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Sustainable Cross-Border Maritime Logistics: Platform Environmental Responsibility and Green Governance

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Abstract

Cross-border e-commerce increases the demand for maritime logistics and creates new environmental governance challenges. This study examines how platform environmental responsibility and green incentives influence sustainable governance in cross-border maritime logistics. A multi-actor Stackelberg decision model involving a regulatory authority, a platform, and merchants is developed for three logistics modes. Using industry-informed normalized parameter settings and a feasibility-screened constrained-equilibrium procedure, the analysis compares platform green governance effort, merchant green participation, modeled residual environmental loss, welfare, and profit outcomes. In the documented baseline scenarios, stronger platform responsibility increases platform governance effort, whereas merchant participation and platform profit decline. The welfare response is conditional on the feasible parameter region and must be assessed jointly with responsibility-related cost. Green incentives increase both platform and merchant efforts in the modeled scenarios. These results are comparative model implications under documented parameter assumptions rather than direct empirical estimates of emissions, costs, or policy effects for a particular platform or route.

Keywords: maritime logistics; cross-border e-commerce; platform environmental responsibility; green governance; green incentives

1. Introduction

1.1. Background and Motivation

Cross-border e-commerce is changing international trade through smaller orders, shorter delivery expectations, and more frequent logistics movements. Maritime transport remains important for moving these goods over long distances, but its expansion also raises environmental governance concerns regarding shipping, ports, warehousing, and inland distribution. Sustainable cross-border maritime logistics is therefore not only an operational issue but also a governance issue concerning how responsibility and incentives are distributed between connected actors.

Research on vessel retrofitting, emissions trading, decarbonization costs, and shipping technology innovation shows that maritime transition depends on technical options, as well as policy and incentive design [1–5]. However, in cross-border e-commerce logistics, environmental decisions are influenced not only by carriers but also by digital platforms,

Check for updates

Academic Editor: Tim Gray

Received: 26 May 2026
Revised: 23 June 2026
Accepted: 28 June 2026
Published: 6 July 2026

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merchants, logistics service providers, ports, and regulators. This shifts attention from technology adoption alone to the allocation of responsibility for greener logistics choices.

Ports and information systems provide an operational setting for this governance problem. Studies on smart and green ports, digital governance, shore power, and integrated port energy systems show that infrastructure and coordination jointly affect cleaner maritime operations [6–18]. These studies support a chain-wide view of logistics governance in which platforms and cargo owners can influence the selection and visibility of environmentally preferable services.

Related studies further indicate that fuel choices, congestion, carbon policy, alternative fuels, activity-based emissions measurement, and port energy dispatch can influence maritime environmental outcomes [19–29]. They also show why information visibility is important for policy design. Nevertheless, the present study does not estimate vessel-level energy use or emissions; it models the governance consequences of logistics choices through environmental loss and effort parameters.

Cross-border e-commerce provides a relevant setting for such analysis because platforms can affect logistics mode selection, service standards, data disclosure, and merchant behavior [30–34]. Research on low-carbon supply chain coordination, green trade barriers, transport-sector green innovation, port-area emissions control, and shipping carbon taxation further suggests that responsibility and incentives should be jointly considered [35–39]. Accordingly, this study focused on how platform responsibility and green incentives operate under different maritime logistics organization modes.

1.2. Research Gap and Research Questions

Although previous studies explain many technical and policy paths for maritime sustainability, the allocation of environmental responsibility between platforms and merchants in cross-border maritime logistics remains insufficiently examined. Greener service choices may entail monitoring, information sharing, and coordination costs, and these costs can weaken participation if placed on only one actor.

Digital platforms merit particular attention because they organize order information, match logistics services, and influence merchant choices, even when they do not operate vessels or ports. Stronger platform responsibility may improve platform governance efforts, but it may also encourage merchants to rely on the platform rather than actively participate in green logistics practices.

The effect of responsibility may also depend on the logistics organization. Integrated platform-led logistics, platform-coordinated third-party logistics, and merchant-autonomous third-party logistics differ in their control, information visibility, and merchant autonomy. A uniform responsibility standard may therefore be less suitable than differentiated arrangements linked to the platform's actual control over logistics decisions.

The specific research gap addressed in this paper is therefore the lack of a mode-sensitive governance explanation for whether platform environmental responsibility improves cross-border maritime logistics sustainability without crowding out merchant participation. Existing maritime sustainability studies mainly focus on vessels, fuels, port operations, and carbon policies, while many supply chain governance studies treat logistics as a generic distribution process. This study asks three questions: How does platform environmental responsibility affect platform green governance efforts and merchant green participation? Can green incentives mitigate a possible crowding-out effect on merchant participation? How do these relationships differ across maritime logistics modes with different levels of platform control and information visibility?

1.3. Objectives and Contributions

This study develops a multi-actor decision framework involving a regulatory authority, a digital platform, and merchants, and compares three logistics organization modes: integrated platform-led logistics, platform-coordinated third-party logistics, and merchant-autonomous third-party logistics. The analysis focuses on platform green governance efforts, merchant green participation efforts, modeled environmental loss, and social welfare. Platform green governance efforts refer to maritime logistics actions that guide, monitor, or improve the environmental characteristics of services, such as lower-impact carrier screening, environmental data disclosure, and logistics service coordination; merchant green participation efforts refer to merchants' cooperation in selecting, reporting, and accepting environmentally preferable maritime logistics choices.

The paper makes three contributions. First, it clarifies a responsibility–participation trade-off that is less visible in technology-centered maritime sustainability research: assigning more responsibility to platforms can strengthen platform governance but may reduce merchants' own participation incentives. Second, it extends existing Stackelberg-based green supply chain models by linking platform responsibility to maritime logistics control and information visibility rather than treating the platform as a generic sales intermediary. Third, it compares three cross-border maritime logistics modes and explains why responsibility and incentive arrangements should differ depending on whether the platform directly organizes logistics, coordinates third-party logistics, or primarily provides transaction matching.

The numerical component is designed as an industry-informed, normalized comparative-statics framework rather than a forecasting model for a single observed platform, route, or merchant population. Supplementary Note S1 documents the economic meaning, source category, scaling logic, relative ordering, and candidate range of the principal numerical parameters. Accordingly, the conclusions are interpreted as conditional mechanism-based implications within the documented feasible parameter region.

The remainder of the paper is organized as follows. Section 2 reviews maritime sustainability, green port governance, digital platform participation, and green supply chain incentives. Section 3 develops the three-actor Stackelberg model, defines the three logistics modes, and explains the equilibrium solution procedure. Section 4 reports the numerical analysis, robustness checks, and illustrative real-world comparison. Section 5 summarizes the conclusions, theoretical implications, practical implications, and limitations. Figure 1 summarizes the methodological flow of the study.

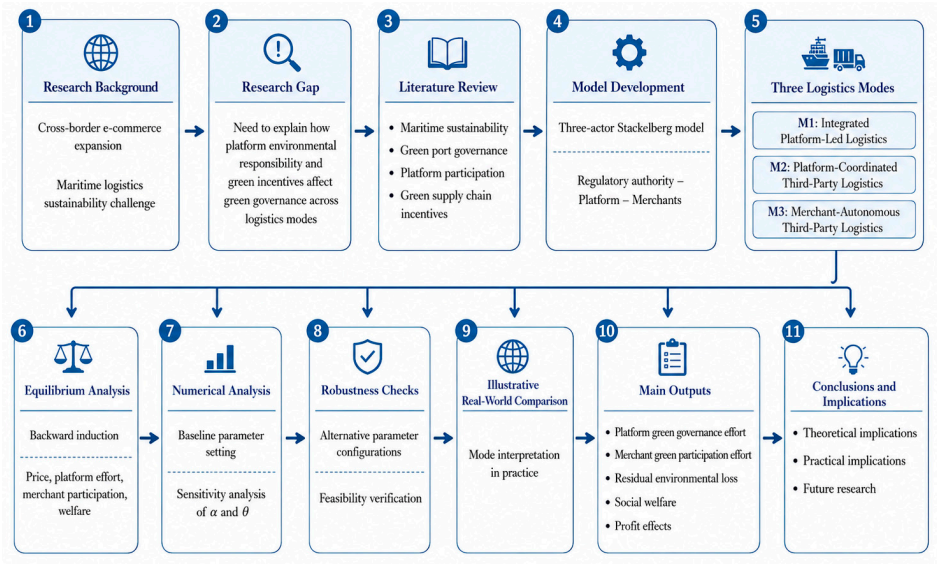


Figure 1. Research framework and methodological flow.

2. Literature Review

2.1. Sustainable Maritime Logistics and Environmental Governance

Sustainable maritime logistics seeks to maintain transport service while reducing environmental burdens across connected ships, ports, terminals, and inland distribution links. For this study, the relevant issue was how logistics actors are encouraged to choose and support environmentally preferable services. The study, therefore, adopted an environmental governance perspective rather than claiming to measure actual energy efficiency or carbon abatement.

Previous studies have provided a strong foundation for understanding maritime decarbonization. Xiao et al. linked sustainable maritime transport to intelligent shipping technology and green port construction, suggesting that smart systems and environmental infrastructure should be developed in tandem [1]. Mallouppas and Yfantis reviewed key technological and policy paths for reducing emissions in the shipping industry. They showed that decarbonization requires a combination of fuel innovation, operational improvement, and regulatory support [2]. These studies indicate that the sustainability of maritime logistics depends not only on individual low-carbon technologies but also on their integration into a broader logistics governance system.

