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TRUST-BASED AGENT ADAPTATION IN DIGITALLY FRAGMENTED LOGISTICS NETWORKS: A CASE STUDY OF AN INDONESIAN EXPORT HUB

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Abstract

Fragmented digital infrastructure and uneven institutional readiness often generate coordination inefficiencies in air cargo export logistics, particularly in developing countries. This study aims to examine how trust-based behavioural adaptation influences coordination effectiveness in logistics systems operating under conditions of digital inequality. An integrated simulation framework combining Agent-Based Modelling and a Graph-Based Digital Twin is developed to model adaptive decision-making and the structural evolution of coordination networks among freight forwarders, airlines, ground handling agents, and customs authorities under varying levels of trust and interoperability. Simulation results indicate that high interoperability and organically established institutional trust significantly reduce partner switching rates, shorten clearance times, and produce denser and more resilient coordination networks, whereas policy-driven artificial interoperability, while improving coordination performance, exhibits lower resilience. Overall, the findings demonstrate that effective logistics coordination requires the alignment of digital infrastructure development with relational mechanisms to enhance systemic resilience in fragmented digital environments.

Keywords: Agent-based modelling, Air cargo, Graph-based digital twin, Logistics coordination, Trust dynamics.

1. Introduction

The growth of international trade has increased the need for efficient and resilient air logistics systems, especially for high-value commodities. In developing countries such as Indonesia, export logistics coordination is often hampered by digital fragmentation and disparities in technological readiness among stakeholders [1, 2]. Actors such as freight forwarders, airlines, ground handling agents, and customs authorities generally operate on non-integrated systems, causing clearance delays, increased administrative burdens, and reduced logistics competitiveness [3, 4]. In this context, coordination effectiveness is not only determined by formal systems but also by informal mechanisms such as trust, interpersonal communication, and adaptive learning [5]. Trust becomes a key element in creating coordination stability, especially when real-time information is limited and uncertainty is high. Therefore, understanding how logistics actors adjust their behaviour in a fragmented digital ecosystem is crucial for designing more effective coordination systems.

To tackle the problem in consideration, the research merges Agent-Based Modelling (ABM) techniques with Graph-Based Digital Twin (GBDT). ABM enables the modelling of different agents demonstrating adaptive behaviour. On the contrary, GBDT defines the dynamic process of coordinating the relationships between the agents [6, 7]. The hybrid technique provides a methodology to unleash the influence of the resulting trust behaviour dynamics on the efficiency of logistics coordination in the digital era. This research aims to examine the following: (1) how trust processes affect the dynamics of coordination in a digitally fragmented air logistics chain system, and (2) the development of the network structure in the process of coordinating under different conditions of interoperability/trust. This research focuses on the air export at Soekarno-Hatta International Airport. The research scope involves the interactions between the key stakeholders such as freight forwarders, airlines, ground handling agents (GHAs), and customs services. The research aims to bridge the literature gap in the fields of digital innovations and social processes by incorporating both in one simulation framework. A literature map in the form of a table (Table 1) highlights the research contributions in the form of the combination of Agent-Based Modelling (ABM) simulation techniques and Graph-Based Digital Twin (GBDT) for the analysis of trust-facilitated logistics in the context of less digitally matured environments.

Table 1. Research gaps in digital logistics coordination.

Key Focus	Research by	Approach	Identified Gap
Big Data in Air Logistics	[8-11]	Big Data Analytics	Trust-based agent adaptation and digital coordination using ABM and GBDT approaches
Blockchain in Supply Chain	[5], [12, 13]	Blockchain-based Coordination	
IoT in Air Logistics	[4], [14, 15]	IoT Implementation	

2. Literature Review

This research is grounded in two main theoretical frames: the theory of coordination in the context of logistics networks, and the construct of trust in the context of inter-organizational decision-making. The topic of supply chain-coordination in the research context has been operationalized in the following manner: it refers to the effort to coordinate the processes of different actors in the interest of systemic efficiency [16]. In the digital world, the need for coordination also necessitates the need for "interoperability where the ability of different systems to share and use information effectively" [17]. On the other hand, the role of "trust" in the context of logistics networks acts as a substitute for a lack of appropriate treatment of uncertainty in the system. Trust can reduce the complexity of interactions, encourage information sharing, and build a strong commitment to cooperation [18].

