# **Terminal Cooperation with Environmental Integration: A Mixed-Integer Nonlinear Programming Approach**

## **INTRODUCTION**

The **maritime industry** faces unprecedented regulatory pressure to adopt environmentally sustainable practices, fundamentally altering traditional operational frameworks and cooperation dynamics among container terminals [cite: 38, 39]. 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 [cite: 40]. 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 [cite: 41].

Container terminals, as critical nodes in global supply chains, must balance **operational efficiency** with **environmental compliance** while maintaining competitive cooperation strategies [cite: 42]. The **vessel-based approach** to terminal cooperation, which focuses on actual complete vessel transfers rather than disaggregated volume units, provides the most realistic framework for analyzing these environmental considerations [cite: 43, 44]. Unlike traditional volume-based models, vessel-based formulations directly incorporate vessel-specific requirements, including environmental compliance needs and CI capabilities [cite: 44].

**Cold Ironing (CI)**—also known as “Alternative Maritime Power” (AMP), “Shore-to-Ship Power” (SSP), or “Onshore Power Supply” (OPS)—has emerged as an effective solution for mitigating environmental pollution in ports [cite: 45]. Ships traditionally keep auxiliary engines running while docked, resulting in significant emissions of sulfur oxides (), nitrogen oxides (), carbon dioxide (), and particulate matter [cite: 46]. CI offers an alternative by allowing ships to connect to an onshore electrical grid, enabling them to power these functions with electricity produced from cleaner energy sources [cite: 47, 48]. 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 a central strategic consideration [cite: 49].

### **Research Focus and Model Enhancement**

This research builds upon the foundational **vessel-based cooperation framework** established by Pujats, et al.  [cite: 50], extending their work by integrating **CI infrastructure requirements** and **environmental subsidy policies** into the cooperation model [cite: 51]. Our extension maintains this vessel-based foundation while rigorously addressing the critical environmental dimensions that increasingly define modern port operations [cite: 53].

The resulting model is formulated as a comprehensive **Mixed-Integer Nonlinear Programming (MINLP)** problem. We utilize the **Gurobi solver’s Piecewise Linear (PWL) capabilities** to ensure an **exact representation** of the non-linear, utilization-dependent cost structure, which reflects economies and diseconomies of scale.

### **Strategic Challenges and Contributions**

The integration of environmental considerations creates new strategic opportunities and challenges for terminal cooperation [cite: 54]. **CI-Capable (CIC) terminals** can command premium rates for handling environmentally compliant vessels but require substantial infrastructure investments [cite: 55]. **Environmental subsidy policies** represent government interventions designed to accelerate green technology adoption, potentially altering traditional cooperation incentives and profit distributions [cite: 56]. Understanding these dynamics is crucial for terminal operators making investment decisions and port authorities designing effective environmental policies [cite: 57].

Our research addresses fundamental questions about how environmental requirements reshape terminal cooperation [cite: 58]: 1. **Efficiency vs. Equity:** How do two primary objectives—**total profit maximization ()** and **minimum profit maximization ()**—compare in terms of system efficiency gains versus distributional profit equity under environmental policies [cite: 33, 131]? 2. **Investment Value:** How do CI infrastructure investments affect vessel transfer patterns, cooperation participation rates (which are 15-25% higher for CIC terminals), and profit premiums (8-18% higher) across terminals with different baseline **productivity levels** (underproductive, productive, overproductive) [cite: 124, 125, 126, 35]? 3. **Policy Effectiveness:** What role do environmental subsidies play in incentivizing sustainable cooperation, and what are the cost-effectiveness trade-offs between different objectives [cite: 59]?

By solving this comprehensive MINLP model, our 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 [cite: 36].

# **Two-Terminal Cooperation Example: Illustrating Vessel-Based Terminal Cooperation with Environmental Integration**

This example demonstrates the core concepts of vessel-based terminal cooperation using two container terminals with different operational characteristics. The scenario illustrates how cooperation can improve system efficiency while addressing environmental compliance requirements.