Green fuel and vessel retrofitting are among the most discussed approaches to maritime energy transition. Liang et al. examined retrofitting green-fuel-powered vessels and showed that policy incentives can affect firms' willingness to adopt cleaner vessel technologies [3]. Sun et al. studied liquefied-natural-gas-powered ships under a maritime emissions trading system. They found that shipping alliances may adjust fuel choices and deployment strategies in response to carbon regulation [19]. These findings are relevant to this study because they show that green technology adoption is not only a technical decision but is also shaped by market rules, policy pressure, and cost-sharing mechanisms.

Market-based environmental policies have also received increasing attention. Wang et al. studied sustainable maritime transportation operations under emission trading and showed that carbon market rules can influence operational decisions in maritime transport [4]. Sun et al. compared carbon trading and carbon tax policies in the context of liner speed optimization, highlighting that different policy instruments may elicit distinct operational responses [20]. Wu et al. analyzed the impacts of a shipping carbon tax on dry bulk shipping costs and maritime trade, showing that environmental policies may alter transport costs and trade patterns [35]. These studies suggest that environmental governance in maritime logistics must carefully balance emissions reduction and economic feasibility.

Alternative fuels and energy efficiency standards are another important research stream. Cullinane and Yang reviewed the costs of shipping decarbonization and noted that cost pressures are a major barrier to green transformation [5]. Zhang et al. compared different alternative fuel options based on the carbon intensity index and emphasized that fuel choice should be evaluated from environmental and economic perspectives [21]. Díaz-Secades discussed extending energy efficiency measures to fishing vessels, suggesting that energy regulation can be broadened to encompass a wider range of maritime activities [22]. This cost issue is especially important for cross-border e-commerce logistics, where merchants and platforms are often sensitive to service pricing and delivery times.

Overall, maritime sustainability research clarifies the importance of fuels, carbon policies, and port operations. However, it pays less attention to how platforms and merchants share responsibility for green logistics choices in cross-border e-commerce. This provides the basis for incorporating platform participation and responsibility allocation into the analytical framework.

2.2. Green Port Governance and Environmental Performance

Ports are key nodes in maritime logistics networks, as they connect sea and land transport and bring together shipping companies, terminal operators, customs authorities, logistics firms, and cargo owners. Because ports host many energy-intensive activities, they are important places to reduce emissions and improve environmental performance. Green port governance focuses on how ports use technologies, rules, and coordination mechanisms to reduce environmental impacts while maintaining operational efficiency.

A growing body of literature has examined green port governance from different perspectives. Jugović et al. identified key factors affecting the establishment of green port governance models and emphasized that port sustainability depends on policy design, stakeholder coordination, and environmental monitoring [6]. Chen et al. proposed a governance framework for green and smart ports, suggesting that environmental performance should be linked with digital infrastructure and management innovation [7]. Balić et al. reviewed port sustainability research and found that the port system must simultaneously address environmental, economic, and social issues [40]. These studies provide useful support for viewing ports not only as transport nodes but also as governance platforms for sustainable logistics.

Recent studies have further explored the factors and technologies that support green port transformation. Su et al. focused on digital technology and found that digital tools can support green port transformation by improving information flow and operational control [8]. Paulauskas et al. assessed green transformation factors in ports and found that port sustainability is influenced by infrastructure, management capacity, and stakeholders' willingness to cooperate [9]. This is closely related to the present study because cross-border maritime logistics also depends on information visibility. Without reliable data on routes, energy use, and logistics service choices, it is difficult to fairly assign environmental responsibility.

Shore power is one of the most direct examples of port energy management. Zhang et al. studied the collaborative optimization of shore power and berth allocation and found that economic, environmental, and operational efficiency should be considered together [10]. Rogosic et al. examined shore-side power as a way to reduce greenhouse gas emissions from cruise ships, showing that using electricity during berthing can reduce emissions from onboard engines [11]. Kim analyzed the economic and environmental benefits of shore power use by container ship size and showed that its benefits may differ across vessel types [12]. These findings suggest that port energy management is not a single-technology issue. It requires matching energy infrastructure with vessel operations and berth scheduling.

Integrated energy systems and new energy equipment further expand the meaning of green port governance. Zhao et al. investigated probabilistic load forecasting for green marine shore power systems, which can improve the reliability of energy planning [13]. Tang et al. studied load forecasting and optimal dispatching for integrated port energy systems, showing that demand response can improve port energy utilization [25]. Chu et al. examined the joint scheduling of new energy hybrid tugboats and berths under shore-power constraints, demonstrating that green equipment and operational coordination can improve energy efficiency [26]. These studies show that energy-efficient governance requires infrastructure investment and coordinated operation.

Environmental performance in ports is also influenced by congestion and ship behavior. Liu et al. analyzed carbon emission dynamics under ship in-port congestion and showed that waiting and congestion can increase emissions [27]. Lin et al. used ship activity data to identify the spatial and temporal characteristics of ship carbon emissions in a major port area [28]. Paulauskas et al. proposed methods to decrease emissions from ships in

port areas, further confirming that port-related emissions should be managed through technical and operational measures [36]. These findings support the view that sustainable maritime logistics should focus on the entire ship and cargo movement process, not just long-distance sailing.

The literature on green ports shows that environmental performance depends on infrastructure, data, operational coordination, and stakeholder governance. However, most green port studies take the port or shipping company as the main actor. In cross-border e-commerce logistics, platforms and merchants may also influence cargo flow, delivery standards, and logistics service selection. Therefore, green port governance should be aligned with platform-based logistics governance to better explain environmental responsibility in cross-border maritime logistics.

2.3. Digital Transformation and Platform Participation in Maritime Logistics

Digital transformation has become an important driver of maritime logistics modernization. It can improve visibility, reduce information asymmetry, and support better decisions in shipping and port operations. In the context of sustainability, digitalization is especially important because environmental governance requires reliable data. Without data on transport routes, vessel movements, port operations, and logistics service choices, it is difficult to measure emissions or evaluate green performance.

Heikkilä et al. discussed innovation in smart ports and pointed out that digitalization can support automation, collaboration, and sustainability in container ports [14]. Zeng et al. reviewed enablers and barriers of digitalization in the maritime logistics industry. They found that organizational readiness, data integration, and cooperation between actors are critical for successful digital transformation [15]. Jović et al. conducted a bibliometric and thematic analysis of digitalization in maritime transport and seaports, showing that digital transformation has become a major research direction in maritime studies [16]. These studies show that digitalization is not simply the use of new technology; it also changes how actors communicate, coordinate, and make decisions.

Digital governance is closely related to port and maritime management. Jović et al. used Croatia as a case study to assess digital transformation in the maritime transport sector. They showed that stakeholders may differ in their readiness and ability to adopt digital systems [17]. Gómez Díaz et al. proposed a digital governance approach for the Spanish port system, demonstrating that governance structures must adapt to the growing use of data and digital platforms [29]. These findings are important because cross-border maritime logistics involves actors with different digital capabilities. Large platforms may have strong data systems, while small merchants and logistics providers may lack the resources to track environmental performance.

Energy infrastructure also benefits from digital transformation. Daniel et al. reviewed digital transitions in critical energy infrastructure in maritime ports and emphasized that energy systems, data systems, and port operations are increasingly interconnected [18]. This connection is important for energy-efficient governance because environmental responsibility cannot be assigned only through general rules. It also requires measurable data on energy use, emissions, and operational choices. In this sense, digital infrastructure provides the technical basis for responsibility allocation.

The role of platforms has been discussed more fully in the supply chain literature than in the maritime logistics literature. In platform-based supply chains, platforms may influence supplier behavior through pricing rules, service requirements, data use, and subsidy mechanisms. Mu et al. studied cooperative green technology innovation in an e-commerce sales channel and showed that cooperation between supply chain actors can improve green innovation outcomes [30]. Gao et al. examined the formation of green supply

chains and government subsidy pricing strategies in the presence of an online trading platform, showing that platform participation can shape the effectiveness of government subsidies [31]. These findings suggest that platforms should be treated as active governance actors rather than neutral transaction channels.

In cross-border maritime logistics, platform participation is particularly important. Platforms connect overseas consumers, domestic merchants, logistics providers, ports, and regulatory systems. They often control key information, such as orders, service promises, delivery choices, and customer feedback. Therefore, platforms may guide merchants toward greener logistics options if proper incentives and responsibilities are in place. However, if platform rules focus only on low prices and fast delivery, merchants may choose logistics options with higher environmental impacts. This creates a need to examine how platform responsibility and green incentives jointly affect logistics sustainability.

2.4. Cross-Border E-Commerce Logistics and Green Supply Chain Incentives

Cross-border e-commerce has changed the demand structure of international logistics. Traditional trade often relies on large-scale, relatively stable shipments, while cross-border e-commerce involves smaller orders, more frequent transactions, and flexible delivery requirements. This creates new challenges for logistics organizations and makes environmental governance more complex because cargo flows become more fragmented and more dependent on platform rules.

Li et al. examined the factors and formation path of cross-border e-commerce logistics mode selection. They showed that logistics choices are shaped by service capability, cost, market demand, and platform conditions [32]. He et al. analyzed the relationship between international logistics and cross-border e-commerce trade and found that logistics capability and trade development are closely linked [33]. These studies provide the basic context for this study: cross-border e-commerce logistics is not only a supporting service for trade but also a key factor affecting trade efficiency and sustainability.

Green trade barriers and environmental requirements have complicated logistics decisions. Xu et al. studied green packaging and self-logistics decisions in cross-border e-commerce under green trade barriers, showing that firms may adjust logistics strategies when facing environmental constraints [37]. This study is especially relevant because it connects cross-border e-commerce with green logistics choices. However, the study focuses more on packaging and self-logistics decisions, whereas the present study further emphasizes maritime logistics, energy-efficient governance, and responsibility allocation among regulators, platforms, and merchants.