Some studies have shown that coordination challenges in air logistics often come from a lack of technological integration and uneven digital capabilities among actors. For instance, Aytekin et al. [9] and Wu and Yang [11] highlighted how big data analytics can improve operational efficiency but did not address inter-agent behavioural issues. Some research studies, for example, the works of Barrane et al. [12] and Zhang et al. [13] demonstrate the abilities of blockchain to encourage trust through transparency but fail to comment upon the adaptive behaviour of the participants in a constrained technological environment. Meanwhile, studies such as those by Jurgelāne-Kaldava et al. [4] and Omoruyi et al. [14] focused more on IoT applications for asset tracking and supply chain visibility, without exploring the behavioural dimension of coordination. This synthesis suggests that despite the extensive research on advanced technologies, a gap remains in integrating behavioural adaptation with digital coordination structures.

There exists a research void in integrating adaptive behavioural modelling of trust and coordination decisions at the agent level, and dynamic structural representation of evolving coordination networks within a single simulation framework. To overcome the challenge, the research relies on the integrated approach that combines Agent-Based Modelling (ABM) and Graph-Based Digital Twin (GBDT) to tackle the problem. ABM helps to develop the model of the logistics agents whose behaviour relies on the principles of adaptation in the context of trust-building processes. Meanwhile, GBDT enables the analysis of the dynamics of the structure of the networks of the processes of coordination. The theoretical position of the research leans on the assumption about the premise that the efficiency of the processes of the network of the specified type of the digital system depends on the endogenous processes of social relationships [6].

Figure 1 presents the conceptual framework used in this study. In the proposed framework, the logistics agents interact with system configurations that have varying levels of interoperability and trust. These activities cause modifications to the topology of the coordination network, which in turn helps analyse the effects of these modifications on the logistics efficiency. With the proposed approach, the research work attempts to shed more insights into the mechanisms of trust in the context of co-ordination in a digital fragmented system.

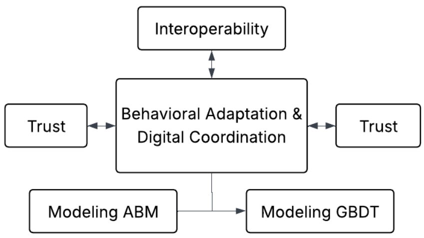

Fig. 1. Integration of ABM and GBDT for trust-based coordination in digital logistics networks.

3. Methods

To address the identified research gap concerning the integration of behavioural adaptation and evolving coordination structures in digitally fragmented logistics systems, this study adopts a simulation-based methodological approach. The proposed method combines Agent-Based Modelling (ABM) and a Graph-Based Digital Twin (GBDT) to simultaneously capture micro-level decision-making processes and macro-level network dynamics within the air cargo export ecosystem. The methodology is designed to examine how trust evolution and interoperability constraints jointly influence coordination behaviour, network topology, and operational performance under different digital scenarios. Accordingly, the methodological framework is structured into three components: the system architecture of the integrated ABM-GBDT model, the experimental setup and scenario design, and the performance metrics used to evaluate coordination effectiveness and system resilience.

