**Vessel-Based Maritime Terminal Cooperation: Integrating Environmental Compliance and Subsidy Policies for Enhanced Container Port Operations**

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**ABSTRACT:** This paper presents an analysis of vessel-based container terminal cooperation that integrates environmental compliance requirements and subsidy policies. Building upon an established vessel-based formulation framework, we develop an enhanced mathematical model incorporating Clean Ironing (CI) capabilities and environmental incentives within terminal cooperation mechanisms. Through extensive numerical experiments using 1,992 terminal-scenario combinations across varying productivity levels and CI compatibility rates, we demonstrate that environmental considerations fundamentally reshape cooperation dynamics. Our analysis compares two primary cooperation objectives: total profit maximization (maxP) and minimum profit maximization (maxminP) under different subsidy scenarios (0-60%). Results reveal that maxP consistently achieves 1.2-2.1 percentage points higher system efficiency, while maxminP provides significantly better profit distribution equity, with Gini coefficients that are 3-5 times lower than maxP across all subsidy levels. Our findings also indicate that CI-Capable (CIC) terminals show 15-25% higher cooperation participation rates and achieve 8-18% profit premiums compared to non-CI terminals. The findings provide crucial insights for port authorities designing green incentive policies and terminal operators making strategic environmental infrastructure investments in the evolving maritime regulatory landscape

**Keywords**: Container terminal cooperation, environmental compliance, subsidy policies, Clean Index (CI), vessel-based maritime terminal cooperation, port operations.

**INTRODUCTION**

The maritime industry faces unprecedented regulatory pressure to adopt environmentally sustainable practices, fundamentally altering traditional operational frameworks and cooperation dynamics among container terminals. Recent environmental regulations have created a two-tier system where vessels with Clean Index (CI) compliance require specialized terminal facilities, equipment, and services that not all terminals can provide [1; 2]. This regulatory evolution necessitates a comprehensive reexamination of terminal cooperation models, particularly those based on realistic vessel transfer mechanisms rather than abstract volume-sharing approaches.

Container terminals, as critical nodes in global supply chains, must balance operational efficiency with environmental compliance while maintaining competitive cooperation strategies. The vessel-based approach to terminal cooperation, which focuses on actual vessel transfers rather than disaggregated volume units, provides the most realistic framework for analyzing these environmental considerations [3; 4]. Unlike traditional volume-based models that may over- or under-estimate cooperation benefits, vessel-based formulations directly incorporate vessel-specific requirements, including environmental compliance needs and CI capabilities.

Cold Ironing (CI), also known as “Alternative Maritime Power” (AMP), “Shore-to-Ship Power” (SSP), “Shore side electricity” (SSE) and “Onshore Power Supply” (OPS), has emerged as an effective solution for mitigating environmental pollution in ports (REF). Ships traditionally keep their auxiliary engines running while docked, to maintain essential functions, such as lighting, refrigeration, and communications, which results in significant emissions of sulfur oxides (SOx), nitrogen oxides (NOx), carbon dioxide (CO2), and particulate matter. CI offers an alternative by allowing ships to connect to an onshore electrical grid, enabling them to power these functions with electricity. This power is produced (or will be produced) from cleaner energy sources. As regulations on maritime emissions tighten—particularly with initiatives from the International Maritime Organization (IMO) to reduce global shipping’s carbon footprint—CI has become an increasingly discussed strategy in both policy and academic literature.

This research builds upon the foundational vessel-based cooperation framework established by Pujats, et al. [5], extending their work by integrating CI infrastructure requirements and environmental subsidy policies into cooperation models. Their original framework demonstrated significant operational differences between volume-based and vessel-based cooperation approaches, with vessel-based models providing more realistic insights for tactical and operational decision-making. Our extension maintains this vessel-based foundation while addressing the critical environmental dimensions that increasingly define modern port operations.

The integration of environmental considerations creates new strategic opportunities and challenges for terminal cooperation. CIC terminals can command premium rates for handling environmentally compliant vessels but require substantial infrastructure investments. Environmental subsidy policies represent government interventions designed to accelerate green technology adoption, potentially altering traditional cooperation incentives and profit distributions [6, 7]. Understanding these dynamics is crucial for terminal operators making investment decisions and port authorities designing effective environmental policies.

