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Original Article

EXTENDED SECURITY CONTROL AND DELAY PROPAGATION IN AIR CARGO TRANSPORT OPERATIONS: IMPLICATIONS FOR SUPPLY CHAIN CONTINUITY

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Highlights:

- comparative, process-timed study of extended security checks in a regional versus an international air cargo terminal (2022–2024);
- decomposition of total delay into T_D, T_{Ch}, T_M and T_W reveals that manual inspection T_M and waiting-for-uplift T_W dominate the delay budget;
- extended checks are applied to 3…6% of consignments in the regional terminal and 12…15% in the international terminal, with mean delays of 14…20 h versus 84…95 h;
- one-way ANOVA on annual mean values and scenario analysis quantify the impact of organisational choices, especially on-call versus batch specialist availability;
- practical recommendations balance regulatory compliance with efficiency and resilience by linking staffing, information handovers and digital tools to delay propagation.

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Abstract. Prior research on security controls in air cargo terminals has primarily focused on protecting passengers, crews, and airport infrastructure, while largely overlooking the maintenance of supply chain continuity. The present study addresses this gap by analysing how the configuration, spatial placement, and scheduling of screening procedures affect the stability of cargo flows, as well as the incidence and propagation of delays in air freight operations. Evidence was collected at 2 terminals – a regional facility in southern Poland and a large international terminal in southern Europe, which enabled a comparative assessment that accounts for organisational and structural differences. The analysis mapped screening procedures onto the operational timeline of cargo-handling. Standard screening consisted of radiographic inspection of palletised consignments using an X-ray system. A negative result triggered an extended screening path comprising, in sequence, canine inspection, chemical screening using reactive swabs, and manual inspection of the load unit after opening by a qualified specialist. The total delay was computed as the sum of the times associated with the additional screening steps and the waiting time for the substitute uplift. Findings for 2022–2024 indicate pronounced differences between terminals in both the scale and effectiveness of controls. At the regional terminal, 3…6% of shipments were routed to extended screening, the average duration of additional actions was 1…2 h, and the final delay was 14…20 h. At the international terminal, the corresponding values were 12…15%, 5…7 h, and 84…95 h. The most significant delays were generated by procedures requiring external specialists, such as crate-opening technicians, and by the organisation of replacement transport. Where specialist support was provided periodically, the waiting time for inspection could reach up to 7 days, whereas smaller facilities operated with near-immediate response times. Based on these results, several operational improvements are indicated. Recommended actions include maintaining specialists on-call, issuing immediate notifications of adverse X-ray outcomes to planning teams, and selectively automating repetitive steps. Implementing these measures is expected to reduce inspection-related delays, improve on-time delivery performance, and enhance the resilience of air cargo supply chains.

Keywords: air cargo transport, security screening, extended checks, delay propagation, supply chain continuity, terminal operations, scheduling.

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Notations

ACLPP – air cargo load planning problem;
ACRP – air cargo recovery problem;
AI – artificial intelligence;
AMR – aircraft maintenance routing;
ANN – artificial neural network;
ANOVA – analysis of variance;
ARIMA – autoregressive integrated moving average;
BOM – bi-objective optimisation;
COM – combinatorial optimisation;
CSA – Cuckoo search;

CT – computed tomography;
CVaR – conditional value at risk;
DPC – differential phase contrast;
GLN PSO – global/local/near-neighbourhood-best PSO;
IATA – International Air Transport Association;
IOM – improved combinatorial optimisation;
IoT – internet of things;
MILP – mixed-integer linear programming;
MINLP – mixed-integer nonlinear programming;
ML – machine learning;
NMR – nuclear magnetic resonance;
NQR – nuclear quadrupole resonance;
PC – phase contrast;
PDPTW – pickup and delivery problem with time windows;
PSO – particle swarm optimisation;
RFID – radio-frequency identification;
SARIMA – seasonal ARIMA;
SCO – security control operator;
SDE – secondary decomposition-ensemble;
TR – time when the cargo is ready for loading for the next journey stage;
TW – waiting time for replacement transport;
ULD – unit load device;
WSN – wireless sensor network;
XRD – *X*-ray diffraction;
YOLOv8 – You Only Look Once version 8 (*https://yolov8.com*).

1. Introduction

Cargo security control in airport terminals is a layered, risk-based system essential for civil aviation safety and the ongoing stability of modern supply chains. Instead of a single checkpoint, it encompasses preventive, detective, and responsive measures spread throughout the shipment's life cycle. In practice, X-ray imaging, chemical detection, and canine screening are combined with thorough documentary verification, which maintains an unbroken chain of custody and allows for the reconstruction of provenance, routing, and destination. The operational benefits of such control go beyond immediate protection of passengers and crews: the design and timing of screening activities can prevent unnecessary delays, help maintain schedule adherence, and thus reduce the risk of production halts and sales disruptions. In transnational networks, outcomes also depend on cooperation and effective information exchange among entities operating under different jurisdictions, since reliable upstream screening decreases redundant interventions and limits the possibility of cascading disruptions.

Existing studies detail the technologies and regulatory justifications for air cargo screening but pay less attention to the time-related effects of extended security measures on freight operations. Specifically, there is limited comparative evidence on how the arrangement and spatial positioning of extended checks within terminal layouts of varying sizes impact end-to-end delays and how these delays spread through multi-leg air cargo networks. A process-oriented view embedded in the terminal timeline has been largely missing, which obscures the control stages that most significantly contribute to delays. Operational experience indicates that bottlenecks often occur, particularly in activities reliant on limited human resources – such as canine teams and crate-opening specialists – as well as in the timing and quality of information exchanges with transport-planning teams.