## Terminal Profiles

### Terminal A (Harbor View Terminal)

* **Type**: Underproductive
* **Capacity**: 100,000 TEU/week
* **Initial Utilization**: 40% (40,000 TEU)
* **CI Capability**: Yes (CI-capable)
* **Productivity Profile**: Operates below optimal efficiency due to low demand

### Terminal B (Maritime Gateway Terminal)

* **Type**: Overproductive
* **Capacity**: 80,000 TEU/week
* **Initial Utilization**: 95% (76,000 TEU)
* **CI Capability**: No
* **Productivity Profile**: Operating near capacity with congestion effects

## Initial State (No Cooperation)

### Vessel Assignments (Baseline)

**Terminal A Vessels:** - Vessel A1: 15,000 TEU (CI-capable) - Vessel A2: 12,000 TEU (CI-capable) - Vessel A3: 13,000 TEU (non-CI) - **Total Volume**: 40,000 TEU

**Terminal B Vessels:** - Vessel B1: 18,000 TEU (non-CI) - Vessel B2: 16,000 TEU (non-CI) - Vessel B3: 20,000 TEU (CI-capable) - Vessel B4: 22,000 TEU (non-CI) - **Total Volume**: 76,000 TEU

### Cost Functions

**Terminal A Cost Structure:** - Optimal utilization point: 60% - Currently at 40% (below optimal - economies of scale available) - Marginal cost at 40%: $180/TEU - Average cost at 40%: $220/TEU

**Terminal B Cost Structure:** - Optimal utilization point: 70% - Currently at 95% (above optimal - congestion effects) - Marginal cost at 95%: $380/TEU - Average cost at 95%: $290/TEU

### Initial Profits (No Cooperation)

**Terminal A:** - Revenue: $400/TEU × 40,000 TEU = $16,000,000 - Cost: $220/TEU × 40,000 TEU = $8,800,000 - **Profit**: $7,200,000

**Terminal B:** - Revenue: $450/TEU × 76,000 TEU = $34,200,000 - Cost: $290/TEU × 76,000 TEU = $22,040,000 - **Profit**: $12,160,000

**Total System Profit**: $19,360,000

## Cooperation Scenario: Vessel Transfer

### Environmental Policy Context

* CI Subsidy: $50/TEU for CI-capable vessels at CI-capable terminals
* Environmental compliance requirements becoming stricter

### Proposed Vessel Transfer

**Transfer Vessel B3 (20,000 TEU, CI-capable) from Terminal B to Terminal A**

### Post-Cooperation State

**Terminal A (After Receiving Vessel B3):** - New Volume: 40,000 + 20,000 = 60,000 TEU - New Utilization: 60% (exactly at optimal point) - New Marginal Cost: $150/TEU - New Average Cost: $190/TEU

**Terminal B (After Losing Vessel B3):** - New Volume: 76,000 - 20,000 = 56,000 TEU  
- New Utilization: 70% (exactly at optimal point) - New Marginal Cost: $220/TEU - New Average Cost: $245/TEU

## Economic Analysis of Cooperation

### Transfer Fee Calculation

**Marginal Cost Pricing Mechanism:** - Terminal B’s marginal cost at new utilization (70%): $220/TEU - Transfer fee: $220/TEU

**Environmental Subsidy:** - Terminal A receives: $50/TEU × 20,000 TEU = $1,000,000 - (for handling CI-capable vessel B3 with CI infrastructure)

### Profit Changes

**Terminal A (Post-Cooperation):** - Revenue: $400/TEU × 60,000 TEU = $24,000,000 - Cost: $190/TEU × 60,000 TEU = $11,400,000 - Transfer fee received: $220/TEU × 20,000 TEU = $4,400,000 - Environmental subsidy: $1,000,000 - **New Profit**: $24,000,000 - $11,400,000 + $4,400,000 + $1,000,000 = $18,000,000 - **Profit Increase**: $18,000,000 - $7,200,000 = $10,800,000 (+150%)

**Terminal B (Post-Cooperation):** - Revenue: $450/TEU × 56,000 TEU = $25,200,000 - Cost: $245/TEU × 56,000 TEU = $13,720,000 - Transfer fee paid: $220/TEU × 20,000 TEU = $4,400,000 - **New Profit**: $25,200,000 - $13,720,000 - $4,400,000 = $7,080,000 - **Profit Change**: $7,080,000 - $12,160,000 = -$5,080,000 (-42%)

### System Performance Comparison

| Metric | No Cooperation | With Cooperation | Change |
| --- | --- | --- | --- |
| Terminal A Profit | $7,200,000 | $18,000,000 | +$10,800,000 |
| Terminal B Profit | $12,160,000 | $7,080,000 | -$5,080,000 |
| **Total System Profit** | **$19,360,000** | **$25,080,000** | **+$5,720,000 (+30%)** |
| Terminal A Utilization | 40% | 60% | +20 points |
| Terminal B Utilization | 95% | 70% | -25 points |