Green supply chain research provides useful theoretical support for this study. Li et al. examined green technology investment, data-driven marketing, and government subsidies in a platform supply chain. They showed that data and subsidies can jointly influence green investment decisions [34]. Ran and Xu studied low-carbon supply chain coordination under carbon tax and government subsidy policies, indicating that policy tools can improve coordination when properly designed [38]. Li and Li provided evidence from China's transport sector showing that green technology innovation can promote sustainable supply chain development [39]. These studies suggest that environmental policy should combine pressure and support. Responsibility alone may not be sufficient if actors face high costs or weak incentives.

Government subsidies and green incentives are particularly important in platform-based logistics systems. Gao et al. showed that government subsidy pricing strategies can influence the formation of green supply chains when an online trading platform is involved [31]. This implies that platform decisions and government incentives may interact. If a platform has stronger environmental responsibility but lacks the corresponding

incentive, it may face higher costs and be less willing to invest in green governance. If merchants receive incentives but platform rules do not support green logistics, merchant efforts may also be weakened. Therefore, responsibility allocation and incentives should be designed together.

In this study, the incentive coefficient θ is therefore interpreted as a non-fiscal behavioral benefit rather than a direct public subsidy. It represents certification value, green reputation, priority exposure in platform search or recommendation systems, preferential access to greener logistics services, and recognition for reliable environmental reporting. Such mechanisms can be incorporated into payoff functions because they improve the perceived private returns from green governance or participation, even when no direct cash transfer is made. This interpretation also distinguishes the baseline welfare calculation from a fiscal subsidy model; if θ were implemented as a government payment, the corresponding fiscal cost would need to be deducted from social welfare.

For this study, cross-border maritime logistics involved three related decisions: regulators decide how much environmental responsibility should be assigned to platforms and how much incentive should be provided; platforms decide how much effort to put into green governance, such as selecting low-carbon logistics providers, monitoring emissions, and guiding merchants; and merchants decide whether to participate in green logistics practices, such as choosing cleaner services or reducing unnecessary logistics-related waste. These decisions are connected, and a change in one actor's behavior may affect the others.

2.5. Research Positioning and Analytical Focus

The reviewed literature establishes that maritime environmental outcomes are influenced by technologies, port operations, digital information, and policy instruments. It also suggests that platforms can influence green supply chain decisions. What remains less clear is whether assigning environmental responsibility to a platform improves logistics governance without weakening merchant participation, particularly when the platform has different levels of logistics control.

A more focused comparison with game-theoretic green supply chain studies further clarifies this research position. Existing Stackelberg and supply chain governance models have examined government subsidies, carbon taxes, platform participation, green technology investment, and emission-control targets [41–43]. These studies establish that pressure to take responsibility and incentive support can alter firms' environmental decisions. Still, they generally treat logistics networks as generic production or distribution systems and do not explicitly compare maritime logistics modes with different platform control and information visibility.

Accordingly, the present model departs from prior studies in two respects. First, it treats the platform not only as a trading intermediary but also as a governance actor that may influence maritime logistics service selection, environmental information disclosure, and merchant participation. Second, it compares integrated platform-led logistics, platform-coordinated third-party logistics [44–46], and merchant-autonomous third-party logistics, thereby linking responsibility allocation to the degree of logistics control rather than assuming a uniform platform role.

This study addressed that mechanism through a multi-actor decision model. Rather than estimating actual fuel use or emissions, it evaluated how responsibility allocation and green incentives affect governance effort, participation effort, residual environmental loss, and social welfare across three logistics modes. The following section elaborates on the model and defines the accounting boundaries used in the numerical comparison.

3. Model Development

This section develops an analytical framework for green governance in cross-border maritime logistics. The model represents residual environmental loss associated with insufficiently governed logistics choices and examines how a regulatory authority, a digital platform, and merchants respond to responsibility and incentive settings.

3.1. Research Setting and Decision Structure

Cross-border e-commerce maritime logistics involves regulatory authorities, digital platforms, merchants, logistics service providers, ports, and consumers. The regulatory authority seeks to improve social welfare by reducing residual environmental loss while avoiding excessive governance costs. The platform connects orders, logistics services, and environmental information, whereas merchants choose prices and their level of participation in green logistics practices.

The model is formulated as a three-level Stackelberg decision system with incomplete information in M2 and M3. In the first stage, the regulatory authority selects the platform environmental responsibility coefficient $\alpha \in [0, 1]$. In contrast, the green incentive coefficient θ is treated as an externally specified policy-setting parameter in the scenario analysis. In the second stage, the platform observes the prior type distribution ρ_0, but not the type of each individual merchant. It selects its green governance effort $\beta \in [0, 1]$ and, where applicable, the logistics-related charge ω. In the third stage, each merchant observes its own participation type and chooses the common market price p and its type-specific participation effort $\delta_i \in [0, 1]$, where $i \in \{H, L\}$. In M1, participation is directly observable and is represented by a single merchant effort δ. The platform and regulatory authority set expectations for merchant outcomes based on the prior type distribution.

To keep the analysis focused on governance rather than engineering measurement, the model uses cost and loss parameters instead of a vessel-level fuel or emissions function. C_h denotes the regulatory intervention cost, C_p denotes the platform's responsibility-related compliance or remediation cost, C_m denotes the corresponding merchant cost, and L denotes the direct residual environmental loss when insufficiently governed logistics behavior occurs. These terms represent modeled economic consequences and should not be read as measured carbon emissions.

Although L is modeled in an aggregate form, it has a maritime-specific interpretation in this paper. It refers to residual environmental loss associated with cross-border maritime logistics choices, including vessel or carrier selection, shipping-service frequency, inefficient routing and transshipment, port waiting and congestion, insufficient use of shore power or cleaner port services, and weak disclosure of logistics-related environmental information. The model, therefore, does not estimate vessel-level emissions directly. Still, it interprets environmental loss as a governance consequence of maritime logistics decisions that platforms and merchants can influence through service selection, information disclosure, and participation rules.

Parameter Scaling, Information Structure, and Feasible Strategy Set

The numerical quantities in the model are expressed on a common normalized scale. The demand term Q_0 is a representative market-size index; the operating-cost, logistics-charge, responsibility-cost, environmental-loss, and incentive terms are normalized payoff components; and the effort-cost coefficients represent the curvature of increasing governance and participation costs. These inputs are not literal monetary amounts or literal shipment counts for a single firm, route, or port. Public industry information and related literature are used to discipline their economic meaning, relative magnitude, and candidate range, as documented in Supplementary Note S1.

The strategy space is explicitly constrained. Candidate parameter values are selected from the documented normalized ranges and are then screened ex post for economic admissibility. Thus, positive demand and bounded effort are verification conditions for a candidate equilibrium, rather than the sole basis for selecting a parameter value.

$$\mathcal{F} = \{(\alpha, \beta, \delta_H, \delta_L, p, \omega) : 0 \leq \alpha \leq 1,\ 0 \leq \beta \leq 1,\ 0 \leq \delta_i \leq 1, p \geq 0, \omega \geq 0, Q > 0\}.$$

For M2 and M3, the prior probability ρ_0 is common knowledge to the platform and regulator but does not reveal an individual merchant's type. Conditional type-specific effort responses are therefore evaluated separately, whereas demand, environmental loss, platform return, expected merchant return, and welfare are formed by aggregating those responses with ρ_0 and $1 - \rho_0$.

3.2. Logistics Modes and Basic Assumptions

Two logistics arrangements are considered: under S, the platform directly manages its own logistics; under N, it relies on cooperating third-party logistics providers. For merchant logistics choices, J indicates a logistics service organized or designated by the platform, while T indicates a third-party service independently selected by the merchant. X refers to a business operated within the platform-led arrangement, and Y refers to external merchants trading through the platform.

Three representative modes are examined: M1 involves integrated platform-led logistics, in which the platform organizes logistics and can directly observe the merchant's green participation effort, while the platform and merchant remain separable payoff participants in the model. M2 involves platform-coordinated third-party logistics: external merchants use a platform-coordinated logistics service. M3 involves merchant-autonomous third-party logistics: external merchants independently select logistics services, while the platform primarily provides transaction matching. The modes, therefore, represent different levels of logistics control and information visibility.

The model makes five assumptions: First, the regulatory authority maximizes social welfare, whereas the platform and merchants maximize their own returns. Second, decisions follow the sequential order described above. Third, higher β and δ reduce the likelihood that an undesirable environmental outcome will remain uncontrolled. Fourth, consumers value visible green logistics performance. Fifth, θ represents a non-fiscal incentive benefit, such as service priority, certification value, or market recognition; a government subsidy budget is not modeled in the baseline welfare calculation.

In this maritime logistics setting, β denotes platform actions such as screening lower-impact carriers, requiring environmental data from logistics providers, coordinating port and warehouse information, guiding merchants toward consolidated or lower-emission shipping options, and improving visibility into cleaner maritime services. The merchant effort δ denotes cooperation in choosing greener maritime logistics options, providing shipment information, accepting verified low-carbon service alternatives, avoiding unnecessary fragmented shipments, and using platform-recognized maritime logistics channels when feasible. These interpretations embed the abstract effort variables in maritime logistics governance rather than treating them as generic supply chain efforts.