Against this backdrop, the present study aims to quantify the impact of security control configuration and scheduling on the emergence and propagation of delays in air cargo operations, and to identify procedural levers that can reduce inspection-related latency. Screening activities are mapped along the cargo-handling timeline, and total delay is broken down into operational components. Empirical data are collected from 2 terminals that differ in scale and organisation – a regional facility in southern Poland and a high-throughput international terminal in southern Europe – thereby enabling a comparative assessment of operating conditions and divergent procedures. The contribution is both methodological and practical: a temporal breakdown of inspection-driven delay at the terminal level is proposed; comparative evidence is provided linking terminal scale and control design factors to delay propagation; and organisational recommendations are formulated to target the main sources of latency.

This design leads to the following research hypotheses:

- ***H1***: the frequency and duration of extended screening stages account for the majority of total cargo delay;
- ***H2***: a larger terminal scale increases both the frequency and duration of extended screening, amplifying delay propagation unless specialist availability and information handovers are optimised;
- ***H3***: on-call specialist coverage and earlier notification of transport-planning teams after adverse X-ray outcomes reduce total delay and downstream disruption under a common regulatory framework.

The rest of the article is organised as follows:

- Section 1 – introduction;
- Section 2 reviews the current knowledge and identifies the research gap;
- Section 3 explains the research methodology;
- Section 4 provides a comparative analysis and discussion of results from a regional cargo terminal in southern Poland and a high-throughput international terminal in southern Europe;
- Section 5 summarises the main conclusions and suggests organisational measures to reduce supply chain delays caused by cargo security control.

2. Literature review

The review section is organised into 2 domains:

- Section 2.1 synthesises research on continuity in air transport supply chains, including capacity, infrastructure layout, planning, information exchange, and resilience;

- Section 2.2 examines the security controls for cargo shipments as a determinant of continuity, with emphasis on the placement and design of screening procedures along the cargo-handling timeline.

2.1. Ensuring the continuity of supply chains in air transport

The continuity of air transport supply chains relies on the alignment of 3 key levers: demand, inventory, and cargo carriage. The performance ceiling is influenced by operating costs, infrastructure quality, and storage capacity (Milambo, Phiri 2019; Pyza, Golda 2011). In this context, cargo terminal operations function as a system of communicating vessels, where capacity is coordinated with infrastructure layout, planning, communication, information technologies, and dimensions of sustainable development (Feng *et al.* 2015).

Capacity remains the fundamental constraint of the system (Rodbundith *et al.* 2021). Its alleviation is achieved, among other methods, through offshore consolidations that reduce queues and delays (Chu *et al.* 2024). From a network perspective, the airport functions as a node, with transport capacity aggregated across connections (Wang *et al.* 2022). Therefore, allocations are guided by CVaR and ANN methods (İlgün, Alptekin 2022), and any unused baggage capacity is redirected, where feasible, to cargo transportation (Ma *et al.* 2025). Within this context, spatial design plays an enhancing role: transhipment facilities facilitate flow (Rabten *et al.* 2021), the organisation of loading points improves efficiency (Romero-Silva, Mujica Mota 2022), location strategies accelerate unloading (Cheng *et al.* 2024), and entire logistics parks are optimised using genetic algorithms based on forecast volume, zone sizes, and their correlations (Chen 2024).

Furthermore, the outcome depends on the accuracy of planning and routing. The ACLPP problem includes aircraft configuration, pallet assembly, palletisation, and weight and balance (Brandt, Nickel 2019). Integer programming aids in routing and packing with irregular ULD (Zhou *et al.* 2024), and routing models must account for the limited availability of aircraft (Kushwaha, Sen 2023). In practice, planning is expressed as BOM/COM/IOM (Zhao *et al.* 2023), and cost minimisation employs PSO and GLN PSO to combine and optimise cargo (Sahoo *et al.* 2023). Temporal alignment completes the process: the co-design of cargo and flight routes reduces dwell time at nodes (Xiao *et al.* 2022; Zheng *et al.* 2023), and in the express segment, planning is the main factor influencing outcomes (Lu, Chung 2023). Heuristics that explicitly consider transport corridors, schedules, and pallet allocations are supplemented with MILP using CPLEX (*https://www.ibm.com/products/ilog-cplex-optimization-studio*), reducing planning cycles to seconds (Mesquita, Sanches 2024; Kaeothep, Nonsiri 2022). Recent developments include intelligent decision support for complex geometries and ULDs, as well as digital twins capable of dynamic loading (Wong *et al.* 2021; Lee *et al.* 2021).

At the blockchain-based level, layers of maintenance and topology are added. In AMR, benefits are generated through blockchain-based cooperation, recovery, and proactive control, supported by IoT and ML, as well as the assistance of autonomous systems (Ma *et al.* 2022). In turn, swarm intelligence methods guide the selection of routes and the design of point-to-point and hub-and-spoke networks, revealing critical nodes and suggesting appropriate transhipment techniques (Lee *et al.* 2019).

Since disruptions are costly – as additional cargo tasks can increase operational costs by up to $38000 per flight hour (Liu *et al.* 2019) – the focus shifts to integrated recovery. In the ACRP approach, ML-driven column and row generation simultaneously recover flights, aircraft, and cargo (Huang *et al.* 2023). A similar strategy is applied when the system faces demand shocks (Delgado *et al.* 2020). Multi-criteria linear programming optimises additional ULD handling across multi-stage routes, considering constraints related to weight, volume, fit, and centre of gravity (Zhao *et al.* 2024). Additionally, considerations include hold structure, separation of dangerous goods, and oversize items (Lu *et al.* 2023).