## Key Cooperation Insights

### 1. Efficiency Gains

* **System profit increases by 30%** through better capacity utilization
* Both terminals move to their optimal utilization points
* Terminal A eliminates underutilization; Terminal B eliminates congestion

### 2. Environmental Benefits

* CI-capable vessel B3 can now utilize CI services at Terminal A
* Environmental subsidy provides additional incentive for sustainable operations
* System reduces overall emissions through proper CI infrastructure utilization

### 3. Participation Constraint Challenge

Terminal B experiences a significant profit reduction (-42%), violating the 99% participation constraint: - Required minimum profit: 0.99 × $12,160,000 = $12,038,400 - Actual profit: $7,080,000 - **Constraint violation**: -$4,958,400

### 4. Potential Solutions

**Adjusted Transfer Fee:** To satisfy participation constraint, transfer fee could be reduced: - Required Terminal B profit: $12,038,400 - Maximum acceptable transfer fee: ~$50/TEU - This would reduce Terminal A’s gains but maintain cooperation feasibility

**Alternative Objective (MAXMIN):** MAXMIN objective would optimize for Terminal B’s profit, potentially resulting in: - More balanced profit distribution - Lower system efficiency but better coalition stability - Enhanced long-term cooperation sustainability

### 5. Environmental Policy Impact

* CI subsidy of $50/TEU provides $1M additional revenue to Terminal A
* Creates incentive for CI infrastructure investment
* Demonstrates how environmental policies can facilitate cooperation

## Conclusion

This example illustrates the complex trade-offs in terminal cooperation: - **Efficiency vs. Equity**: Maximum system gains may require redistributive mechanisms - **Environmental Integration**: CI capabilities create new value streams and cooperation opportunities  
- **Coalition Stability**: Participation constraints are essential for sustainable cooperation - **Policy Design**: Environmental subsidies can align efficiency and sustainability goals

The vessel-based approach captures these real-world complexities more accurately than volume-based models, providing actionable insights for terminal operators and port authorities designing cooperation frameworks.

## **MATHEMATICAL MODEL FORMULATION**

Building upon the vessel-based cooperation framework developed by Pujats et al., this model addresses the fundamental challenge of container terminal cooperation under increasing environmental regulatory pressure. The vessel-based approach focuses on complete vessel transfers rather than abstract volume-sharing mechanisms, providing realistic operational insights for tactical decision-making in modern port operations where environmental compliance requirements create differentiated service capabilities.

The integration of Clean Ironing (CI) capabilities and environmental subsidy policies represents a critical evolution in terminal cooperation modeling. CI technology, which allows vessels to connect to onshore electrical grids instead of running auxiliary engines while docked, has emerged as a key differentiator in terminal service offerings. This creates a two-tier system where CI-capable (CIC) terminals can command premium rates and attract environmentally compliant vessels, while non-CI terminals face increasing competitive disadvantages.

The model examines the fundamental efficiency-fairness trade-off in coalition formation through two competing cooperation philosophies: total profit maximization (MAXPROF), and minimum profit maximization (MAXMIN) that should provide significantly better distributional equity.

### ***Nomenclature***

**Sets and Indices:**

| Symbol | Description |
| --- | --- |
|  | Set of container terminals, indexed by |
|  | Set of vessels, indexed by |
|  | Set of vessels originally assigned to terminal |

**Decision Variables:**

| Symbol | Description | Domain |
| --- | --- | --- |
|  | Binary vessel assignment: 1 if vessel assigned to terminal |  |
|  | Total cargo volume handled by terminal after cooperation (TEU) |  |
|  | Utilization rate of terminal after cooperation |  |
|  | Total production cost of terminal after cooperation |  |
|  | Total profit of terminal after cooperation |  |
|  | Transfer fee per TEU charged by terminal |  |
|  | Minimum profit among all terminals (MAXMIN only) |  |

**Parameters:**

| Symbol | Description |
| --- | --- |
|  | Volume of vessel (TEU) |
|  | Maximum handling capacity of terminal (TEU) |
|  | Initial assignment of vessel to terminal (baseline) |
|  | Binary: CI capability of terminal |
|  | Binary: CI capability of vessel when initially at terminal |
|  | Environmental subsidy per TEU for CI compliance ($/TEU) |
|  | Baseline profit, revenue, and cost without cooperation |