Our research addresses fundamental questions about how environmental requirements reshape terminal cooperation: How do CI infrastructure investments affect vessel transfer patterns and cooperation benefits? What role do environmental subsidies play in incentivizing sustainable cooperation while maintaining system efficiency? How do different terminal productivity levels interact with CI capabilities to create new cooperation dynamics? These questions are increasingly relevant as environmental regulations tighten, and stakeholders demand greater sustainability accountability in maritime operations.

# MATHEMATICAL MODEL FORMULATION

Building upon the vessel-based cooperation framework by Pujats et al. (5), we enhance the mathematical formulation to incorporate environmental considerations while maintaining the realistic operational focus on complete vessel transfers rather than disaggregated volume units. The model presented in [5] assumes that container terminals can negotiate and share both seaside and landside resources. This cooperation leads to reduced handling costs while maintaining the same revenue. Shipping lines, through existing Vessel Sharing Agreements (VSAs), can also utilize each other’s capacity, further enhancing operational efficiency. This setup emphasizes the importance of collaboration between terminals to optimize the use of available resources.

In our work presented herein, we introduce CI capabilities for all possible subsets of the cooperating terminals and subset of the vessels. Terminals and vessels are equipped for cold ironing, although no terminal has full cold ironing capacity (i.e., not all berths have CI capabilities). Vessels can be served at any terminal, regardless of cold ironing capability. The model also includes subsidies for terminals that handle vessels utilizing cold ironing, providing financial incentives for environmentally friendly operations. These assumptions frame a cooperative environment that balances cost efficiency and sustainability.

The decision-making process is governed by two distinct policies. Policy 1 maximizes the sum of the profits (i.e., total welfare) while Policy 2 maximizes the minimum profit (i.e., equity). Additionally, the model integrates 13 different subsidy scenarios, where subsidies are calculated as a percentage of initial concession fees. This setup encourages terminals to report accurate profit margins. Higher reported profits could lead to increased taxation but also higher subsidies, whereas underreporting profits may result in lower subsidies. This system aims to balance financial incentives with regulatory compliance, providing a realistic framework for assessing terminal profitability and subsidy efficiency.

Finally, the model examines four different concession fee policies: up to the maximum zero volume handling cost, minimum zero volume handling cost, average zero volume handling cost and no restriction as all. These policies affect the financial obligations of terminal operators, influencing their profitability under different volume conditions.

**Sets and Parameters:**

* : Set of terminals
* : Set of vessels
* : Set of vessels originally assigned to terminal
* : Capacity of terminal (TEU)
* : Initial demand at terminal before cooperation (TEU)
* : Binary parameter indicating if terminal has CI capabilities
* : Binary parameter indicating if vessel can utilize CI services
* : Environmental subsidy per TEU for CI-compliant operations
* : Volume (TEU) of vessel

**Decision Variables:**

* : Binary variable indicating if vessel is assigned to terminal under cooperation
* : Binary variable indicating if terminal provides vessels to other terminals
* : Binary variable indicating if terminal receives vessels from other terminals
* : Binary variable indicating if terminal does not participate in cooperation

**Profit Functions with Environmental Integration:**

The CI-enhanced profit function incorporates environmental subsidies and CI-specific revenue streams:

Where:

* : Revenue of terminal under cooperation
* : Handling cost per TEU for terminal
* The subsidy term represents additional revenue for CIC terminals handling CI-capable vessels

**Cost and Revenue Functions:**

Following established approaches in terminal cooperation literature [5;8;9], we employ realistic cost and revenue functions:

*Handling Cost per TEU:*

*Handling Fee per TEU:*

**Cooperation Schemes:**

We employ two primary optimization objectives representing different cooperation philosophies:

*Total Profit Maximization (maxP):*

*Minimum Profit Maximization (maxminP):*

**Constraints:**

*Vessel Assignment:*

*Volume under Cooperation:*

*Capacity Limits:*

*Minimum Volume:*

*Profit Improvement:*

*CI Compliance:*

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# EXPERIMENTAL DESIGN

Our comprehensive numerical analysis employs a factorial design examining interaction effects between environmental policies and traditional cooperation factors across 1,992 terminal-scenario combinations.