3.3. Green Participation, Demand, Environmental Loss, and Social Welfare

In M2 and M3, external merchants may differ in their willingness or ability to adopt green logistics practices. The platform observes the common prior proportion ρ_0 of high-participation merchants, but it cannot perfectly observe the type of an individual merchant. A high-participation merchant (H) and a low-participation merchant (L) therefore choose

their own conditional participation efforts, δ_H and δ_L, while the platform anticipates their aggregate effect through expected participation.

$$E[\delta] = \rho_0 \delta^H + (1 - \rho_0)\delta^L \tag{1}$$

where $\rho_0 = Pr(H)$ is the prior proportion of high-participation merchants and $1 - \rho_0 = Pr(L)$. The values δ_H and δ_L are conditional type-specific participation efforts. The corresponding expected probability that merchant participation fails to prevent an undesirable environmental outcome is

$$E[1 - \delta] = \rho_0 \left(1 - \delta^H\right) + (1 - \rho_0)\left(1 - \delta^L\right) \tag{2}$$

Consumers are assumed to respond to product price and visible green logistics performance. For M2 and M3, performance includes platform governance and expected merchant participation; in M1, merchant effort is directly observable, and $E[\delta]$ is replaced by δ. The market demand Q is a common market-level quantity. In M2 and M3, the type-specific merchant payoff is interpreted as the payoff of a representative merchant conditional on type; it is not added twice as two separate full-market payoffs. Instead, the expected merchant return is weighted by probability before welfare is calculated.

Accordingly, for M2 and M3, the expected merchant return is calculated as the type-probability-weighted aggregation of the two conditional representative merchant returns. The same prior weights enter expected participation and expected failure probability, which in turn determine market demand, residual environmental loss, the platform's anticipated return, and social welfare. The prior probability, therefore, affects leader decisions through expected aggregate outcomes, while each merchant's effort decision remains conditional on its own type-specific cost coefficient.

$$E[\pi_{\mathrm{m}}] = \rho_0 \pi_{\mathrm{m}},^{\mathrm{H}} + (1 - \rho_0)\pi_{\mathrm{m}},\mathrm{L}$$

$$Q = Q_0 - \eta p + \tau(\beta + E[\delta]), \quad Q > 0 \tag{3}$$

where Q_0 is the basic market demand, η is the price sensitivity coefficient, and τ is the consumer preference coefficient for visible green logistics performance. The consumer surplus is represented as

$$CS = \frac{Q^2}{2\eta} \tag{4}$$

The residual environmental loss represents the modeled social cost of environmentally undesirable logistics outcomes that remain uncontrolled. In M1, the platform directly observes merchant participation, and the loss expression is

$$Loss^{M1} = (L + C_h)(1 - \delta)(1 - \beta) \tag{5}$$

In M2 and M3, the platform faces merchant heterogeneity and uses the expected failure probability. The residual environmental loss is therefore expressed as

$$Loss^{M2/M3} = (L + C_h)E[1 - \delta](1 - \beta) \tag{6}$$

In both expressions, L is the direct residual environmental loss, and C_h is the cost of regulatory intervention following an uncontrolled outcome. The social welfare is defined as.

Conceptually, L can be understood as the combined residual loss from three maritime logistics components: sea-transport emissions and service selection; port and terminal operation impacts; and inland connection or warehousing impacts induced by cross-border

maritime logistics decisions. A higher β reduces this loss by improving platform coordination and information governance, while a higher δ reduces it by increasing merchant cooperation with greener logistics choices. This treatment keeps the model tractable while making clear that the environmental loss is anchored in maritime logistics processes.

$$\mathrm{SW} = \pi_p + \pi_m + \mathrm{CS} - \mathrm{Loss} \tag{7}$$

In Equation (7), π_p denotes the platform return. In M1, π_m denotes the directly observed merchant return; in M2 and M3, π_m is shorthand for the expected merchant return $E[\pi_m] = \rho_0 \pi_{m,H} + (1-\rho_0)\pi_{m,L}$. CS is consumer surplus, and $Loss$ is residual environmental loss. The logistics service provider is not treated as an independent strategic decision maker in the revised model. Logistics fees are included in the platform and merchant payoff functions, and therefore, an undefined logistics-provider payoff term is not included in welfare. The terms C_p and C_m are interpreted as real compliance or remediation costs already reflected in private returns, rather than as transfer payments. Likewise, $\theta\beta$ and $\theta\delta$ are modeled as non-fiscal incentive benefits; if θ were implemented as a public subsidy, a corresponding fiscal cost would need to be added to the welfare calculation.

The variables and parameters used in the model are summarized in Table 1.

Table 1. Symbols and definitions for the sustainable maritime logistics model.

Category	Symbol	Meaning in the Present Study
Decision variable	α	Platform share of residual environmental responsibility-related cost
Decision variable	β	Platform green governance effort
Decision variable	δ	Merchant green participation effort; directly observed in M1
Decision variable	p	Unit product price determined by the merchant or integrated operator
Decision/parameter	ω	Platform commission or service charge; endogenous in M2 and exogenous in M3
State/type	δ_H, δ_L	Conditional participation efforts of high- and low-participation merchants in M2/M3; the platform observes only their prior distribution.
Welfare term	CS	Consumer surplus
Cost parameter	c_m	Merchant unit operating and supply cost
Cost parameter	c_l	Unit logistics service fee paid by a merchant
Cost parameter	c_t	Unit cost paid by the platform to a third-party logistics provider
Cost parameter	k_p	Platform green governance cost coefficient
Cost parameter	k_m, k_{mH}, k_{mL}	Green participation cost coefficients for merchants
Cost parameter	C_p	Platform unit responsibility-related compliance or remediation cost
Cost parameter	C_m	Merchant unit responsibility-related compliance or remediation cost
Cost parameter	C_h	Regulatory unit intervention cost following an uncontrolled outcome

Table 1. *Cont.*

Category	Symbol	Meaning in the Present Study
Loss parameter	L	Direct unit residual environmental loss from an uncontrolled outcome
Market parameter	ρ_0	Prior probability of a high-participation merchant; used to aggregate $E[\delta]$, $E[1-\delta]$, $E[\pi_m]$, demand, loss, and welfare in M2/M3.
Policy parameter	θ	Green incentive benefit coefficient; treated as non-fiscal in baseline welfare
Market parameter	Q_0	Basic market demand
Preference parameter	η	Consumer price sensitivity coefficient
Preference parameter	τ	Consumer preference coefficient for visible green logistics performance
State/expectation	$E[\delta]$	Expected participation in M2/M3: $E[\delta] = \rho_0\delta_H + (1-\rho_0)\delta_L$; equals δ in M1.
State/expectation	$E[1-\delta]$	Expected failure probability in M2/M3: $E[1-\delta] = \rho_0(1-\delta_H) + (1-\rho_0)(1-\delta_L)$.
Welfare term	π_p, π_m	Platform and merchant returns; π_m denotes $E[\pi_m] = \rho_0\pi_{m,H} + (1-\rho_0)\pi_{m,L}$ in M2/M3. The logistics-provider payoff is not an independent welfare term.

3.4. Payoff Functions Under the Three Logistics Modes

The payoff functions translate the governance process into economic terms. Each participant's payoff comprises operating returns, green effort costs, responsibility-related costs arising from residual environmental risk, and non-fiscal incentive benefits associated with green action. The modes differ in their platform logistics control and logistics-related returns, allowing the model to compare how responsibility performs under different governance capacities.

3.4.1. Integrated Platform-Led Logistics Mode (M1)

In M1, the platform directly manages logistics and can observe the merchant's participation effort. To avoid double-counting of sales revenue and operating cost, the revised payoff structure separates the merchant product margin from the platform logistics-service margin. The merchant receives the product sales margin after paying the logistics service fee. In contrast, the platform obtains the logistics-service margin and bears the platform-side governance and responsibility-related costs. Equation (8) defines the merchant return, Equation (9) defines the platform return, and Equation (10) defines welfare in the integrated arrangement.

$$\pi_m^{M1} = (p - c_m - c_l)Q - \frac{1}{2}k_m\delta^2 - (1-\alpha)C_m(1-\delta)(1-\beta) + \theta\delta \tag{8}$$

$$\pi_p^{M1} = (c_l - c_t)Q - \frac{1}{2}k_p\beta^2 - \alpha C_p(1-\delta)(1-\beta) + \theta\beta \tag{9}$$

$$\max \mathrm{SW}^{\mathrm{M1}} = \pi_{\mathrm{p}}^{\mathrm{M1}} + \pi_{\mathrm{m}}^{\mathrm{M1}} + \mathrm{CS} - \mathrm{Loss}_{\mathrm{M1}} \tag{10}$$

In Equations (8) and (9), Q is generated by the same demand function used throughout the model, but revenue is not counted twice. The merchant receives $(p - c_m - c_l)Q$, whereas the platform receives $(c_l - c_t)Q$ from organizing logistics services. The quadratic

terms represent increasing effort costs. The residual-risk term $(1-\delta)(1-\beta)$ means that responsibility-related costs arise only if merchant participation and platform governance are both insufficient. The terms $\theta\delta$ and $\theta\beta$ represent the modeled non-fiscal benefits of green action.

3.4.2. Platform-Coordinated Third-Party Logistics Mode (M2)

In M2, external merchants operate through the platform and use logistics services coordinated by it. Equation (11) describes a conditional representative merchant payoff for type $i \in \{H, L\}$, where $k_{m,i}$ takes k_{mH} or k_{mL} according to merchant type. Equation (12) describes the platform's payoff, which is a function of total market demand Q and anticipated participation. Equation (13) defines welfare using $E[\pi_m]$, not the unweighted sum of two full-market merchant payoffs.

$$\pi_{m,i}^{M2} = (p - c_m - c_l - \omega)Q - \frac{1}{2}k_{m,i}\delta_i^2 - (1-\alpha)C_m(1-\delta_i)(1-\beta) + \theta\delta_i, \quad i \in \{H, L\} \tag{11}$$

$$\pi_p^{M2} = (\omega + c_l - c_t)Q - \frac{1}{2}k_p\beta^2 - \alpha C_p E[1-\delta](1-\beta) + \theta\beta \tag{12}$$

$$\max \mathrm{SW}^{\mathrm{M2}} = \pi_{\mathrm{p}}^{\mathrm{M2}} + \mathrm{E}\left[\pi_{\mathrm{m}}^{\mathrm{M2}}\right] + \mathrm{CS} - \mathrm{Loss}_{\mathrm{M2}} \tag{13}$$

Unlike M1, M2 contains external merchants whose participation effort is imperfectly observed. The platform anticipates the conditional responses δ_H and δ_L through ρ_0; therefore, the expected failure term, expected demand component, expected merchant return, and welfare calculation use the same probability weights. M2 represents a setting in which platform responsibility is accompanied by coordination capacity but not full information.