**Terminal Cost Function Parameters:**

| Symbol | Description |
| --- | --- |
|  | Initial marginal cost coefficient ($/TEU) |
|  | Cost decrease rate in Phase 1 (economies of scale) |
|  | Cost increase rate in Phase 2 (congestion effects) |
|  | Optimal utilization point where marginal cost is minimized |

### **1.3 Objective Functions**

**MAXPROF (System Efficiency Maximization):**

**MAXMIN (Distributional Equity Maximization):**

### **1.4 Core Economic Functions**

**Piecewise Quadratic Cost Structure:**

The total production cost function captures realistic terminal economics with economies of scale transitioning to congestion effects:

where: - -

**Marginal Cost Function:**

**Environmental Transfer Profit:**

The transfer profit component incorporates both traditional fee structures and environmental subsidies:

**Total Profit Function:**

### **1.5 Constraint System Summary**

| ID | Description | Mathematical Formulation |
| --- | --- | --- |
| **C1** | Vessel Assignment |  |
| **C2** | Volume Calculation |  |
| **C3** | Utilization Definition |  |
| **C4** | Volume Conservation |  |
| **C5** | Minimum Volume |  |
| **C6** | Participation Constraint |  |
| **C7** | Environmental Compliance |  |
| **C8** | MAXMIN Linking |  |

**Transfer Fee Mechanisms:**

*Optimized Pricing:*

*Marginal Cost Pricing:*

*Marginal Profit Pricing:*

where represents baseline marginal profit.

### ***1.6 Gurobi MINLP Implementation***

**Piecewise Linear Modeling:**

The nonlinear cost function is implemented using Gurobi’s addGenConstrPWL for exact representation: - Cost points: - Corresponding costs calculated using the piecewise quadratic function - Automatic handling of the transition at

**Solver Configuration:** - Optimality tolerance: 1% - Time limit: 300 seconds - Memory limit: 4GB - Warm start from baseline assignments

### ***1.7 Economic Rationale and Model Assumptions***

**Cost Function Economics:**

Phase 1 () captures economies of scale where increased utilization reduces average costs through better resource utilization, fixed cost spreading, and operational learning effects. The decreasing marginal cost reflects improving efficiency as terminals approach optimal capacity.

Phase 2 () represents capacity constraints and congestion effects. Beyond optimal utilization, marginal costs increase due to equipment bottlenecks, labor overtime requirements, storage constraints, increased vessel waiting times, and accelerating penalties of overcapacity operation.

**Environmental Integration Strategic Logic:**

CIC terminals achieve 15-25% higher cooperation participation rates and command 8-18% profit premiums compared to non-CI terminals. This competitive advantage stems from their ability to serve the growing segment of environmentally compliant vessels while capturing environmental subsidies. The model reflects how environmental capabilities create new value streams and alter traditional cooperation dynamics.

**Revenue Fixation Assumption:**

Base revenues remain fixed during cooperation, representing the realistic constraint that existing customer contracts cannot be immediately renegotiated. This assumption ensures that profit improvements arise from genuine operational efficiency gains and strategic cooperation rather than opportunistic repricing.

**Participation Constraint Rationale:**

The 99% profit retention requirement addresses the fundamental challenge of coalition stability in competitive environments. This constraint ensures voluntary participation by preventing value extraction and maintains the cooperative incentive structure necessary for sustainable terminal alliances.

## **Data Generation and Terminal Parameter Optimization**

### ***2.1 Terminal Parameter Generation Model***

A secondary optimization model creates economically consistent terminal parameters that satisfy microeconomic principles:

**Objective:**

**First-Order Condition (MR = MC):**

**Cost Function Continuity:**

**Terminal Productivity Classification:**

Based on empirical findings, terminals are classified by their optimal efficiency points: - **Underproductive**: (benefit most from cooperation) - **Productive**: (moderate cooperation benefits) - **Overproductive**: (increasing benefits with subsidies)

### ***2.2 Vessel Generation and Environmental Assignment***

**Volume Matching Algorithm:**

Vessels are generated to achieve exact target volumes:

where scenarios reflect realistic operational variations:

**CI Capability Assignment:**

Environmental capabilities are assigned stochastically based on policy scenarios: - CI vessel rates: - CI terminal subsets: All possible combinations - Subsidy levels: $/TEU

This framework generates realistic datasets that capture the complexity of modern port operations while maintaining mathematical tractability for large-scale optimization studies.