In the face of uncertainty, risk and cooperation are crucial. SARIMA forecasts delays and delivery costs (Kim, Lee 2019). Distribution models combine capacity, disruption probabilities, demand, and rates, supporting forwarder selection (Feng *et al.* 2020). 2-point contracting coordinates capacity, prices, and penalties (Amaruchkul 2019). On the forwarder side, planning includes subcontractor risk assessment (Kulak *et al.* 2018); on the side of the entire chain, multimodal integration and airline–forwarder alliances provide benefits (Zhang *et al.* 2007). In the risk-mitigation arsenal, there are IoT smart containers for monitoring and control (Spandonidis *et al.* 2022). Resilience is evaluated by factors such as transport work, flight production, profits, shipment time value, and inventory costs at nodes (Janić 2019).

Demand variability requires the integration of forecasts with reservation control, as prices respond to the level and variability of demand (Wen *et al.* 2020). Therefore, SDE with CSA (Li *et al.* 2020), ANN (Gerardo Muros Anguita, Díaz-Olariaga 2023), and the Holt–Winters method (Kaščeev *et al.* 2022) are utilised. Hybrid decision support improves request handling (Huang, Lu 2015), and 2-stage stochastic programming predicts the number and types of containers, linking the loading plan to consolidation (Zhu *et al.* 2023). PDPTW models offer benefits in disrupted conditions (Delgado, Mora 2021), and algorithms forecast available cargo space and shipment dimensions (Tseremoglou *et al.* 2022).

All this is interconnected through connectivity and information exchange; continuity depends on strong cargo connectivity and network-quality measures that account for transhipment and time effects (Boonekamp, Burghouwt 2017; Suwanwong *et al.* 2018; Niu *et al.* 2019). Unified digital platforms facilitate information interactions and offer end-to-end visibility (Molchanova 2021); central planning that integrates routing with operations scheduling reduces transport and waiting times (Bombelli, Fazi 2022). When demand patterns demand it, including smaller airports improves efficiency and reliability (He *et al.* 2024).

The COVID-19 period acted as a stress test, exposing capacity shortages, commercial uncertainty, and pressure on profitability (Li 2020). Continuity was maintained, among other measures, through the conversion of passenger aircraft into cargo, and the resulting loading issues were tackled using MINLP (Desai *et al.* 2023; Zheng *et al.* 2024). Meanwhile, digitalisation accelerated: ergonomics and process studies justified further digitisation (Diefenbach *et al.* 2023); the adoption of cargo technologies led to increased efficiency and greater satisfaction among service providers (Adenigbo *et al.* 2023); blockchain-based communication and data exchange enhanced traceability, though not without trade-offs (Lau *et al.* 2024); collaboration in monitoring gained new tools (Tu *et al.* 2023); and AI algorithms for barcode scanning ensured the continuity of ongoing processes (Bierwirth *et al.* 2021).

Recent research on continuity and resilience views cargo terminals as vital nodes whose capacity to absorb, adapt to, and recover from disruptions influences the stability of supply chains (Li *et al.* 2024). Delay-propagation studies also demonstrate that local processing delays at network bottlenecks can cascade through tightly coordinated flight schedules once buffers are exceeded (Zapola *et al.* 2024), especially where resources are shared and turnaround times are shortened. Simultaneously, the digitalisation of air cargo operations – including standards like IATA ONE Record and smart-cargo facility concepts – is increasingly seen as a way to achieve earlier visibility into disruptions, quicker replanning, and reduced inspection-related delays.

Finally, sustainability and adaptability jointly influence the durability of outcomes: Frankfurt Cargo Services (Germany) reported an increase in the recovery of hazardous and non-hazardous waste between 2008 and 2019 (Baxter 2022). Fuel choices are embedded within regulatory frameworks as a key aspect of sustainable supply chain design (Farid, Donyatalab 2022; Nazeer *et al.* 2024), and adaptability has been associated with environmental, operational, and social outcomes, which naturally prompts the question of how shipment security control contributes to this broader context.

2.2. Security control of shipments in air cargo transport

Cargo security control aims to identify threats before they disrupt transportation and compromise flight safety. Despite extensive literature on passenger and baggage control (Skorupski, Uchroński 2018; Sekhar *et al.* 2024; Latscha *et al.* 2024), studies specifically focused on cargo are rare, even though cargo safety significantly affects demand for air services (Florido-Benítez 2023). Additionally, the regulatory framework is considered inadequate (Domingues *et al.* 2014); therefore, emphasis is placed on a proactive approach that ensures compliance and consistent execution of procedures (Hassam *et al.* 2018).

From a technological perspective, the range of methods is extensive, including CT and XRD, as well as PC and DPC, NQR and NMR, ultrasound, millimetre waves, and neutron scanning – all aimed at more effective pre-screening (Kierzkowski, Kisiel 2015; Cordova 2022). Dual-channel solutions that combine neutron and X-ray radiation enable more reliable differentiation of materials in shipments (Lee *et al.* 2023). The techniques for detecting dangerous materials – originally developed for baggage – are now adapted for cargo applications (Velayudhan *et al.* 2023). At the system level, the cargo screening process simulator improves the detectability of hazardous goods (Siebers *et al.* 2009). Simulations, combined with computer vision – for example, in a *Pygame* environment – use YOLOv8 to identify hazardous objects on conveyor belts (Meenakshi Sundaram *et al.* 2024). Beyond the checkpoints themselves, WSNs with RFID facilitate ongoing flow control and enhance security in terminals (Le 2018).