3.4.3. Merchant-Autonomous Third-Party Logistics Mode (M3)

In M3, external merchants select third-party logistics services independently. Equation (14) gives the platform payoff based mainly on commission income, governance costs, anticipated responsibility-related costs, and incentive benefits; Equation (15) gives the conditional representative merchant payoff for $i \in \{H, L\}$; and Equation (16) defines welfare using $E[\pi_m]$. Here, ω is treated as an exogenous commission or service-charge parameter rather than a platform logistics pricing decision.

$$\pi_p^{M3} = \omega Q - \frac{1}{2}k_p\beta^2 - \alpha C_p E[1-\delta](1-\beta) + \theta\beta \tag{14}$$

$$\pi_{m,i}^{M3} = (p - c_m - c_l - \omega)Q - \frac{1}{2}k_{m,i}\delta_i^2 - (1-\alpha)C_m(1-\delta_i)(1-\beta) + \theta\delta_i, \quad i \in \{H, L\} \tag{15}$$

$$\max \mathrm{SW}^{\mathrm{M3}} = \pi_{\mathrm{p}}^{\mathrm{M3}} + \mathrm{E}\left[\pi_{\mathrm{m}}^{\mathrm{M3}}\right] + \mathrm{CS} - \mathrm{Loss}_{\mathrm{M3}} \tag{16}$$

M3 represents decentralized logistics governance: the platform may assume environmental responsibility but has weaker direct influence over service selection and information collection. The type prior ρ_0 remains relevant because the platform anticipates $E[\delta]$ and $E[1-\delta]$ when evaluating governance effort and expected responsibility exposure. The comparison with M2 therefore isolates how governance outcomes vary when platform responsibility is not accompanied by the same degree of logistics coordination.

3.5. Equilibrium Solutions

The three-level Stackelberg model is solved by backward induction over the constrained strategy set defined above. For every mode, the analysis first derives an unconstrained first-order candidate for each follower and leader decision. The projection notation $\Pi_[0,1](\cdot)$ is used only as compact notation for the explicit candidate classification stated

below; it does not replace the comparison of interior and active-boundary candidates. Each candidate is retained only when it satisfies the demand-feasibility condition $Q > 0$ and the relevant price and charge constraints.

$$x^* = 0 \; if \; \widetilde{x} \leq 0; \; x^* = \widetilde{x} \; if \; 0 < \widetilde{x} < 1; \; x^* = 1 \; if \; \widetilde{x} \geq 1, \; for \; x \in \{\beta, \delta_H, \delta_L\}.$$

For each value of α and θ, the computational procedure compares the admissible interior candidate with the lower- and upper-boundary candidates for β and δ_i. If a candidate produces $Q \leq 0$, it is classified as infeasible and is not used in the reported comparative-statics results. When more than one admissible candidate remains, the platform and regulatory choices are evaluated using the corresponding anticipated payoffs and welfare values. The reported baseline results are therefore restricted to the documented parameter region in which the candidate-selection routine identifies a single feasible welfare-maximizing outcome.

3.5.1. Equilibrium Under M1

Equations (17)–(20) report the corrected equilibrium price, merchant green participation effort, platform green governance effort, and welfare-based platform responsibility coefficient in M1. Because participation is directly observable in this mode, Equation (18) uses a single merchant participation effort δ^*_{M1}. Equation (20) is expressed as a bounded welfare maximization problem rather than an unsupported closed-form expression.

$$p^*_{M1} = \frac{Q_0 + \eta(c_m + c_l) + \tau(\beta + \delta)}{2\eta} \tag{17}$$

$$\delta^*_{M1} = \Pi_{[0,1]}\left\{\frac{(1-\alpha)C_m(1-\beta) + \theta + \tau(p - c_m - c_l)}{k_m}\right\} \tag{18}$$

$$\beta^*_{M1} = \Pi_{[0,1]}\left\{\frac{\alpha C_p(1-\delta) + \theta + \tau(c_l - c_t)}{k_p}\right\} \tag{19}$$

$$\alpha^*_{M1} = \arg\max_{\alpha \in [0,1]} SW_{M1}(\alpha, \theta) \tag{20}$$

Equation (17) links price with demand, operating cost, and visible green logistics performance. For M1, the joint merchant problem in p and δ is locally concave in the interior whenever $2\eta k_m > \tau^2$, because the own second derivatives are negative and the determinant of the merchant Hessian is positive under this condition. Equation (18) gives the conditional interior participation candidate, and the constrained response is obtained by comparing it with $\delta = 0$ and $\delta = 1$. Equation (19) gives the platform's conditional interior governance candidate, because the platform's own effort cost is quadratic; its curvature is negative when $k_p > 0$. These expressions are evaluated only under $Q > 0$, $\beta \in [0, 1]$, and $\delta \in [0, 1]$.

3.5.2. Equilibrium Under M2

Equations (21)–(25) describe the corrected equilibrium decisions in M2, where the platform coordinates third-party logistics services and external merchants, both of which remain heterogeneous decision makers. Equation (21) gives the type-specific merchant participation solution for $i \in \{H, L\}$; Equation (22) gives the price solution using expected participation $E[\delta]$; Equation (23) gives the platform-governance solution; Equation (24)

defines the logistics-related charge as a platform optimization problem; and Equation (25) gives the welfare-based responsibility coefficient.

$$\delta_{i,M2}^{*} = \Pi_{[0,1]}\left\{\frac{(1-\alpha)C_m(1-\beta)+\theta+\tau(p-c_m-c_l-\omega)}{k_{m,i}}\right\}, \quad i \in \{H,L\} \tag{21}$$

$$p_{M2}^{*} = \frac{Q_0+\eta(c_m+c_l+\omega)+\tau(\beta+E[\delta])}{2\eta} \tag{22}$$

$$\beta_{M2}^{*} = \Pi_{[0,1]}\left\{\frac{\alpha C_p E[1-\delta]+\theta+\tau(\omega+c_l-c_t)}{k_p}\right\} \tag{23}$$

$$\omega_{M2}^{*} = \underset{\omega\geq 0}{\operatorname{argmax}}\,\pi_p^{M2}(\omega,\beta,E[\delta]) \tag{24}$$

$$\alpha_{M2}^{*} = \arg\max_{\alpha\in[0,1]} \mathrm{SW}_{M2}(\alpha,\theta) \tag{25}$$

The expressions clarify the platform's dual role in M2. Conditional on type i, the merchant response is locally concave when $2\eta k_{m,i} > \tau^2$ and $k_{m,i} > 0$. The platform then anticipates the probability-weighted responses through $E[\delta]$ and $E[1-\delta]$. Candidate solutions are classified as interior, lower-boundary, upper-boundary, or infeasible according to the constrained-response rule, rather than being interpreted automatically as unrestricted closed-form equilibria.

3.5.3. Equilibrium Under M3

Equations (26)–(29) report the corrected equilibrium results in M3, where merchants retain autonomy in selecting third-party logistics services, and the platform primarily receives commission income. The expressions retain the distinction between high- and low-participation merchants and use expected merchant participation in the demand, loss, and welfare terms.

$$p_{M3}^{*} = \frac{Q_0+\eta(c_m+c_l+\omega)+\tau(\beta+E[\delta])}{2\eta} \tag{26}$$

$$\delta_{i,M3}^{*} = \Pi_{[0,1]}\left\{\frac{(1-\alpha)C_m(1-\beta)+\theta+\tau(p-c_m-c_l-\omega)}{k_{m,i}}\right\}, \quad i \in \{H,L\} \tag{27}$$

$$\beta_{M3}^{*} = \Pi_{[0,1]}\left\{\frac{\alpha C_p E[1-\delta]+\theta+\tau\omega}{k_p}\right\} \tag{28}$$

$$\alpha_{M3}^{*} = \arg\max_{\alpha\in[0,1]} \mathrm{SW}_{M3}(\alpha,\theta) \tag{29}$$

Equations (26) and (27) show how price and type-specific merchant participation respond to incentives, consumer preferences, and responsibility allocation, while Equation (28) describes platform governance effort under commission-based returns. The same conditional-concavity and boundary-candidate checks used in M2 apply to the type-specific merchant responses in M3. Equation (29) gives the responsibility coefficient as the solution to a bounded welfare maximization problem. The comparison with M1 and M2 is interpreted as a model-based comparison of governance arrangements, not as direct evidence of actual energy savings or emission reductions.

Taken together, the equilibrium expressions identify three relationships to be evaluated in Section 4. First, increasing platform responsibility is expected to strengthen platform green governance because platforms bear a greater share of environmental risk. Second, this shift in responsibility may reduce merchants' own participation incentives if their residual environmental burden decreases. Third, green incentives can support platform governance and merchant participation, thereby helping to reduce the tension between

responsibility transfer and joint environmental action. The comparison across M1, M2, and M3 allows these relationships to be evaluated under different levels of logistics control.