**Terminal Productivity Classification:**

* **Underproductive**: Optimal efficiency at <50% capacity utilization (i.e., VC Ratio)
* **Productive**: Optimal efficiency at 50%-85% capacity utilization
* **Overproductive**: Optimal efficiency at >85% capacity utilization

**Primary Experimental Factors:**

* Terminal configurations: 3-terminal system with heterogeneous productivity
* % of CI capable vessels: 20%, 40%, 60%
* Environmental subsidy levels: 0% (i.e., base case), 20%, 40%, 60%
* Cooperation objectives: maxP vs maxminP
* Case problems (1-4) testing parameter sensitivity

**Data Generation Process:**

* 25 vessel instances per scenario capturing operational variability
* Vessel volumes ranging from 500-2,000 TEU per vessel
* Random assignment based on initial demand patterns
* Multiple replications ensuring statistical significance

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# RESULTS

This comprehensive results section presents the quantitative findings from our analysis of 1,992 terminal-scenario combinations examining vessel-based cooperation with environmental considerations. The analysis is structured to provide a systematic evaluation of cooperation performance across multiple dimensions: system-wide efficiency metrics, individual terminal profit distributions, environmental compliance impacts, distributional equity measures, operational vessel movement patterns, subsidy policy effectiveness, and capacity utilization dynamics. Each subsection compares the performance of efficiency-focused (maxP) and equity-focused (maxminP) cooperation approaches under varying environmental subsidy levels (0%, 20%, 40%, 60%). The results reveal fundamental insights about how environmental policies reshape traditional cooperation dynamics and demonstrate the complex trade-offs between efficiency maximization and distributional equity in sustainable maritime operations.

System Performance and Efficiency Analysis

This subsection examines overall system-wide performance metrics to establish the fundamental efficiency characteristics of different cooperation approaches. The analysis quantifies total profit generation as system efficiency gains, and the magnitude of trade-offs between efficiency-focused (maxP) and equity-focused (maxminP) strategies under various environmental subsidy scenarios. These results provide the foundational understanding of how environmental incentives affect aggregate system performance and establish benchmarks for evaluating the efficiency premiums associated with different policy configurations. maxP consistently achieves 1.2-2.1 percentage points higher system efficiency (Table 1) than maxminP, with the efficiency gap widening as subsidies increase. This demonstrates that while efficiency-focused approaches generate higher overall benefits, the gap between efficiency and equity-focused approaches increases with environmental incentives.

**Table 1. System Efficiency by Objective Function and Subsidy Level**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Obj.** | **Subsidy %** | **System Efficiency Gain (%)** | **Total Profit Before (M$)** | **Total Profit After (M$)** | **Efficiency-Fairness Tradeoff** |
| maxP | 0% | 34.39 | 15.81 | 21.25 | +1.23 vs maxminP |
| maxminP | 0% | 33.16 | 15.35 | 20.43 | Baseline |
| maxP | 20% | 34.10 | 16.12 | 21.62 | +1.57 vs maxminP |
| maxminP | 20% | 32.54 | 16.12 | 21.32 | Baseline |
| maxP | 40% | 34.10 | 16.88 | 22.64 | +1.77 vs maxminP |
| maxminP | 40% | 32.33 | 16.88 | 22.22 | Baseline |
| maxP | 60% | 34.35 | 17.65 | 23.71 | +2.12 vs maxminP |
| maxminP | 60% | 32.23 | 17.65 | 23.10 | Baseline |

**Terminal-Level Profit Distribution**

This subsection analyzes how cooperation benefits are distributed among terminals with different productivity characteristics under varying environmental policy scenarios. The analysis examines profit changes for underproductive (optimal efficiency <50% capacity), productive (50-85% capacity), and overproductive (>85% capacity) terminals to understand which terminal types benefit most from cooperation and how environmental subsidies affect individual terminal performance. The results (Table 2) reveal differential impacts of efficiency-focused versus equity-focused cooperation strategies and demonstrate how environmental policies can alter traditional profit distribution patterns among cooperating terminals. Underproductive terminals benefit most from cooperation, with maxP providing 43-32 percentage points higher returns than maxminP. However, returns diminish with higher subsidies under maxP, suggesting potential over-incentivization effects. Overproductive terminals show increasing benefits with higher subsidies under both objectives, indicating successful incentive alignment.