The operational layer completes the picture: micro-scale models based on Petri nets enable the estimation of control capacity under disruptions (Skorupski, Uchroński 2023), and the structure of the load – the number of items in a shipment and total mass – turns out to have a measurable impact on the result (Ryczyński *et al.* 2024). The human factor cannot be omitted either: work schedules of cargo-handling personnel are optimised with load-equalisation methods (Nobert, Roy 1998), and the training and experience of SCO translate both into screening effectiveness and into the economics of the entire process (Ryczyński, Kierzkowski 2023).

Finally, perspectives of sustainability and corporate governance consolidate the system approach: simulation models compare configurations of inspection devices and procedures (Kierzkowski *et al.* 2023), and the postulates of holism call for linking cargo screening with access control to airside zones and with identity management for employees and drivers (Rountree, Demetsky 2006; Park *et al.* 2023)

In conclusion, the literature provides a convincing explanation for designing and maintaining the continuity of supply chains. Still, it does not answer how security control itself – as a specific operational module – conditions this continuity. To date, studies have focused more on the impact of security supervision on prices and demand than on temporal reliability. Therefore, the analysis carried out by the authors in the article focuses its efforts on the placement and design of control in the cargo stream, aiming to fill the existing research gap and demonstrate its translation into operational outcomes.

Synthesis and link to the present study.

Taken together, the reviewed strands of continuity, resilience, delay propagation and digitalisation indicate 3 mechanisms that are directly relevant here:

- local processing delays at terminal bottlenecks are relayed to multi-leg air cargo networks once schedule buffers are exceeded;
- human-dependent resources, including specialist inspectors, are the least flexible capacity element during disruptions;

- timely information handovers to planning teams determine the size of the downstream waiting.

These insights motivate the process-timed mapping in Figure and the decomposition of total lateness into T_D, T_{Ch}, T_M and T_W in the empirical part of the article, enabling identification of the dominant contributors to delay propagation.

3. Methodology

3.1. General assumptions

Security control in air cargo terminals is conceived as a layered, risk-based regime that detects items hazardous to the transport process and flight safety. Non-intrusive inspection constitutes the baseline: palletised consignments undergo X-ray imaging interpreted by SCO, with anomaly recognition guided by contrasts arising from differential attenuation across materials. When indicated, screening is complemented by canine teams and by hands-on examinations that incorporate chemical swab analyses. In parallel, documentary verification preserves the chain of custody and supports end-to-end traceability. In combination, these measures enable the timely identification of dangerous consignments and sustain operational reliability. According to IATA guidance, screening should commence not later than 8 h before the planned departure to the subsequent transport leg.

The empirical objective was twofold: to quantify consignments that failed security screening and to estimate the consequent extension of door-to-port delivery times. Baseline processing begins at the conveyor in-feed T_0. It proceeds through a dedicated X-ray system, culminating in expert image assessment by SCO personnel trained to identify atypical shapes, density discontinuities, and foreign objects. The non-destructive nature of X-ray imaging enables the rapid handling of large volumes without opening consignments, thereby maintaining throughput while preserving a high level of safety.

Screening is escalated when suspicious indicators are present. Secondary diagnostics may involve multi-view X-ray imaging, canine inspection, and targeted chemical testing. In high-risk cases, pallet loads are deconsolidated, or crates are opened, allowing individual items to be examined directly. Opening and deconsolidation are carried out by external specialists, after which SCO personnel perform detailed checks. Figure depicts the escalation path and highlights the stages associated with delay accumulation. Each escalation step consumes additional time and commonly precludes delivery within the planned initial window, thereby perturbing the supply chain.

Canine inspection deploys trained dog-handler teams to localise trace odours of explosives, narcotics, chemicals, and related hazards. Coverage is extensive, and access to occluded locations is improved relative to fixed-view imaging. Chemical-reagent screening operates on surface swabs analysed by portable detectors; colorimetric or electronic responses indicate the presence of target compounds. Ambiguous findings at any stage trigger further escalation to physical inspection, which, while time-consuming, provides the highest diagnostic certainty in safety-critical contexts.

Delay quantification follows from the durations depicted in Figure: T_D, T_{Ch}, T_M, and T_R. 2 components require further detail. T_D is the sum of the waiting time for a canine team and the time taken to conduct the dog inspection. T_M is the sum of the waiting time for a crate-opening specialist and the duration of the manual examination. These values vary by shipment due to geometry, size, and specialist availability. When X-ray screening clears a consignment, T_R = T_{delay} = 0 and the shipment proceeds on schedule. When X-ray screening fails, T_R it equals the sum of the ensuing inspection times. In the worst case, when the full escalation path in Figure is followed, the delay time T_{delay} is:

$$T_{delay} = T_D + T_{Ch} + T_M, \quad (1)$$

where: T_D – dog inspection time; T_{Ch} – inspection time using chemical-reagents; T_M – time of manual inspection of the shipment.