3.1. System architecture

To assess coordination problems in distributed digital logistics environments, this study adopts an integrated simulation architecture that combines Agent-Based Modelling (ABM) and a Graph-Based Digital Twin (GBDT). This hybrid architecture is designed to capture both micro-level behavioural adaptation and macro-level structural evolution of coordination networks in air cargo logistics systems operating under conditions of digital fragmentation [13, 19, 20]. Within this architecture, ABM is used to represent heterogeneous logistics actors with bounded rationality, adaptive decision-making, and learning capabilities. In parallel, the GBDT framework models the coordination structure as a dynamic graph, where agents are represented as nodes and active coordination relationships are represented as edges. This dual-layer architecture enables the simultaneous analysis of agent behaviour and network topology, allowing structural changes to emerge endogenously from local interaction rules. The integrated ABM-GBDT architecture supports the examination of how trust dynamics and interoperability constraints jointly influence coordination effectiveness, network cohesion, and system resilience across simulation cycles.

3.2. Experimental setup

The simulation model incorporates four primary agent types: freight forwarders, airlines, ground handling agents (GHAs), and customs authorities. These agents represent key stakeholders involved in Indonesia's air cargo export process and exhibit varying levels of digital capability, responsiveness, and coordination behaviour. Model parameters and behavioural rules were informed by field observations and semi-structured interviews conducted at Soekarno-Hatta International Airport, Indonesia's largest air export hub. Empirical inputs were obtained through direct observation of export clearance processes and interviews with eight industry participants representing freight forwarding companies, airlines, and customs authorities. Additional sources, including standard operating procedures (SOPs), historical clearance time data, and national logistics digitalization policies, were reviewed to calibrate simulation parameters and validate scenario assumptions.

Multiple simulation scenarios were designed to represent varying levels of digital interoperability (low, medium, and high) and initial trust configurations, including distributed, clustered, and asymmetric trust distributions. Additional scenarios were implemented to test extreme conditions, such as limited digital access and policy-driven artificial interoperability. Through these controlled experimental settings, the model captures coordination dynamics under both organically evolving and institutionally imposed digital integration.

3.3. Performance metrics

Agent behaviour within the simulation is governed by internal state variables, including trust level, interoperability index, switching cost, and response time. Trust and interoperability evolve dynamically based on interaction outcomes, following a weighted learning mechanism derived from behavioural supply chain literature [13]. This adaptive process enables the simulation of trust stabilization or erosion over time. To evaluate coordination effectiveness and system performance, three primary metrics are employed. Switching Rate (SR) measures the frequency of partner changes among agents, reflecting coordination stability.

Coordination Density (CD), derived from the GBDT representation, quantifies network cohesion as the ratio of active coordination links to the total possible links within the network. Average Clearance Time (ACT) is used as an operational performance indicator, measuring the average duration required for shipments to complete the clearance process. These metrics allow for an integrated evaluation of efficiency, stability, and resilience in digitally dispersed logistics systems by capturing both structural adaptation at the network level and behavioural adaptation at the agent level. Figure 2 illustrates the overall simulation structure, including agent interactions, trust evolution, digital constraints, and output performance indicators.

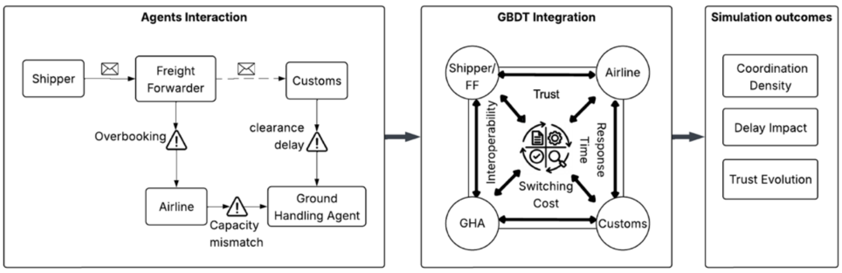

Fig. 2. Integrated simulation framework: agent-based modelling and graph-based digital twin in fragmented logistics ecosystems.

4. Results

The following section highlights the simulation experiment results performed in different levels of interoperability and trust settings. Every scenario also takes into account the unique digital readiness and behavioural structure of the agents in the air cargo export chain. The simulation design includes baseline configurations (low, medium, and high interoperability) as well as policy-driven scenarios in which artificial interoperability is enforced through centralized governance mechanisms [6, 21]. Additional exploratory simulations are included to capture extreme conditions such as complete digital isolation and centralized trust patterns.