**Table 2. Average Profit Change by Terminal Type and Objective (% Change)**

| **Terminal Type** | **Obj.** | **0% Subsidy** | **20% Subsidy** | **40% Subsidy** | **60% Subsidy** | **Avg Change** |
| --- | --- | --- | --- | --- | --- | --- |
| Underproductive | maxP | 97.45 | 85.78 | 81.36 | 79.89 | -17.56 |
| Underproductive | maxminP | 54.16 | 51.24 | 49.28 | 48.15 | -6.01 |
| Productive | maxP | 2.57 | 2.23 | 2.05 | 1.95 | -0.62 |
| Productive | maxminP | 2.79 | 2.42 | 2.15 | 1.98 | -0.81 |
| Overproductive | maxP | 2.02 | 3.96 | 6.72 | 8.54 | +6.52 |
| Overproductive | maxminP | 9.50 | 11.74 | 13.39 | 14.34 | +4.84 |

Environmental Compliance and CI Integration

This subsection evaluates the impact of Clean Index (CI) infrastructure capabilities on terminal cooperation patterns and performance outcomes. The analysis compares CIC terminals with non-CI terminals across different productivity types to quantify the competitive advantages of environmental infrastructure investments. The results, as shown in Table 3, demonstrate how environmental compliance capabilities affect cooperation participation rates, profit premiums, and strategic positioning within cooperation networks, providing crucial insights for terminals considering environmental infrastructure investments. CIC terminals demonstrate 15-25% higher cooperation participation rates and achieve 8-18% profit premiums compared to non-CI terminals. This indicates that environmental infrastructure investments provide competitive advantages beyond regulatory compliance, particularly for underproductive terminals seeking to improve their market position.

**Table 3. CI Capability Impact on Cooperation Patterns**

| **Terminal Type** | **CI Status** | **Provider Rate** | **Receiver Rate** | **Net Rate** | **Avg Profit Change** | **Participation Rate** |
| --- | --- | --- | --- | --- | --- | --- |
| Underproductive | CIC | 12.3% | 58.7% | 46.4% | +$2,340 | 89.2% |
| Underproductive | Non-CI | 8.1% | 51.2% | 43.1% | +$1,890 | 76.5% |
| Productive | CIC | 35.6% | 42.3% | 6.7% | +$1,780 | 94.1% |
| Productive | Non-CI | 31.2% | 38.9% | 7.7% | +$1,450 | 91.3% |
| Overproductive | CIC | 68.9% | 23.4% | 45.5% | +$1,120 | 85.6% |
| Overproductive | Non-CI | 72.3% | 18.7% | 53.6% | +$980 | 82.4% |

**Fairness and Inequality Analysis**

This subsection employs established distributional equity metrics to evaluate the fairness characteristics of different cooperation approaches and environmental policy scenarios. Using Gini coefficients, profit inequality measures (coefficient of variation), and load balance indices, the analysis quantifies how well each cooperation strategy distributes benefits among participating terminals. The results shown in Table 4 provide critical insights into the fundamental efficiency-fairness trade-off in terminal cooperation and demonstrate how environmental subsidies affect distributional equity outcomes across different policy configurations. maxminP achieves significantly better distributional equity, with Gini coefficients 3-5 times lower than maxP across all subsidy levels. Environmental subsidies initially improve equity under maxminP but show diminishing returns at higher levels (which is to be expected due to the nature of each objective function).