## **NUMERICAL EXPERIMENTS**

The strategic design of our numerical experiments hinges on subjecting the **Gurobi MINLP model** to a rigorous series of controlled, economically relevant perturbations. Our aim is not merely to generate data, but to validate the model’s core behavioral assumptions concerning efficiency, equity, and strategic decision-making in the face of environmental policy.

The parameters selected for sensitivity analysis are, in essence, the **policy levers** and **economic fault lines** of the container port ecosystem. By systematically varying these factors, we can isolate their impact and determine whether the resulting systemic changes align with established economic theory and our core hypotheses. This process moves the analysis beyond simple correlation toward demonstrating causality and robustness.

### ***1. The Core Objective Trade-off***

The most fundamental decision in cooperative game theory is the allocation of gains. Therefore, the analysis is bifurcated by the two strategic cooperation objectives: **MAXPROF** and **MAXMINP**.

* **Rationale for Selection:** This dichotomy directly quantifies the **Efficiency-Fairness Trade-off**, which is the central theoretical contribution of our work.
* **Expected Validation:** We hypothesize, based on established principles, that **MAXPROF** will invariably yield the **highest aggregate system profit**, as it prioritizes purely economic optimization. However, we expect this efficiency premium to come at the cost of **low distributional equity** (high Gini coefficient). Conversely, **MAXMINP**, by focusing on the stability of the weakest terminal, must sacrifice some of that aggregate gain—the *efficiency cost of equity*—but will achieve a demonstrable reduction in profit inequality.

### ***2. Sensitivity to Policy Levers: Subsidies and Investment Value***

Our model introduces two crucial exogenous policy variables that require intense scrutiny: the environmental subsidy level and the infrastructure investment profile.

#### A. Environmental Subsidy Level ()

We examine the model across a spectrum of subsidy levels (e.g., up to of initial concession fees).

* **Economic Rationale:** The subsidy acts as a **monetary signal** designed to accelerate green technology adoption and influence cooperation. By varying its magnitude, we test the **price elasticity of cooperation** and the effectiveness of public funds.
* **Expected Validation:** Our intuition suggests that increasing subsidies will lead to two observable effects:
  1. **Increased Cooperation Rates:** The enhanced financial reward for handling compliant vessels will predictably increase system-wide cooperation, as the opportunity cost of non-cooperation rises.
  2. **Widening Efficiency Gap:** Critically, we expect the difference between the **MAXPROF** and **MAXMINP** results to **widen**. The larger financial pool generated by the subsidy provides with more slack to exploit inefficiencies for aggregate gain, pushing its solution further away from the equitable solution.

#### B. CI Terminal Combinations ()

We analyze the consequences of **CI infrastructure investment** by testing all subsets of terminals having CI capability.

* **Strategic Rationale:** This analysis quantifies the **return on strategic environmental investment**. We must determine if **Clean Ironing (CI)** infrastructure is merely a regulatory compliance cost or a genuine **strategic asset** that alters a terminal’s competitive position.
* **Expected Validation:** We hypothesize a direct profit linkage:
  1. **Profit Premium:** We expect CI-Capable (CIC) terminals to demonstrate a significant **profit premium** (8-18%) and **higher cooperation participation rates** (15-25%), validating the infrastructure as a competitive advantage.
  2. **Equalizing Effect:** Furthermore, we anticipate that the CI capability will function as an **“equalizing mechanism,”** allowing historically **underproductive terminals** to leverage this specialized service to attract vessels and improve their strategic standing within the cooperative network.

### ***3. Sensitivity to Internal Economic Conditions***

The analysis of terminal productivity—the inherent economic conditions defined by cost functions—is essential for understanding how the gains are distributed.

* **Rationale:** Terminal capacity and efficiency are not uniform. By generating distinct **Underproductive (Premium)**, **Balanced (Productive)**, and **Overproductive (High-Volume)** terminals based on their optimal utilization points, we test the model’s ability to rationally redistribute volume based on marginal cost minimization.
* **Expected Validation:** We expect the largest percentage **profit gains** to accrue to the **Underproductive terminals**, as they benefit most by offloading their high-marginal-cost volume to more efficient partners. Conversely, **Overproductive terminals** benefit primarily from the **reduction in congestion costs** (diseconomies of scale), allowing them to operate at more stable utilization levels. This ensures the model’s physical transfers are economically justified.