In digitally fragmented logistics systems, these scenarios enable the assessment of trust evolution, agent switching behaviour, network structural transformation, and clearance performance [20].

4.1. Trust dynamics and switching behaviour

The simulation outcome suggests that the influence of trust between the logistics partners has nonlinear behaviour in nature, driven by the quality of the digital infrastructure deployed in the simulation experiment. In settings of low levels of interoperability in the simulation experiment, freight forwarders have a tendency to change their partners depending on service performance. As a result, the values of the trust index fall drastically in the case of freight forwarders and ground handling agents. Similar patterns of trust erosion have been observed in prior studies involving digitally constrained logistics networks [13].

Switching behaviour is measured using the Switching Rate (SR), calculated as the frequency of partner switching relative to coordination opportunities:

$$SR = \left(\frac{Total\ Switching\ Events}{The\ Coordination\ Opportunities}\right) x\ 100 \quad (1)$$

The frequency of agent switching sharply declines with increasing digital interoperability. In the high-interoperability scenario, there is a 41% reduction in switching events compared to the baseline scenario.

The simulation indicates that the availability of information, responsiveness, and consistency in mutual performance are critical factors in facilitating trust stabilization [8]. Trust values are updated dynamically using a weighted learning function based on recent outcomes, following behavioural agent-based modelling principles from the literature [13]:

$$T_{ij}(t+1) = \alpha \cdot T_{ij}(t) + (1-\alpha) \cdot Outcome_{ij}(t) \quad (2)$$

According to this conclusion, depending on the consistency of agent interaction quality, behavioural adaptation through the evolution of trust can either lessen or increase coordination inefficiencies in fragmented digital systems.

4.2. Network coordination structure

Beyond individual behaviour, the simulation tracks the evolution of coordination structures using the Graph-Based Digital Twin (GBDT) approach. In low interoperability scenarios, the resulting networks are sparse, with low density, limited central connectivity, and a high number of structural holes. These fragmented networks are less cohesive and highly sensitive to disruptions such as node removals or delays. Prior studies have confirmed that such low-density configurations increase system vulnerability and reduce coordination performance [22].

In contrast, scenarios with high interoperability or digitally integrated systems driven by policy show stronger structural features, including higher centrality of customs and ground handling agents, as well as increased modularity and redundancy. These features are consistent with the resilient network topologies documented in adaptive supply chain systems [23]. Network cohesion is evaluated using the Coordination Density (CD) metric, which represents the ratio of active coordination links to the total possible links within the network:

$$CD = \frac{2E}{N(N-1)} \quad (3)$$

where "E" represents the number of active coordination edges and "N" is the number of active agents in the system. In scenarios with high trust and high interoperability levels, the network structure becomes denser, indicating more efficient and stable coordination relationships. This supports the view that digitally supported trust dynamics foster the emergence of resilient coordination topologies within export logistics environments [24].

4.3. Clearance performance and systemic impact

Improvements in behavioural coordination and network structure led to measurable gains in system performance. One of the key indicators, Average Clearance Time (ACT), was used to assess operational efficiency. ACT is calculated as the average time required from the entry of goods until clearance during the simulation:

$$ACT = \frac{1}{n}\sum_{i=1}^{n}(t_{exit,i} - t_{entri,i}) \quad (4)$$

The average clearance time was significantly reduced in the context of high trust and high levels of interoperability, from 72 hours to 46 hours. This represents a 36% improvement. Artificially high levels of interoperability made possible by organizational policy also reduced clearance times but remained slightly less efficient than in the context of high organically established levels of trust. These findings support existing research that improved logistics performance relies on the integrated effects of both technical and behavioural fundamentals [6]. To summarize the systemic impact of each scenario, Table 2 presents four key performance metrics: average clearance time, switching rate, average trust index, and coordination density.