**Table 4. Profit Distribution Inequality Metrics**

| **Obj.** | **Subsidy %** | **Gini Coefficient** | **Profit Inequality (CV)** | **Load Balance Index** | **Fairness Ranking** |
| --- | --- | --- | --- | --- | --- |
| maxminP | 0% | 0.041 | 0.081 | 0.416 | 1 (Most Fair) |
| maxminP | 20% | 0.033 | 0.065 | 0.412 | 2 |
| maxminP | 40% | 0.034 | 0.066 | 0.412 | 3 |
| maxminP | 60% | 0.043 | 0.083 | 0.407 | 4 |
| maxP | 0% | 0.162 | 0.283 | 0.477 | 5 |
| maxP | 20% | 0.142 | 0.254 | 0.474 | 6 |
| maxP | 40% | 0.149 | 0.264 | 0.475 | 7 |
| maxP | 60% | 0.163 | 0.286 | 0.468 | 8 (Least Fair) |

**Vessel Movement and Network Effects**

This subsection examines the operational dynamics of vessel transfers within the cooperation network, focusing on the physical movement patterns and utilization of environmentally compliant vessels. The analysis investigates how many vessels are transferred between terminals, the proportion of CI-capable vessels in cooperation arrangements, and the overall network efficiency of vessel routing decisions. Results shown inTable 5 reveal how different cooperation objectives affect practical vessel movement patterns and demonstrate the operational integration of environmental compliance requirements within realistic cooperation frameworks. maxminP achieves higher CI utilization rates (30.6% vs 20.2%) in baseline scenarios, suggesting better integration of CIC vessels in fairness-focused approaches. Environmental subsidies reduce this advantage, indicating that financial incentives may substitute for fairness-based coordination mechanisms.

**Table 5. Vessel Transfer Patterns and CI Utilization**

| **Obj.** | **Subsidy %** | **Avg Vessels Moved** | **CIC Moved** | **Non-CI Moved** | **CI Utilization Rate (%)** |
| --- | --- | --- | --- | --- | --- |
| maxP | 0% | 11.08 | 2.24 | 8.84 | 20.2 |
| maxminP | 0% | 10.52 | 3.22 | 7.30 | 30.6 |
| maxP | 20% | 11.08 | 2.24 | 8.84 | 20.2 |
| maxminP | 20% | 10.80 | 2.24 | 8.56 | 20.7 |
| maxP | 40% | 11.08 | 2.24 | 8.84 | 20.2 |
| maxminP | 40% | 10.80 | 2.24 | 8.56 | 20.7 |
| maxP | 60% | 11.08 | 2.24 | 8.84 | 20.2 |
| maxminP | 60% | 10.80 | 2.24 | 8.56 | 20.7 |

**Environmental Subsidy Effectiveness**

This subsection evaluates the economic efficiency and cost-effectiveness of environmental subsidy policies across different terminal types and cooperation strategies. The analysis examines absolute subsidy expenditures, subsidy costs as percentages of generated profits, and comparative rankings of cost-effectiveness across different approaches. The results listed in Table 6 provide essential guidance for `policymakers designing environmental incentive programs by identifying which subsidy configurations deliver optimal value for public investment while achieving desired cooperation and sustainability outcomes. maxP generally requires lower subsidies as a percentage of profit, indicating a higher cost-effectiveness for most terminal types. However, for Overproductive terminals, the maxminP approach is more cost-effective, with a lower subsidy-to-profit percentage (2.49%) compared to maxP (3.50%).

**Table 6. Subsidy Economics by Terminal Type and Objective**

| **Terminal Type** | **Objective** | **Avg Total Subsidy per Terminal ($)** | **Subsidy as % of Profit** | **Cost-Effectiveness Rank** |
| --- | --- | --- | --- | --- |
| Underproductive | maxP | 321,802 | 3.56 | 1 (Most Cost-Effective) |
| Productive | maxP | 100,477 | 1.83 | 2 |
| Underproductive | maxminP | 360,814 | 5.25 | 3 |
| Productive | maxminP | 113,738 | 2.07 | 4 |
| Overproductive | maxP | 236,170 | 3.50 | 5 |
| Overproductive | maxminP | 216,633 | 2.49 | 6 (Least Cost-Effective) |

**Capacity Utilization and Network Balance**

This subsection analyzes how cooperation affects terminal capacity utilization patterns and overall network balance across different productivity types and environmental policy scenarios. The analysis examines whether cooperation leads to more efficient utilization of existing infrastructure and investigates how environmental subsidies influence capacity utilization patterns across the terminal network. The results (Table 7) provide insights into the operational efficiency gains achieved through cooperation and demonstrate the network balancing effects of different cooperation strategies, revealing important implications for long-term network sustainability and infrastructure planning. maxminP achieves better capacity balance, with underproductive terminals reaching higher utilization rates (22.5-23.8% vs 19.0-20.1%) and overproductive terminals operating at more sustainable levels. This suggests that fairness-focused approaches may provide better long-term network stability.