Air cargo transport imposes an additional scheduling constraint. If security checks extend beyond the available buffer, substitute uplift must be sourced. Priority is given to belly-hold carriage on passenger flights, subject to weight and dimensional limits, aircraft capacity, and residual space on the targeted departure. If the booking is infeasible, it is deferred to the next cargo flight, which typically operates at a lower frequency than passenger services. Both pathways introduce further waiting, which is incorporated as:

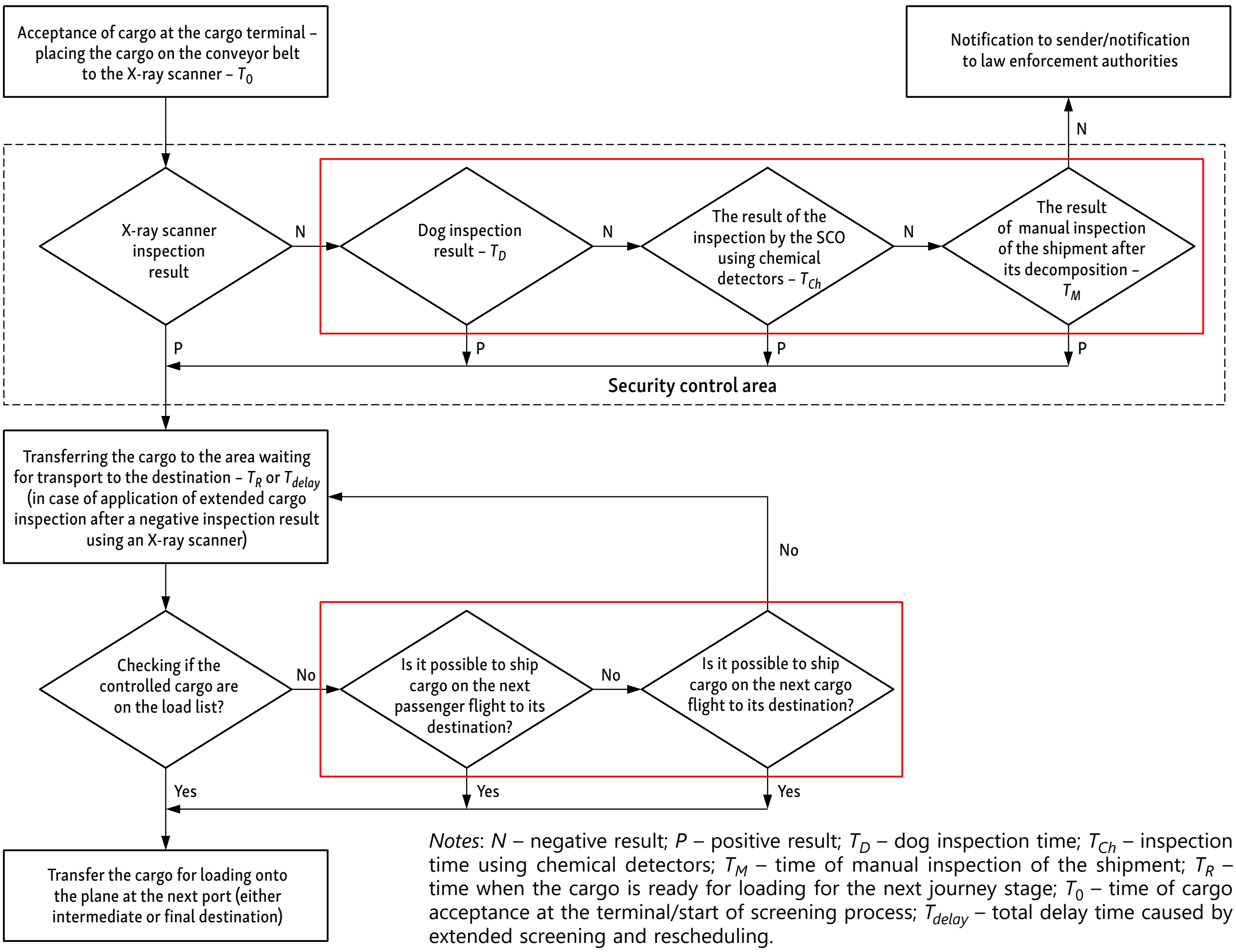
$$T_{delay} = T_D + T_{Ch} + T_M + T_W, \quad (2)$$

where: T_W denotes the TW.

Equations (1) and (2) formalise the inspection-and schedule-driven components of delay that propagate across the supply chain.

3.2. Data and analytical procedure

The empirical analysis uses operational screening logs and terminal timeline records from 2 cargo facilities: a regional terminal in southern Poland and a high-throughput international terminal in southern Europe. The observation window covers January 2022 – December 2024. Cases are included whenever an adverse X-ray outcome triggers escalation to extended screening. For each such consignment, timestamps are extracted for baseline screening, canine inspection, chemical swabbing, manual or crate-opening inspection, and the subsequent re-uplift decision. Total delay T is computed as the sum of extended-inspection durations and the T_W, in line with Equations (1) and (2) and the escalation algorithm in Figure. Descriptive statistics are then compared across terminals and years to identify dominant delay components and scale effects.



Notes: *N* – negative result; *P* – positive result; T_D – dog inspection time; T_{Ch} – inspection time using chemical detectors; T_M – time of manual inspection of the shipment; T_R – time when the cargo is ready for loading for the next journey stage; T_0 – time of cargo acceptance at the terminal/start of screening process; T_{delay} – total delay time caused by extended screening and rescheduling.

Figure. Algorithm for the impact of the extended security checks in air cargo terminals on disruptions in the form of delays in supply chains (*source*: own elaboration of the authors)

3.3. Data sources and cleaning

The components T_D, T_{Ch}, T_M, T_W of times were determined based on:

- automatic timers from critical and on-site testing systems;
- security operator logs for the service dog and manual inspection (package opening, visual inspection, photographic documentation);
- shift logs used to monitor incidents and data completeness.