Table 2. Coordination outcomes across simulation scenarios.

Scenario	Avg. Clearance Time (hours)	Switching Rate (%)	Avg. Trust Index (0-1)	Coordination Density
Low Interoperability, Low Trust	72	65	0.42	0.31
Medium Interoperability, Medium Trust	60	38	0.61	0.48
High Interoperability, High Trust	46	14	0.83	0.72
Artificial Interoperability (Policy Scenario)	49	20	0.78	0.68

These findings suggest the need to factor both structural and behavioural aspects of coordination to improve the efficiency of the logistics systems in a digitally fragmented context. A top-down approach to digital connectivity may offer some benefit for improved functionality in a digitally fragmented context but the more robust and optimal systems would develop in conditions where digital connectivity and trust would grow in a self-organized manner. The simulation highlights the truth of the argument that the digital infrastructure would not serve the purpose without strategies for relational continuity and behavioural adaptation [21]. These have very important implications for the export enhancement of newly developed economies in a digitally transformed logistics framework.

5. Discussion

The simulation results demonstrate that trust-based behavioural adaptation functions as a stabilizing mechanism in digitally fragmented logistics environments, particularly under conditions of incomplete interoperability. In such settings, trust mitigates coordination uncertainty by reducing excessive partner switching and reinforcing interaction consistency. This finding aligns with prior studies indicating that relational mechanisms can partially compensate for governance and digital infrastructure gaps in logistics systems [25]. The observed reduction in switching behaviour and the stabilization of trust levels under high-interoperability scenarios indicate a positive feedback loop between digital connectivity and relational trust, which jointly enhances coordination resilience.

From a network engineering perspective, the Graph-Based Digital Twin (GBDT) enables the analysis of how micro-level behavioural adaptation translates into macro-level structural change. Simulation outcomes show that increasing trust and interoperability not only improves bilateral coordination among agents but also induces topological transformation of the coordination network. Higher coordination density, modularity, and redundancy emerge as agents converge toward stable partnerships, consistent with principles of complex adaptive systems and network resilience [24]. These structural properties enhance robustness by reducing dependency on single coordination paths and increasing tolerance to local disruptions.

In contrast, scenarios involving policy-driven artificial interoperability demonstrate that centralized digital integration can accelerate structural cohesion and improve short-term coordination efficiency. However, the resulting network structures tend to be more centralized and broker-dependent, making their resilience contingent on governance reliability. While such configurations exhibit high coordination density, they lack the distributed redundancy characteristic of trust-driven network evolution. This distinction highlights an important engineering trade-off between structural efficiency and systemic robustness. Figure 3 illustrates the contrasting coordination network structures under low and high interoperability conditions. Low-interoperability scenarios are characterized by sparse and fragmented networks with limited connectivity, whereas high-interoperability scenarios exhibit dense, modular structures with multiple interconnected hubs. These visual patterns confirm that digitally supported trust dynamics foster the emergence of stable coordination equilibria, where network cohesion reinforces behavioural stability.

Beyond structural visualization, the aggregated behavioural and structural implications of each simulation scenario are summarized in Table 3. The table consolidates agent behaviour patterns, resulting network structures, and system-level resilience outcomes, providing a comparative synthesis of coordination dynamics across scenarios. By comparing these dimensions, the table clarifies how different combinations of interoperability and trust give rise to distinct coordination regimes, ranging from fragmented and unstable networks to dense and resilient structures. This synthesis supports the interpretation of resilience as an emergent system property shaped by both behavioural adaptation and network configuration.