4. Results and Analysis

This section evaluates the equilibrium relationships described in Section 3 through feasibility-screened numerical sensitivity analysis. It compares changes in platform green-governance effort, merchant green-participation effort, modeled residual environmental loss, social welfare, and participant returns under documented normalized parameter settings. All numerical findings are interpreted as conditional comparative model outcomes within the admissible parameter region, rather than as empirical estimates of actual energy use, emissions, transaction costs, or policy effects for a particular platform or route.

4.1. Baseline Settings and Analytical Scenarios

Table 2 reports the baseline values used in the numerical analysis. These values are industry-informed normalized calibration parameters rather than empirical carbon inventories, literal transaction records, or direct estimates for a single platform or route. Supplementary Note S1 documents the economic meaning, source category, reference scale where applicable, relative-ordering logic, and candidate range of each key input. The baseline values preserve economically motivated relationships, including $L > C_h$, $C_m > C_p$, $c_t < c_l$, and $k_{mH} < k_m < k_{mL}$.

Table 2. Baseline parameter settings for the numerical sensitivity analysis.

Symbol	Value	Interpretation	Symbol	Value	Interpretation
Q_0	180	Normalized baseline market-size index; industry-informed scaling with Q > 0 checked ex post	c_t	3	The platform's third-party logistics cost
η	0.8	Consumer price sensitivity	ω	5	Fixed commission in M3; M2 solves for ω*
τ	0.4	Preference for greener logistics	k_m	600	M1 normalized convex merchant participation-cost coefficient; candidate range documented in Supplementary Note S1; bounded response checked ex post
L	1000	Direct unit residual environmental loss	k_{mH}	500	High-participation merchant normalized cost coefficient; kmH < km < kmL; candidate range documented in Supplementary Note S1
C_h	300	Regulatory intervention cost	k_{mL}	800	Low-participation merchant normalized cost coefficient; candidate range documented in Supplementary Note S1

Table 2. *Cont.*

Symbol	Value	Interpretation	Symbol	Value	Interpretation
C_p	15	Platform responsibility-related remediation cost	k_p	600	Normalized convex platform governance-cost coefficient; candidate range documented in Supplementary Note S1; bounded response checked ex post
C_m	100	Merchant responsibility-related remediation cost; normalized parameter with Cm > Cp	ρ_0	0.6	Prior high-participation merchant share; used to aggregate expected demand, loss, merchant return, and welfare
c_m	100	Merchant operating and supply cost	θ	2	Baseline non-fiscal incentive benefit; varied from 0 to 5 in the focal scenario
c_l	5	Merchant logistics service fee	α	0.5	Neutral midpoint responsibility benchmark; varied from 0 to 1 in the focal scenario

Notes: All values are expressed on the common normalized scale used in the model. Supplementary Note S1 provides the parameter-level source category, scaling rationale, relative-ordering logic, and candidate range. Feasibility checks are conducted after candidate values are specified.

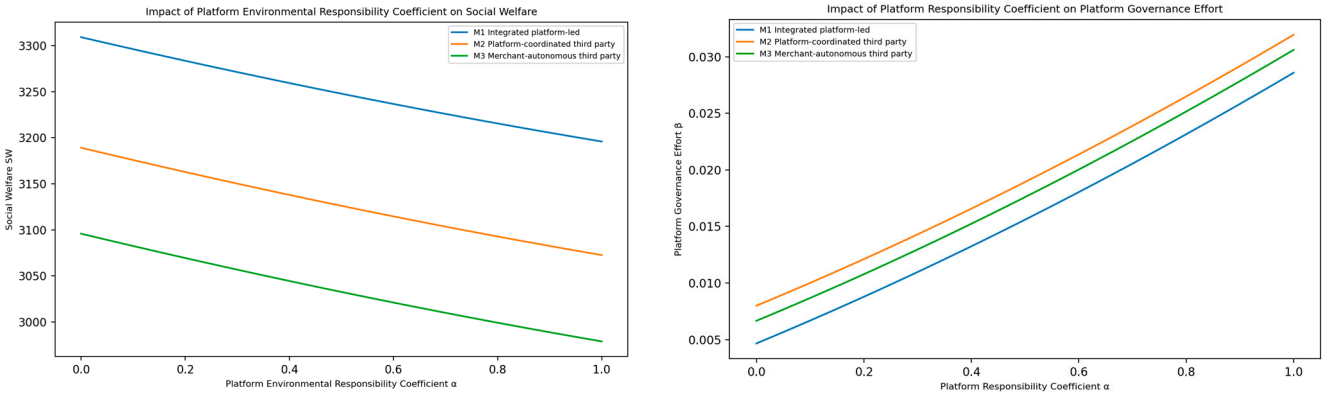
Candidate parameter ranges are specified from the documented literature- and industry-informed relationships before feasibility screening. The positive-demand and bounded-effort requirements are subsequently applied to identify admissible equilibria; they are not the sole basis for selecting baseline values. Two focal sensitivity scenarios are reported. In the first scenario, θ is maintained at its baseline level of 2 while α varies from 0 to 1. In the second scenario, α is fixed at 0.5 while θ varies from 0 to 5. For each scenario, the computation follows the same sequence: parameter input, conditional candidate solution, boundary and feasibility verification, payoff and welfare calculation, and figure generation.

4.2. Effects of Platform Environmental Responsibility

4.2.1. Social Welfare

Figure 2a reports the modeled relationship between platform environmental responsibility and social welfare. Under the displayed baseline parameter setting, social welfare declines as α increases in all three modes. Thus, the numerical result does not support a general claim that transferring a larger share of residual responsibility to the platform automatically improves welfare. In the baseline range, the additional responsibility and governance-cost burden outweighs the modeled reduction in residual environmental loss. The welfare effect must therefore be assessed jointly with the documented parameter region and active feasibility constraints.

M1 remains above M2 and M3 across the examined range of α, where M1's integrated logistics coordination and direct observation of merchant participation reduce the coordination gaps and create the highest welfare baseline. The lower values of M2 and M3 should be interpreted only as comparative modeled outcomes under the assumed parameters, not as observed welfare losses in a real market.



(**a**) (**b**)

Figure 2. (**a**) Effect of the platform environmental responsibility coefficient on social welfare across logistics modes; (**b**) effect of the platform environmental responsibility coefficient on platform green governance intensity.

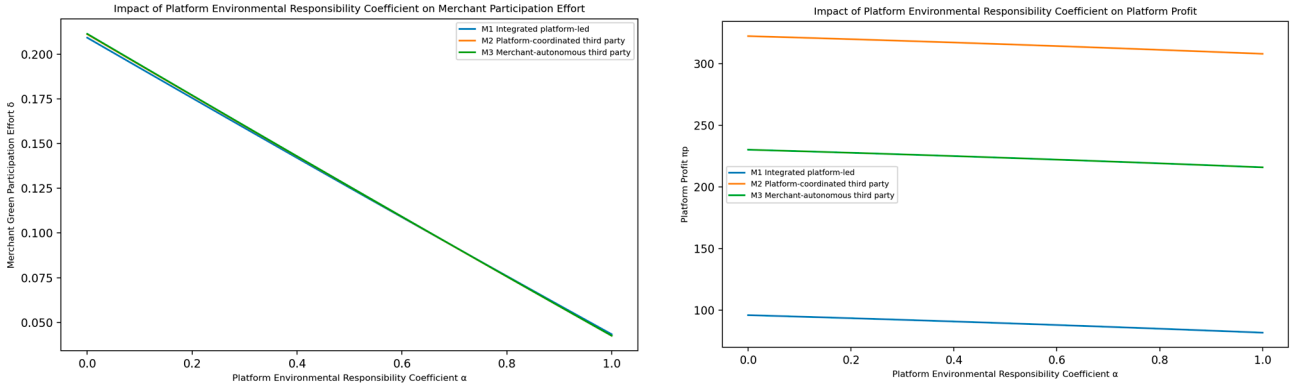
4.2.2. Platform Green Governance Effort

Figure 2b shows that platform green governance effort β increases with α under the assumed parameters. The mechanism is direct: a platform bearing a larger share of residual responsibility-related cost has a stronger modeled incentive to invest in governance effort. In practice, analogous actions may include environmental data requirements, carrier screening, or coordination of lower-impact logistics services.

M2 records the highest modeled platform-governance effort because the platform coordinates third-party services while retaining logistics-related returns. M3 also responds positively to α, but its platform has less direct control over merchant-selected services. M1 shows a more moderate marginal response because direct coordination is already embedded in that mode.

4.2.3. Merchant Green Participation Effort

Figure 3a indicates that merchant green participation effort δ decreases with α under the assumed parameters. This pattern identifies a possible governance trade-off: shifting a larger share of residual responsibility to the platform can reduce merchants' private incentives to adopt green logistics practices.



(**a**) (**b**)

Figure 3. (**a**) Effect of the platform environmental responsibility coefficient on merchant green participation effort; (**b**) Effect of the platform environmental responsibility coefficient on platform profit.

M1 maintains the highest participation level and the smoothest decline because the platform can directly observe merchant participation in the integrated arrangement. The

decline is stronger in M2 and M3, where external merchants can benefit from platform governance while bearing a smaller share of responsibility-related costs. The modeled result, therefore, motivates complementary merchant-side incentives.

4.2.4. Distributional Effects on Platform and Merchant Profits

Figure 3b shows that platform profit declines as α increases in all three modes. A higher responsibility coefficient raises the platform's modeled responsibility-related cost and induces additional governance effort. M1 absorbs this change more readily in the numerical setting, whereas M3 shows the lowest platform-profit level because responsibility is paired with comparatively limited logistics control.