Observations with incomplete start pairs and extraction of individual data from the analysis at a basic level. When available, the elapsed time was computed from the primary timestamp records; if missing, the backup log record was used. Values incompatible with applicability (e.g., alternative times, overlapping intervals) were removed from the sample. Extreme values above the 99th percentile were identified, with the distribution shown not only for rounded averages but also for quartiles and selected percentiles.

To formally examine whether the terminal scale is associated with differences in delays, a one-way ANOVA was conducted on annual averages for 2022–2024, with terminal type (regional vs. international) as the factor and delay rates as the dependent variables. Due to the limited number of observations at the annual average level, this analysis is intended to be supplementary and illustrative, complementing the detailed descriptive analysis at the shipment level.

4. Results and discussion

4.1. Illustrative cases and descriptive statistics

The study examined 2 settings: a regional terminal in southern Poland and a high-throughput international terminal in southern Europe, to assess how security controls propagate supply chain delays. Table 1 collates illustrative consignments for which a negative initial screening triggered an extended inspection. Across cases, delay profiles differ markedly between terminals, a pattern that aligns with terminal scale and, more importantly, with the design and cadence of extended-inspection procedures.

Throughput effects are visible in the international terminal: a larger traffic base yields more suspected consignments, resulting in more frequent use of extended checks (see also the statistics in Table 2). However, higher invocation does not translate into faster execution. Process latency is concentrated in stages that rely on external specialists – canine teams and crate-opening services – where availability is limited. The regional terminal operates with on-call access, which reduces wait times and streamlines manual follow-up. Cargo No 3 exemplifies this dynamic: despite escalation to extended inspection, timely execution preserved the planned uplift with no delay.

In contrast, the international terminal offers specialist services every week. When crate-opening is required, consignments are set aside until the locksmith arrives; if the need arises immediately after the visit, dwell may extend to 7 days (Cargo No 4 and Cargo No 5). These practices elevate the manual-inspection component T_M and, when connections are missed, induce additional waiting for substitute uplift T_W, identifying T_M and T_W as the principal drivers of delay accumulation.

Table 1. Result of research – selected examples

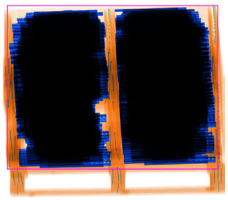
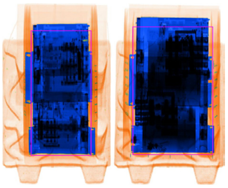
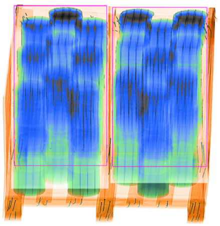
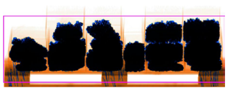
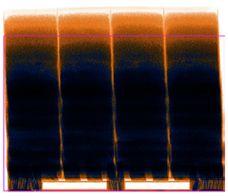
Cargo No	Image from an X-ray scanner – negative control result	Extended security check – actions taken			T_{delay} [h]
		Dog	Chemical detectors	Manual inspection	
Regional cargo terminal					
1		No	Yes	Yes	11
2		Yes	Yes	No	4
3		Yes	Yes	No	0 (in line with the flight schedule)
International cargo terminal					
4		Yes	Yes	Yes	146
5		Yes	Yes	Yes	187
6		Yes	Yes	No	18
7		Yes	Yes	No	29

Table 2. Delays in supply chains due to the need to implement extended security control procedures from 2022 to 2024

Year	Percentage of shipments sent for extended security checks after negative X-ray scan results [%]	Percentage of shipments that arrived at their destination as planned after extended security checks were performed [%]	Average time of additional procedure as part of extended security control [h] (all presented time results are rounded to full hours)				Average delay time T_{delay} [h]
			T_D	T_{Ch}	T_M	T_W	
Regional cargo terminal							
2024	5	2	1	1	6	6	14
2023	3	1	2	1	8	5	16
2022	6	2	2	1	8	9	20
International cargo terminal							
2024	13	3	5	6	57	18	86
2023	15	4	6	5	62	22	95
2022	12	3	5	7	51	21	84

Summary statistics for 2022–2024, presented in Table 2, corroborate these mechanisms.

In addition to the illustrative cases in Table 1, the summary statistics in Table 2 highlight systematic differences within and between terminals over time. In the regional terminal, escalation rates fluctuate modestly between 3% and 6%, with T_M stabilising around 6…8 h and T_W around 5…9 h, resulting in mean total delays T_{delay} in the range of 14…20 h. In the international terminal, escalation is consistently higher (12…15%), T_M remains significantly above regional values (51…62 h), and T_W fluctuates between 18 h and 22 h, leading to mean delays T_{delay} of 84…95 h. No strong trend over time is observed within terminals; instead, a persistent gap emerges between the 2 organisational regimes. This pattern supports the interpretation that differences in the configuration and scheduling of specialist-dependent stages, rather than year-to-year variability in demand or regulation, drive the observed delay contrasts.

4.2. One-way ANOVA on annual mean values

To formally determine whether the terminal scale was linked to differences in inspection-induced delay, a one-way ANOVA was conducted on annual mean values for 2022–2024, with terminal (regional versus international) as the factor and delay indicators as dependent variables (percentage of consignments escalated, percentage remaining on time after extended checks, and component times). Since the analysis depends on annual averages, these findings should be considered indicative and supported by the shipment-level descriptive data in Table 2.