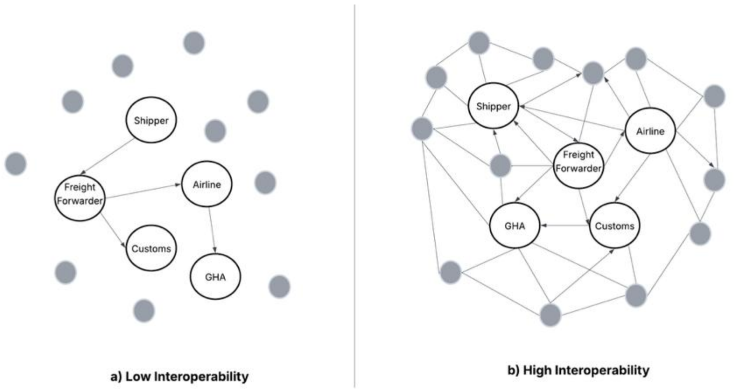

Fig. 3. Coordination network structures under varying interoperability scenarios.

Table 3. Behavioural and structural implications across simulation scenarios.

Scenario	Agent Behaviour	Network Structure	System Resilience
Low Interoperability, Low Trust	High switching, distrust escalation	Sparse, fragmented network	Low
Medium Interoperability, Medium Trust	Conditional cooperation	Moderately connected	Moderate
High Interoperability, High Trust	Stable partnership, adaptive learning	Dense, modular network	High
Artificial Interoperability	Broker-dependent cooperation	Centralized hub structure	High*

*Resilience contingent on governance reliability.

Despite the contributions of the proposed model, several assumptions constrain its generalizability. These include bounded rationality of agents, predefined trust decay and learning parameters, and simplified representations of institutional rigidity. Nevertheless, the simulation framework is grounded in empirical observations from the Soekarno-Hatta International Airport, ensuring contextual relevance to real-world export logistics operations. Overall, the findings emphasize that effective logistics coordination in digitally fragmented environments requires the co-development of technical interoperability and relational governance mechanisms. While top-down digital integration policies can deliver rapid efficiency gains, long-term coordination stability and resilience depend on the endogenous evolution of trust among logistics actors. These insights underscore the importance of integrating behavioural adaptation with digital system design to support the development of competitive and resilient logistics ecosystems in emerging economies such as Indonesia.

6. Conclusions

This research demonstrates that coordination effectiveness in digitally fragmented export logistics environments depends on the combined influence of interoperability and inter-agent trust. A hybrid simulation approach based on the ABM-GBDT model allowed us to reveal that in the export logistics context the upgrading of digitally driven degrees of interoperability cannot ensure a unified network without the support of trust-based relational mechanisms.

Theoretically, this study enriches supply chain literature by integrating behavioural dynamics and network structures in immature digital contexts, offering a new lens for understanding coordination under uneven institutional conditions. From a practical perspective, the findings offer strategic guidance for policymakers and logistics practitioners: digitalization must be accompanied by the development of trust platforms such as shared data protocols, long-term partnerships, and adaptive relational mechanisms. While top-down interoperability can accelerate integration, its effectiveness largely depends on institutional governance and the willingness of actors to actively participate.

Future studies need to collate real-time information sets together with learning algorithms in order to more accurately model the dynamics present in complex behavioural processes. The present research therefore provides a basic framework for the development of efficient logistics networks that can also be more robust in the context of a fragmented digital scenario.

Nomenclature	
ACT	Average Clearance Time (hours)
CD	Coordination Density (dimensionless)
E	Number of active coordination links in the network (count)
I	Interoperability index (dimensionless)
N	Total number of agents in the coordination network (count)
n	Number of shipments processed in the simulation (count)
$Outcome_{ij}$	Outcome of interaction between agent *i* and agent *j* (binary: 0 or 1)
SR	Switching Rate (%)
T_{ij}	Trust level of agent *i* toward agent *j* (dimensionless)
$t_{entri,i}$	Entry time of shipment *i* into the clearance process (hours)
$t_{exit,i}$	Exit time of shipment *i* after clearance completion (hours)
Greek Symbols	
α	Trust learning weight parameter governing trust adaptation (dimensionless)
Abbreviations	
ABM	Agent-Based Modelling
GBDT	Graph-Based Digital Twin
GHA	Ground Handling Agent
INSW	Indonesia National Single Window

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