Figure 4 presents merchant profit. It rises with α in the displayed baseline setting because merchants bear a smaller share of responsibility-related cost while benefiting from stronger platform governance. Taken together, Figures 2a, 3b and 4 indicate a distributional and welfare trade-off: responsibility allocation can reallocate returns and strengthen platform effort, but it does not necessarily raise modeled welfare within the baseline parameter region. This result motivates complementary incentive arrangements and parameter-specific welfare screening. The M2 and M3 merchant-profit curves overlap under the baseline parameter setting; therefore, the M2 curve is not visually distinguishable in Figure 4.

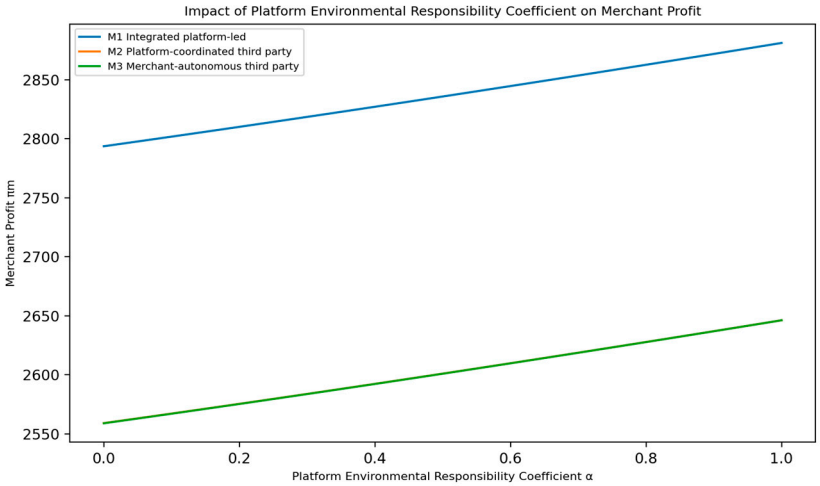


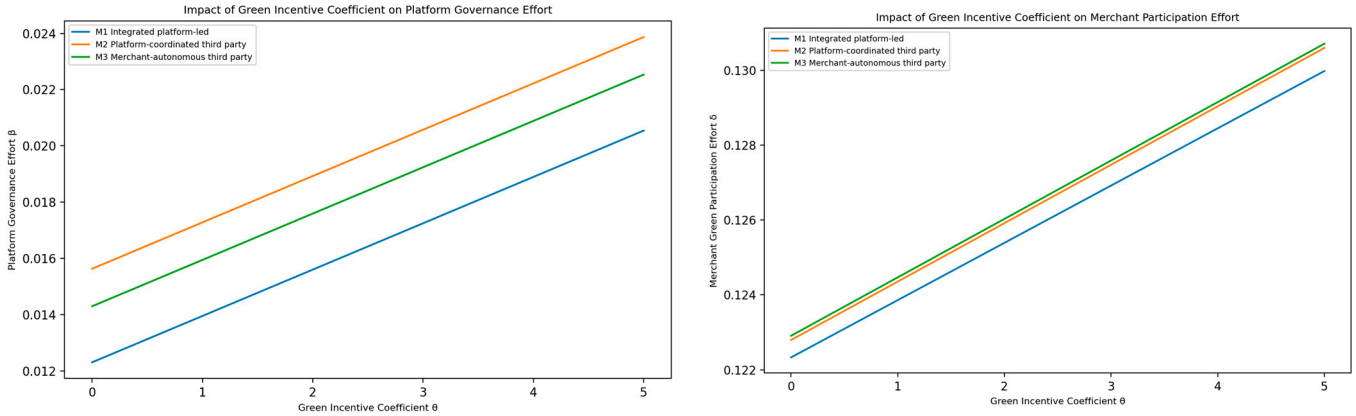
Figure 4. Effect of the platform environmental responsibility coefficient on merchant profit.

4.3. Effects of Green Incentives

The previous analysis indicates that responsibility strengthens platform effort but may weaken merchant participation and reduce platform profit; Figure 2a further shows that the baseline welfare response is not automatically positive. The second scenario, therefore, fixes α at 0.5 and varies θ from 0 to 5. In this study, θ represents a non-fiscal green incentive benefit, such as certification value, priority-service access, or recognition for reliable environmental reporting.

4.3.1. Platform Response to Green Incentives

Figure 5a indicates that platform green governance effort increases with θ in all three modes. The result suggests that positive benefits can complement responsibility requirements in the modeled setting. M2 retains the highest effort level because its platform can combine logistics coordination with governance action, while M3 and M1 also show positive responses.



(**a**) (**b**)

Figure 5. (**a**) Effect of the green incentive coefficient on platform green governance intensity; (**b**) effect of the green incentive coefficient on merchant green participation effort.

4.3.2. Merchant Response to Green Incentives

Figure 5b shows that merchant green participation effort also increases with θ. While a higher α can reduce merchant effort, an incentive benefit restores part of the private return from participation. M1 maintains the highest participation level, while M3 remains slightly above M2 among the third-party modes in this numerical comparison.

Together, Figure 5a,b suggest that incentives can support platform governance and merchant participation, helping to moderate the trade-off associated with transferring responsibility toward the platform.

4.4. Comparative Findings Across Logistics Modes

Table 3 summarizes the modeled comparison across modes. M1 yields the highest welfare and merchant-profit baseline because it combines direct logistics coordination with observable merchant participation. M2 produces the strongest platform-governance response because the coordination capacity is retained in a third-party setting. M3 offers greater merchant autonomy but provides the platform with fewer operational channels through which responsibility can be converted into governance action.

Table 3. Comparative interpretation of numerical findings across logistics modes.

Mode	Governance Characteristics	Main Numerical Pattern	Policy Interpretation
M1	Integrated platform-led logistics; strong operational control and information visibility.	Highest welfare and merchant-profit baseline; welfare response to responsibility must be evaluated over the documented feasible parameter region.	Consider responsibility requirements only after feasibility and welfare screening; support them with standardized environmental reporting.
M2	Platform coordinates third-party logistics and retains service influence.	Platform governance responds strongly to responsibility and incentives; merchant participation still declines when responsibility shifts to the platform.	Consider combining platform responsibility with incentives for platform monitoring and merchant green participation, subject to scenario-specific welfare checks.
M3	Merchants select third-party logistics independently; platform control is limited.	Lowest platform-profit baseline and clear merchant-effort crowding out as platform responsibility increases.	Apply responsibility cautiously and strengthen certified carrier selection, disclosure, and merchant-side incentives; do not infer a welfare gain without parameter-region verification.

These modeled differences support conditional and differentiated governance rather than a single uniform rule. For M1, responsibility can be considered together with standardized environmental reporting and platform-wide service requirements, subject to feasible welfare screening. For M2, platform responsibility may need to be paired with incentives that sustain merchant participation. For M3, disclosure, recognized lower-impact service options, and merchant-side incentives are especially relevant given limited platform control. These are model-based design implications, not direct estimates of realized policy effects.

4.5. Robustness Checks and Discussion

To reduce dependence on a single baseline parameter setting, the numerical verification uses the candidate parameter ranges documented in Supplementary Note S1. The configurations cover residual environmental loss (L), regulatory intervention cost (C_h), platform and merchant responsibility-related costs (C_p and C_m), effort-cost coefficients (k_p, k_m, k_{mH}, and k_{mL}), consumer preference (τ), price sensitivity (η), market size (Q_0), and the prior share of high-participation merchants (ρ_0). For each configuration, the computation records whether $Q > 0$, whether $\beta, \delta_H,$ and δ_L are interior or boundary responses, and whether the welfare comparison is defined over an admissible candidate set.

The sensitivity exercise is interpreted as a feasibility-screened comparative-statics analysis rather than as an external empirical validation. The direction and magnitude of outcomes are therefore reported conditionally on the documented feasible parameter region. In the admissible baseline region, platform governance effort increases with α, while merchant participation remains sensitive to the residual responsibility borne by merchants. The incentive coefficient θ supports both platform governance and merchant participation in the focal scenarios. Parameter combinations that violate positive demand or bounded-response conditions are classified as infeasible or boundary cases rather than being treated as unrestricted equilibria.

The baseline numerical analysis reveals a trade-off between responsibility and participation within the feasible parameter region. Shifting residual environmental responsibility to the platform increases platform governance effort but can reduce merchant participation and platform profit; Figure 2a shows that the welfare response is negative in the displayed baseline scenarios. This result provides a governance explanation for why responsibility allocation should not be considered independently of incentive design, cost structure, and feasibility constraints.

Green incentives moderate the participation side of this trade-off by raising the modeled benefits of platform effort and merchant participation. For cross-border maritime logistics, comparable mechanisms may include recognition of environmental information, access to certified services, or priority arrangements that reward verifiable green logistics behavior. Their welfare implications remain conditional on the specified parameter region and should not be interpreted as direct estimates of fiscal-policy effects.

The comparison indicates that any responsibility arrangement should be interpreted in relation to logistics control, information visibility, and the feasible parameter region. An integrated platform-led arrangement may accommodate a stronger platform role when the welfare screen remains admissible; a platform-coordinated third-party arrangement may require combined responsibility and incentive design; and a merchant-autonomous arrangement requires greater attention to disclosure and merchant-side participation. These interpretations concern modeled governance mechanisms rather than measured energy savings, emissions reductions, or verified policy effects.

4.6. Illustrative Real-World Comparison

To provide a contextual validation of the model logic, the three modes can be compared with common cross-border e-commerce logistics practices. Platform-led logistics programs, in which the platform organizes or strongly standardizes warehousing, carrier selection, tracking, and delivery service rules, correspond to M1. Platform-coordinated third-party services, in which merchants use logistics options designated or coordinated by the platform, but the physical transport is still operated by external providers, correspond to M2. Merchant-selected logistics arrangements, in which merchants independently choose freight forwarders or third-party logistics providers while the platform mainly supports transactions, correspond to M3.

