sensitivity to the cost of error

The following is a stylised parametric illustration, not an empirical result. It is included to show how the abstention threshold responds to the 2024 shift in error costs.

Assume human expert review costs c_h and achieves accuracy q = 0.95. Under a pre-2024 regime where a misclassification on a low-value consignment carried expected cost C_{err} with $c_h / C_{err} = 0.25$, the threshold is $t^* = 0.95 - 0.25 = 0.70$. Any prediction with calibrated confidence above 0.70 is economically automatable.

Now suppose the expected cost of error rises fourfold, reflecting exposure to trade remedy duties, penalty risk under a reasonable-care standard, and safety-certification consequences, so that $c_h / C_{err} = 0.0625$. The threshold becomes $t^* = 0.95 - 0.0625 \approx 0.89$.

If the classifier's calibrated confidence distribution places, say, sixty percent of its predictions above 0.89 and eighty-five percent above 0.70, the required human review volume rises from fifteen percent of the catalogue to forty percent. Nothing about the model changed. The regulatory environment changed, and the automation rate fell by more than half. This is the mechanism by which the 2024 instruments raise compliance cost even for firms that have already invested in automation, and it explains why capability improvements at the margin of accuracy matter

far less than improvements in calibration on the tail.

8. Discussion

8.1 Substitution effects

The consistent finding across Sections 5 and 6 is that algorithmic systems do not remove regulatory obligations. They change the cost structure of discharging them, converting a variable per-consignment cost, previously paid in human classification labour or in unpriced non-compliance risk, into a fixed investment in systems, data, and maintained regulatory content. In the model of Section 3.3, they reduce ρ_c and shift A_c from variable to fixed (Okonkwo *et al*., 2024a; Okonkwo *et al*., 2024b; Okonkwo *et al*., 2024c; Okonkwo *et al*., 2024d).

This has an immediate and under-acknowledged consequence. Fixed costs amortise over volume. A regulatory change that can be absorbed by automation is therefore a regulatory change that advantages high-volume operators, even when its stated purpose is to level the field between cross-border sellers and domestic incumbents. The distributional effect of the 2024 instruments may run in a direction orthogonal to their intent: they do close the gap between direct-dispatch cross-border sellers and domestic importers, which was the stated aim, and they simultaneously widen the gap between large and small cross-border sellers, which was not.

8.2 Optimisation and evasion

Several capabilities described in Section 6 are dual-use in a strong sense (Ebhojie *et al*., 2023a; Ebhojie *et al*., 2023b; Eboh & Aliliele, 2023; Eboh & Aliliele, 2024). A classification system that reports a posterior distribution over codes rather than a single code can be used to select the most defensible code or the cheapest defensible code, and the artefact is identical. An inspection-probability model can be used to buffer delivery promises or to route around scrutiny. A landed cost engine that models the duty consequences of alternative origin structures can support legitimate supply-chain design or support origin manipulation.

The distinguishing feature is not the model but the objective function and the audit record. We suggest three governance requirements as a minimum. Declaration systems should log the model's full ranked output and the reason a particular code was selected, so that a downstream reviewer can determine whether selection was driven by confidence or by rate. Objective functions used in production should be explicitly documented as accuracy-maximising rather than duty-minimising, and this documentation should be auditable. And any systematic pattern in which the selected code has a lower duty rate than the model's highest-confidence code should be flagged as an internal control exception, because that pattern is the observable signature of the substitution.

This matters legally as well as ethically. Reasonable-care standards in customs law generally require that a declarant take affirmative steps to ensure correctness. It is at least arguable that deploying a system whose output distribution is known and whose selection rule is duty-sensitive constitutes a failure of reasonable care regardless of whether any individual declaration is wrong.

8.3 Explainability

The customs literature's emphasis on explainable classification is often read as an ethical or regulatory preference (Mbonu *et al*., 2021b; Mbonu *et al*., 2021c; Mbonu *et al*., 2022a; Mbonu *et al*., 2022b; Mbonu *et al*., 2022c; Onche *et al*., 2024; Ozowara *et al*., 2022). In this domain it is closer to an operational necessity. When a classification is challenged, the declarant must justify it by reference to the interpretive rules of the nomenclature, the section and chapter notes, and applicable rulings. A prediction accompanied only by a confidence score cannot be defended, cannot be corrected in a principled way, and cannot support a claim of reasonable care. Systems that surface the retrieved notes and rulings supporting a prediction are therefore not merely more transparent but more useful, and retrieval-augmented architectures should be preferred to closed classifiers for this reason independent of any accuracy difference.

8.4 Distributional effects

The barriers of Section 5 fall with markedly uneven weight (Liadi, 2023b; Liadi, 2023c; Liadi, 2024a; Liadi, 2024b; Liadi, 2024c; Liadi, 2024d). A seller in a market without established compliance service infrastructure faces the same GPSR responsible-person requirement as a large multinational, but must satisfy it by contracting an authorised representative in the destination market, at a per-jurisdiction cost that does not scale down with order volume. The same seller must produce ten-digit classification for goods it may hold in quantities of one, must register for producer responsibility schemes whose fee structures assume industrial volumes, and lacks the outcome history to build any of the mitigations in Section 6.

The predictable equilibrium is intermediation. Small sellers do not build these capabilities; they access them through marketplaces and specialist logistics providers who build them once and rent them out. This is efficient in a narrow sense and consequential in a broad one, because it makes market access for small cross-border sellers contingent on the commercial terms of a small number of compliance intermediaries. Regulators concerned with the competitive effects of platform power should note that product-safety and customs data requirements are, in this respect, platform-power instruments, whatever their intent.