ANOVA on annual means confirmed the presence of powerful terminal effects. For total delay T_{delay}, the impact of the terminal was highly significant (F – ANOVA F-statistic, p – statistical significance level, p-value, η^2 – proportion of explained variance, eta-squared effect size): $F(1, 4) = 352.9$, $p < 0.001$, $\eta_2 \approx 0.99$ with the international terminal showing a much higher average delay (88.3 h) compared to the regional terminal (16.7 h). The most substantial effects among the components were observed for T_M and T_W:

- manual inspection time T_M: $F(1, 4) = 230.6$, $p < 0.001$, $\eta^2 \approx 0.98$, 7.3 h versus 56.7 h;
- waiting-for-uplift time T_W: $F(1, 4) = 64.7$, $p < 0.001$, $\eta^2 \approx 0.94$, 6.7 h versus 20.3 h.

The frequency of extended checks *pct_ext* also varied significantly between terminals: $F(1, 4) = 48.3$, $p \approx 0.002$, $\eta^2 \approx 0.92$, 4.7% versus 13.3%. These results, summarised in Table 3, support the conclusion that extended screening – particularly stages reliant on specialists and subsequent rescheduling – is the main factor contributing to delay propagation.

Due to the limited number of yearly observations and the aggregation to annual means, this ANOVA should not be viewed as a thorough classical test of shipment-level data but rather as a supplementary, illustrative analysis that underpins – rather than replaces – the descriptive evidence.

4.3. Hypotheses assessment

Based on the data above, the working hypotheses can be reconsidered as follows:

- 1st (***H1***), the data support the hypothesis that extended screening stages mainly cause the overall cargo delay: both T_M and T_W are significantly larger than T_D and T_{Ch}, with powerful terminal effects ($\eta^2 \geq 0.94$);
- 2nd (***H2***), the hypothesis that a larger terminal scale increases delay propagation is also supported, as the international terminal shows both a higher escalation rate and notably longer average T_{delay} and T_M;
- 3rd (***H3***), the evidence comparing the 2 organisational regimes aligns with the hypothesis that on-call specialist coverage and earlier notification of planning teams help reduce total delay, since the terminal implementing these measures has considerably lower T_M and T_{delay} despite operating under the same regulatory framework.

Because the ANOVA assessments are based on aggregate (annual averages), these findings are indicative rather than definitive. The process-level interpretation supports them T_M and T_W as potential bottlenecks in propagation.

Table 3. One-way ANOVA on annual mean values of inspection-induced delay indicators by terminal (2022–2024)

Indicator	Mean – regional terminal	Mean – international terminal	$F(1, 4)$	p-value	η^2
Percentage of consignments escalated *pct_ext*	4.7%	13.3%	48.3	0.0023	0.92
Manual inspection time T_M [h]	7.3	56.7	230.6	<0.001	0.98
Waiting-for-uplift time T_W [h]	6.7	20.3	64.7	0.0013	0.94
Total delay T_{delay} [h]	16.7	88.3	352.9	< 0.001	0.99

Table 4. Scenario analysis for T'_{delay} under hypothetical reductions in T_M and T_W at the international terminal (2024)

Scenario	Assumptions r_M, r_W	T_M [h]	T_W [h]	Total delay T'_{delay} [h]
Baseline	$r_M = 0$, $r_W = 0$	57	18	86.0
Scenario No 1: T_M = 25%	$r_M = 0.25$, $r_W = 0$	42.8	18	71.8
Scenario No 2: T_M = 50%	$r_M = 0.50$, $r_W = 0$	28.5	18	57.5
Scenario No 3: T_M = 50%, T_W = 25%	$r_M = 0.50$, $r_W = 0.25$	28.5	13.5	53.0

4.4. Scenario analysis

To estimate the potential impact of organisational changes on delay levels, a simple sensitivity analysis was conducted based on the observed mean components. The following notation was adopted:

$$T'_{delay} = T_D + T_{Ch} + \left(1 - r_M\right) \cdot T_M + \left(1 - r_W\right) \cdot T_W, \tag{3}$$

where: r_M and r_W represent the relative reduction in manual inspection time and waiting time for alternative transportation, resulting, for example, from the implementation of the on-call model and advance re-planning.

For the international terminal in 2024, the following baseline values were assumed: T_D = 5 h, T_{Ch} = 6 h, T_M = 57 h, T_W = 18 h, resulting in $T'_{delay} = 86$ h. T_M reductions of 25%, 50%, and 75% were assumed, with a constant T_W. The resulting T'_{delay} values were 71.8 h, 57.5 h, and 43.3 h, respectively. With a simultaneous reduction of T_M by 50% and T_W by 25%, the T'_{delay} value drops to approximately 53.0 h.

These scenarios (Table 4) do not constitute a causal estimate in the strict sense – they are "what–if" analyses illustrating the order of magnitude of delay reduction achievable by shortening the dominant T_M and T_W components.

4.5. Cost implications of inspection-induced delays

Delays caused by extended inspections result in tangible economic losses for terminal operators and carriers, as well as for shippers and recipients. The literature on air traffic disruptions indicates that the costs of recovery operations in cargo networks can reach tens of thousands of [$/h] of flight delay, suggesting that even a slight reduction in missed connections results in measurable savings.

At the level of an individual shipment, the cost of delay C_s can be expressed as:

$$C_s = v_s \cdot T, \tag{4}$$

where: v_s – the value of the shipment time (including the costs of tied-up capital, contractual penalties, and the risk of lost sales); T – the observed delay time.

For consolidated batches C_b, the following notation applies similarly:

$$C_b = v_b \cdot T, \tag{5}$$

where: v_b – the value of the batch time.