This comparison is not an empirical test based on proprietary platform order data, but it shows that the model's mode distinction is consistent with observable cross-border logistics organization. In practice, platform-led arrangements have stronger information visibility and can support stricter environmental reporting; platform-coordinated third-party arrangements require both platform monitoring and merchant incentives; and merchant-autonomous arrangements need disclosure rules, certified carrier lists, and merchant-side incentives because the platform has weaker direct control over transport choices.

5. Conclusions

This study examined platform environmental responsibility and green incentives in sustainable cross-border maritime logistics through a multi-actor decision model. It compared integrated platform-led logistics (M1), platform-coordinated third-party logistics (M2), and merchant-autonomous third-party logistics (M3), focusing on the platform environmental responsibility coefficient (α) and green incentive coefficient (θ) as governance parameters.

5.1. Main Conclusions

First, within the documented baseline parameter setting, a higher platform environmental responsibility coefficient increases platform green governance effort but reduces merchant participation effort and platform profit. Figure 2a shows that modeled social welfare declines across the displayed baseline scenarios as α increases. Responsibility allocation therefore generates a governance–participation–welfare trade-off rather than an automatic improvement in welfare.

Second, green incentive benefits increase platform governance and merchant participation in the focal numerical scenarios. They can therefore complement responsibility allocation by mitigating the possible crowding-out effect on merchants. This implication is conditional on the documented normalized parameter ranges and does not constitute a direct estimate of a fiscal-policy effect.

Third, the modeled effects differ across logistics modes. M1 yields the highest baseline welfare level across the displayed scenarios; M2 exhibits strong platform-governance responsiveness; and M3 requires greater caution when assigning platform responsibility, as platform logistics control is limited. These comparisons support conditional mode-sensitive design implications linked to operational control, information visibility, and feasibility screening.

5.2. Theoretical Implications

Theoretically, the study contributes to green supply chain governance by showing that environmental responsibility allocation can create both a governance-enhancing effect and a participation-crowding effect. It also extends platform governance theory by distinguishing the platform's transaction role from its logistics-control role. In maritime logistics, the same

responsibility coefficient does not have the same meaning across logistics modes because the platform's ability to observe, coordinate, and influence service choices differs. The model, therefore, suggests that future environmental responsibility models should incorporate governance capacity and information visibility, rather than assigning responsibility solely based on market position.

5.3. Practical Implications

For policy design, the model suggests that regulators may consider linking platform responsibility to the platform's practical ability to coordinate logistics services and observe environmental information, subject to parameter-specific welfare and feasibility screening. Platforms may support transparent information, verified greener maritime logistics options, and carrier-screening mechanisms; merchants may be encouraged through verifiable non-fiscal benefits, green labels, and service-priority arrangements; and logistics service providers and ports may improve the visibility of lower-impact service alternatives. These are conditional design implications derived from the model, not direct causal estimates of policy performance.

5.4. Limitations and Future Research

This study has several limitations. First, it uses an industry-informed normalized analytical model and feasibility-screened numerical sensitivity analysis to compare governance mechanisms. The results describe conditional directional and relative relationships within the documented parameter ranges; they do not measure actual reductions in fuel use or carbon emissions for a particular route, port, vessel type, or platform, and they should not be interpreted as causal policy-effect estimates. Although the paper includes an illustrative real-world comparison, it does not claim empirical validation based on platform order data.

Second, the study considers three representative logistics modes to keep the analysis clear. Real cross-border maritime logistics networks may include shipping companies, ports, freight forwarders, overseas warehouses, customs services, consumers, and third-party logistics providers, each with varying levels of influence. Future research can introduce more actors into the decision framework and examine how their interests affect green logistics choices.

Third, residual environmental loss is represented in an aggregate form, and the incentive coefficient is treated as a non-fiscal benefit in the baseline welfare comparison. Future research may incorporate vessel-movement data, port energy-use data, platform logistics orders, emission factors, explicit public subsidy costs, and independent logistics-provider payoff data to estimate environmental, fiscal, and distributional effects more directly.

Finally, this study assumes a sequential decision process under relatively stable market conditions. In practice, cross-border maritime logistics is affected by changes in fuel prices, differences in country policies, port congestion, vessel space availability, and supply chain disruptions. Future studies can examine these uncertainties and evaluate whether the proposed responsibility and incentive mechanisms remain effective under changing conditions.

In conclusion, sustainable cross-border maritime logistics requires responsibility allocation and incentive arrangements that are matched to logistics control, information visibility, and the relevant feasible parameter region. The proposed model provides a governance-oriented and mechanism-based basis for subsequent empirical examination of green maritime logistics decisions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18136844/s1, Supplementary Note S1: Parameter Source Investigation and Normalized Calibration Documentation.

Author Contributions: Conceptualization, J.L. (Jun Luo) and L.S.; methodology, J.L. (Jun Luo) and Z.W.; formal analysis, J.L. (Jun Luo) and Z.W.; investigation, J.L. (Jun Luo) and J.L. (Jianlin Lai); writing—original draft preparation, J.L. (Jun Luo) and Z.W.; writing—review and editing, L.S., J.L. (Jianlin Lai) and J.C.; visualization, Z.W.; supervision, L.S.; project administration, L.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Pujiang Project of Shanghai Magnolia Talent Plan (24PJC043).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new empirical datasets were created or analyzed in this study. Supplementary Note S1 provides the parameter data source and calibration documentation, including the normalized scaling logic, relative-ordering conditions, and scenario settings used in the numerical analysis. The constrained-equilibrium procedure is described in Appendix A. Additional details supporting the analytical results are available from the corresponding author upon reasonable request.

Acknowledgments: During the preparation of this manuscript, the authors used DeepSeek-V3 for the purpose of searching and screening relevant literature. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Constrained Equilibrium Verification, Candidate Classification, and Computational Reproducibility

Appendix A.1

Feasible strategy sets and candidate classification. The equilibrium procedure begins by deriving the unconstrained first-order candidate for each decision variable. The strategy set is then restricted by $0 \leq \alpha \leq 1$, $0 \leq \beta \leq 1$, $0 \leq \delta_H \leq 1$, $0 \leq \delta_L \leq 1$, and $Q > 0$. For a generic effort candidate $\widetilde{x} \in \{\beta, \delta_H, \delta_L\}$, the constrained response is obtained by comparing the lower boundary, interior candidate, and upper boundary. This candidate-selection rule makes the active constraint explicit rather than treating the projection operator as a purely mechanical truncation.

Appendix A.2

First- and second-order checks. For each merchant payoff, the first-order conditions are obtained by differentiating the type-conditional payoff with respect to price and participation effort. For M1, the following interior first-order conditions yield Equations (17)–(19). The joint merchant Hessian in price and participation effort is locally negative definite under the sufficient condition shown below. For M2 and M3, the analogous type-specific condition uses the corresponding merchant participation-cost coefficient. For the platform's own governance decision, the quadratic effort-cost term gives negative own curvature whenever the platform governance-cost coefficient is positive. The platform and regulatory authority then evaluate candidate responses after substituting the relevant follower response and rejecting candidates that violate positive demand.

For M2 and M3, the conditional merchant first-order condition preserves the same structure, while the platform response incorporates the expected failure probability and the mode-specific logistics return.

Appendix A.3

Heterogeneity aggregation. In M2 and M3, the prior share of high-participation merchants is used consistently to aggregate expected participation, expected failure probability, and expected merchant return. Thus, the type prior affects platform and regulatory decisions through expected aggregate demand, residual loss, expected merchant return, and welfare. In contrast, each merchant's effort choice is conditional on its own type-specific cost coefficient.

Appendix A.4

Mode-specific accounting. For M1, the merchant product margin and platform logistics-service margin are separated to avoid double-counting. For M2 and M3, merchant payoff is interpreted as a type-conditional representative payoff and is probability-weighted before welfare is calculated. In all modes, the logistics service provider is not modeled as a separate strategic actor; logistics-related charges are included in platform and merchant payoffs, and the welfare expression therefore excludes a separate logistics-provider payoff term.

Appendix A.5

Existence, local uniqueness, and numerical selection. Compact bounded decision domains and continuous payoff functions on the positive-demand region ensure that the constrained candidate problem is well-defined. The paper does not claim global uniqueness for all possible parameter combinations. Instead, the reported baseline and sensitivity results are restricted to documented feasible regions in which the candidate-selection routine identifies a single welfare-maximizing feasible outcome. When a configuration yields multiple admissible boundary candidates, the computation compares the corresponding payoff and welfare values; when $Q \leq 0$, the configuration is classified as infeasible and excluded from comparative interpretation.

Appendix A.6

Computational workflow. The numerical computation follows the sequence: (1) specify a documented normalized parameter configuration; (2) solve type-conditional merchant responses under the boundary rule; (3) form expected participation, expected failure probability, and expected merchant return using the prior type share; (4) solve platform governance and any applicable logistics-related charge; (5) calculate demand and verify positive demand; (6) compare the feasible candidate payoffs, consumer surplus, residual environmental loss, and welfare; and (7) repeat the procedure over the responsibility and incentive scenarios and over the documented sensitivity settings. Supplementary Note S1 provides the parameter-source and scaling documentation used in this workflow. The workflow is specified to make the candidate-selection logic transparent and to support replication when the documented inputs and numerical implementation are made available.

The procedure above replaces the earlier unconstrained interpretation that could generate negative demand or effort values outside the [0, 1] interval. It also clarifies that numerical findings are comparative model outcomes conditional on documented normalized ranges, type aggregation, and feasibility screening.

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