8.5 Drift under regulatory change

Every model described in Section 6 is fitted to a regulatory environment (Tonoyan *et al*., 2022c; Tonoyan *et al*., 2023; Tonoyan *et al*., 2024a; Tonoyan *et al*., 2024b). Tariff schedules are revised, trade remedy lists change, nomenclature is amended on a multi-year cycle, and thresholds move. A classification model, a landed cost engine, and a risk model each degrade differently under this drift, and they degrade silently. The most dangerous case is the landed cost engine, because it produces a customer-facing number that appears correct and generates no error signal until margin analysis catches the discrepancy weeks later.

We recommend that compliance systems maintain explicit versioned bindings to the regulatory content they assume, that they refuse to produce output where that content is

beyond its validity date rather than degrading gracefully, and that model retraining be triggered by regulatory events rather than by calendar schedule.

8.6 From border assessment to point of sale

A structural theme running through the 2024 instruments deserves separate statement (Olaogun *et al*., 2023; Oluwo *et al*., 2024; Sanni *et al*., 2020a; Sanni *et al*., 2020b; Sanni *et al*., 2020c; Sanni & Atima, 2021a; Sanni & Atima, 2021b; Sanni *et al*., 2022a). Value-added tax collection moved from the border to the point of sale in 2021 through the one-stop-shop model. Product safety accountability moved from the border to the listing in 2024 through the responsible-person requirement. Customs duty is proposed to follow through the deemed-importer concept. Advance security data has already moved upstream to pre-loading.

The border, as a physical point of assessment, is being progressively vacated. What replaces it is a distributed regime of point-of-sale obligations enforced substantially through private intermediaries. This is the most consequential development for fulfillment channel design, because it means the choice of channel is becoming less able to determine the obligation set. If the obligation attaches at the listing rather than at the frontier, the classic arbitrage between channel architectures narrows, and the remaining differentiation is in cost and speed rather than in compliance exposure. Fulfillment strategy converges toward a logistics problem again, which is arguably the intended outcome.

8.7 Limitations and further work

This study is conceptual and its central claims are analytical rather than measured (Okonkwo *et al*., 2024e; Okonkwo *et al*., 2024f; Okoruwa *et al*., 2024a; Yeboah & Ike, 2020; Yeboah *et al*., 2024a). Four limitations follow directly.

We do not observe consignment-level outcomes and therefore cannot estimate the parameters of the model in Section 3.3 from data. The illustration in Section 7.4 is parametric and should not be read as an empirical finding. Establishing realistic values for ρ_c, P_c, and the cost-weight matrix w requires access to carrier or marketplace clearance records and is the highest-value next step.

The jurisdictional scope is narrow. Barriers in markets that impose pre-shipment inspection, currency controls, or national identifier requirements at clearance are material and under-analysed here, and they fall on precisely the sellers identified in Section 8.4 as most exposed.

Several instruments analysed were proposals in 2024 rather than final rules, and the analysis of their operational consequence is necessarily conditional on their final form.

The characterisation of commercial algorithmic capability rests on published research and on vendor descriptions that are not independently verified. Independent benchmarking of production classification systems against the protocol of Section 7.3 would be a substantial contribution and does not currently exist in the public literature.

Future work should pursue three lines (Sanni *et al*., 2022b; Sanni & Attah, 2023a; Sanni & Attah, 2023b; Sanni & Attah, 2023c; Sanni *et al*., 2023; Sanni & Wedraogo, 2024; Sanni *et al*., 2024; Wedraogo & Sanni, 2024). First, empirical estimation of the abstention threshold in live deployments, with measured human review accuracy rather than assumed. Second, formal treatment of the adversarial dynamic between administration targeting models and seller-side inverse risk models, which we have described qualitatively and which admits a game-theoretic formulation. Third, quantitative measurement of the distributional claim in Section 8.4, comparing compliance cost per unit of revenue across seller size deciles before and after the 2024 instruments took effect.

9. Conclusion

Cross-border e-commerce grew into a regulatory space that had not been designed for it, and 2024 marks the year that space began to close. The United States proposed to condition low-value entry on ten-digit classification and to exclude trade-remedy goods from de minimis treatment. The European Union extended advance filing to all transport modes and made an EU-established responsible person a precondition of placing any consumer product on its market, with no value threshold and no transition. The common demand across these instruments is not tariff revenue. It is data: earlier, finer, and attached to an identifiable accountable party.

We have argued that this demand distributes very unevenly across fulfillment architectures, falling most heavily on the low-capital direct and postal channels and most lightly on consolidated in-market stocking, and that the hybrid bonded channel is viable only to the extent that per-order clearance can be executed algorithmically. We have argued that algorithmic mitigation is real but substitutive: it converts variable compliance cost into fixed platform investment, which advantages scale and drives small sellers toward intermediation. And we have argued that the automation frontier is advancing into the region where it delivers least, because the 2024 barriers demand legal determinations and legal persons rather than well-formed data, and those are the two things software cannot supply.

The practical recommendation that follows is narrow and, we think, robust. Firms should evaluate compliance automation on cost-weighted, abstention-aware, tail-calibrated metrics rather than on headline accuracy, because the operative quantity is the confidence threshold above which automation is economically preferable, and that threshold moved sharply upward in 2024 without any model changing. Regulators should recognise that data-intensive compliance instruments are, in their competitive effects, instruments of platform consolidation, and should consider whether the accountable-operator requirements they impose can be discharged through shared or public infrastructure rather than only through private intermediation. The direction of travel is toward the vacated border and the accountable listing. The open question is who is able to stand behind the listing, and at what price.

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