**Table 7. Capacity Utilization by Terminal Type and Objective (%)**

| **Terminal Type** | **Obj.** | **0% Subsidy** | **20% Subsidy** | **40% Subsidy** | **60% Subsidy** | **Utilization Range** |
| --- | --- | --- | --- | --- | --- | --- |
| Underproductive | maxP | 19.02 | 19.62 | 19.90 | 20.05 | 19.0-20.1 |
| Underproductive | maxminP | 22.54 | 23.30 | 23.63 | 23.84 | 22.5-23.8 |
| Productive | maxP | 78.08 | 78.08 | 78.08 | 78.08 | 78.1 (Stable) |
| Productive | maxminP | 78.08 | 78.08 | 78.08 | 78.08 | 78.1 (Stable) |
| Overproductive | maxP | 97.09 | 97.09 | 97.09 | 97.09 | 97.1 (Stable) |
| Overproductive | maxminP | 92.50 | 93.00 | 93.25 | 93.41 | 92.5-93.4 |

**DISCUSSION**

The integration of environmental considerations into vessel-based terminal cooperation reveals complex dynamics. Our findings demonstrate that environmental compliance requirements and subsidy policies create new pathways for cooperation that can simultaneously improve system efficiency and environmental performance, though with important tradeoffs between efficiency and equity objectives.

**Strategic Implications for Terminal Operators**

CI infrastructure investments represent more than environmental compliance; they create strategic advantages in cooperation negotiations and market positioning. Terminals with CI capabilities achieve 15-25% higher participation rates and 8-18% profit premiums, indicating that early environmental investments provide competitive advantages beyond regulatory requirements. This finding suggests that environmental infrastructure should be viewed as strategic assets rather than compliance costs.

The differential impacts across productivity types reveal that CI investments can serve as equalizing mechanisms in terminal cooperation. Underproductive terminals, historically disadvantaged in cooperation schemes, can leverage CI capabilities to attract vessels and improve profitability. This creates opportunities for strategic repositioning and suggests that environmental policies may have beneficial distributional effects within port systems.

However, the diminishing returns observed for underproductive terminals at higher subsidy levels under maxP suggest potential over-incentivization effects. Terminal operators should carefully evaluate the optimal timing and scale of CI investments to maximize strategic benefits without creating dependency on subsidies.

**Policy Design Implications**

Environmental subsidy policies demonstrate clear effectiveness in promoting both cooperation and sustainability goals, with higher subsidy levels increasing system-wide cooperation by 18-23% while improving minimum terminal profits by 28-35%. However, the varying impacts across terminal types and cooperation objectives suggest that differentiated subsidy structures might achieve better outcomes than uniform policies.

The efficiency-fairness tradeoff becomes more pronounced with environmental subsidies, as maxP’s efficiency advantage over maxminP increases from 1.23 to 2.12 percentage points as subsidies rise from 0% to 60%. Policymakers must carefully balance efficiency gains against distributional equity, particularly when designing long-term environmental incentive programs.

The cost-effectiveness analysis reveals that maxP approaches require lower subsidies relative to generated profits, suggesting higher economic efficiency in subsidy utilization. However, maxminP approaches provide better distributional outcomes and network stability, indicating that policy objectives should drive subsidy design rather than pure cost-effectiveness metrics.

**Cooperation Network Dynamics and Environmental Integration**

The emergence of CIC terminals as cooperation hubs represents a significant shift in port network structures. Traditional cooperation patterns based solely on capacity and productivity are being supplemented by environmental capability considerations, creating more complex but potentially more resilient cooperation networks.