Due to the lack of full information on the contractual parameters on the part of shippers and recipients, the considerations in this study are of an indicative nature – they aim to link the observed multi-hour delays with the potential economic exposure of the stakeholders.

4.6. Economic balance of specialist availability models

This article compares 2 workflows for specialists responsible for manual inspection (opening packages, visual inspection, documentation):

- a "batch" model, in which specialists perform manual tasks within specific time windows, handling a set of shipments accumulated during that time;
- an on-call model, in which a specialist is called immediately upon detection of a shipment requiring manual inspection.

The cost difference between the 2 models can be expressed as:

$$\Delta C_s = \left(C_{on\text{-}call} - C_{batch}\right) - v \cdot \Delta T, \tag{6}$$

where: $C_{on\text{-}call}$, C_{batch} – the personnel costs associated with the respective models (on-call shifts, readiness allowances, etc.); v – the relevant time value parameter (at the shipment or batch level); ΔT – the delay reduction achieved by switching from the batch model to the on-call model.

The on-call model is economically advantageous when $v \cdot \Delta T$ exceeds the difference in personnel costs between $C_{on\text{-}call}$ and C_{batch}. For illustration, consider the international terminal under analysis: a 50% reduction in T_M implies $\Delta T \approx 28.5$ h; even with conservative values of v, the additional on-call costs are more than offset by the savings associated with shortening the delays of high-value batches. This supports the recommendation to implement on-call models in high-throughput terminals.

4.7. Theoretical Interpretation

The empirical results are consistent with models of delay propagation and resilience of transport systems. The T_M and T_W components act as high-centrality bottlenecks: once the available time buffers before the next transport stage (e.g., the next flight) are exceeded, delays are transmitted to further sections of the network through lost connections, lack of available slots, and the need for rescheduling.

In terms of resilience, the regional terminal demonstrates greater absorption and adaptation capacity: thanks to the on-call model and faster rescheduling, it returns to its target state more quickly. The international terminal, using a more "batch-based" recovery model, is characterized by slower reconfiguration and longer-lasting disruptions.

5. Conclusions and future work

This article contributes to the literature on cargo security and supply chain management by shifting the emphasis from describing technology and regulatory requirements to analysing the process-based effects of extended controls on delays and business continuity. A comparative study of 2 terminals of distinctly different scale, utilizing a consistent set of 3 years of operational data, is employed. The presented approach, which decomposes the total delay T'_{delay} into components T_M, T_{Ch}, T_D, and T_W, assigned to individual stages of the escalation path, and links these components to organizational decisions (specialist work model, information transfer to planners), adds value to the current state of knowledge in this area. To the best of the authors' knowledge, this is one of the 1st comparative, empirically grounded studies on extended cargo controls from the perspective of supply chain continuity. The most important conclusions drawn from the conducted research include 3 elements. 1st, it was shown that extended inspection is used significantly more frequently and lasts significantly longer at the international terminal than at the regional terminal (3...6% vs. 12...15% of shipments, average delays 14...20 h vs. 84...95 h), and the T_M and T_W components dominate the delay budget. 2nd, the differences between terminals are stable over the 3 consecutive years, suggesting that they result from persistent structural differences in the configuration and scheduling of specialist-dependent stages, rather than from demand variability or temporary operational changes. 3rd, it was shown – based on scenario analysis – that even moderate reductions in T_M and T_W, achievable through the use of an on-call model and advance notification of planning teams, lead to significant reductions in T'_{delay}. These results are consistent with theoretical models of cascading delays and resilience, which identify bottlenecks and information transfer as key channels for disruption propagation.

These results indicate that compliance with security regulations and operational efficiency do not necessarily conflict. Inefficiencies and excessive delays result primarily from the organization and staffing of extended inspection stages and coordination with transport-planning, rather than from regulatory requirements themselves.

Therefore, it is recommended that regulatory guidelines on cargo security be supplemented with recommendations regarding:

- minimum requirements for the availability of specialists (e.g., on-call models in high-capacity terminals);
- principles of parallel re-planning (initiated immediately after an unfavourable X-ray examination result);
- maximum permissible delays in the transfer of information between security services and the teams responsible for transport-planning.

This approach helps reduce the risk that extended inspections – necessary from a security perspective – will simultaneously undermine the continuity of supply chains and the competitiveness of operators.

In the next stages of the research, the authors plan to undertake activities aimed at:

- quantitatively estimating losses for shippers, recipients, and carriers based on contractual shipment and batch times;
- analysing the feasibility of implementing digital screening technologies (e.g., CT, AI image analysis systems) and integrating data compliant with the IATA ONE Record standard;
- developing optimization models that balance threat detection effectiveness, throughput, and system resilience to disruptions, taking into account the costs of delays and the availability of resources (including specialists).

Two limitations should be acknowledged. The analysis relied on operational timelines and terminal records rather than on complete consignee-side cost disclosures. In addition, specialist availability and notification practices were observed in 2 specific organisational settings, which may limit generalisability. Future work will quantify consignee losses attributable to inspection-induced delay and will extend the comparative design to additional terminals. As access to sensitive cost data improves, it will be possible to estimate the benefits of on-call specialist coverage and real-time notification and to calibrate screening workflows that balance safety requirements with temporal reliability.

Author contributions

Tomasz Nowakowski was responsible for the concept and development of the study's results, including extended security checks, delay propagation analysis in air cargo operations, and the conclusion.

Jacek Ryczyński was responsible for data collection at regional and international terminals, security control analysis, data interpretation, and article editing.

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