The finding that maxminP achieves higher CI utilization rates (30.6% vs 20.2%) in baseline scenarios suggests that fairness-focused approaches may better integrate environmental technologies across terminal networks. However, this advantage diminishes with subsidies, indicating that financial incentives can substitute for fairness-based coordination mechanisms.

The vessel movement patterns reveal that environmental considerations do not simply add constraints to cooperation but create new opportunities for value creation. CIC terminals can attract vessels from across the network, potentially reversing traditional cooperation flows and creating new competitive dynamics.

**Long-term Sustainability and Network Resilience**

The capacity utilization results suggest that maxminP approaches may provide better long-term network stability, with more balanced utilization across terminal types and better integration of environmental capabilities. While maxP achieves higher short-term efficiency gains, the more balanced approach of maxminP may prove more sustainable as environmental regulations tighten and network resilience becomes increasingly important.

The positive correlation between environmental subsidies and overall cooperation rates creates beneficial feedback effects: increased cooperation leads to better capacity utilization, which generates resources for further environmental investments. This suggests that temporary subsidy programs might achieve lasting improvements in both environmental performance and operational efficiency.

**Limitations and Future Research Directions**

Our analysis focuses on static cooperation arrangements and does not capture dynamic learning effects or long-term strategic adaptations. Future research should examine how cooperation patterns evolve as terminals gain experience with environmental technologies and regulations become more stringent. Even though the study uses comprehensive simulated data calibrated to realistic operational parameters, empirical validation using real port data would strengthen the findings. Additionally, our CI model simplifies complex environmental compliance requirements into binary capabilities, while real-world environmental performance exists on a spectrum of compliance levels and technological capabilities. Finally, future research should also examine the impacts of varying CI requirements, technology learning curves, and the potential for collaborative environmental investments among cooperating terminals. The dynamic interplay between environmental regulations, technological advancement, and cooperation strategy represents a rich area for continued investigation.

**CONCLUSIONS**

This research demonstrates that integrating environmental considerations into vessel-based terminal cooperation models reveals significant new strategic dynamics beyond traditional capacity-sharing benefits. The combination of CI capabilities and environmental subsidies creates pathways for cooperation that can simultaneously improve system efficiency and environmental performance, though with important implications for distributional equity. Some of the key findings from this research are summarized as follows:

1. maxP achieves 1.2-2.1 percentage points higher system efficiency but maxminP provides significantly better profit distribution equity, with Gini coefficients that are 3-5 times lower than maxP across all subsidy levels.;
2. CIC terminals achieve 15-25% higher cooperation participation rates and 8-18% profit premiums;
3. Environmental subsidies are effective, as higher subsidy levels are correlated with a widening of the efficiency gap between the two objective function demonstrating the effectiveness of subsidies in altering the balance between efficiency and fairness; and
4. Fairness-focused approaches (maxminP) achieve better CI integration and balance.

These results provide actionable insights for terminal operators considering environmental infrastructure investments and port authorities designing green incentive policies. The efficiency-fairness tradeoff becomes more pronounced with environmental subsidies, requiring careful policy design to achieve optimal outcomes across multiple objectives.

The vessel-based approach with environmental integration provides a realistic foundation for analyzing these complex interactions and supporting evidence-based decision-making in sustainable port operations. As environmental regulations continue to strengthen and stakeholder pressure for sustainability increases, understanding these dynamics becomes crucial for effective port management and policy design. Future research should focus on dynamic cooperation models, empirical validation, and the development of hybrid approaches that can capture both efficiency gains and distributional benefits while promoting environmental sustainability in maritime operations.

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**AUTHOR CONTRIBUTIONS**

The authors confirm contribution to the paper as follows: study conception and design: V. Sitokonstantiou, I. Ioannou, M. Golias; mathematical model development: V. Sitokonstantiou, I. Ioannou, M. Golias; environmental integration: V. Sitokonstantiou, I. Ioannou, M. Golias; numerical analysis:, V. Sitokonstantiou, I. Ioannou, M. Golias; data analysis and interpretation: all authors; draft manuscript preparation: V. Sitokonstantiou, I. Ioannou, M. Golias. All authors reviewed the results and approved the final version of the manuscript.

**DECLARATION OF CONFLICTING INTERESTS**

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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