JURNAL LOCUS: Penelitian & Pengabdian
Volume 4 No. 10 October 2025
E-ISSN 2829-7334| P-ISSN 2829-5439
Hompage: https://locus.rivierapublishing.id/index.php/jl

Navigating a Greener Horizon: Route Optimization of LNG Shipping

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Abstract

This research addresses a critical gap in maritime logistics optimization by developing the first comprehensive Capacitated Vehicle Routing Problem (CVRP) framework specifically designed for Japan's domestic Liquefied Natural Gas (LNG) terminal distribution network. Despite Japan being the world's second-largest LNG consumer with 37 operational terminals, no prior academic research has systematically optimized inter-terminal routing within this strategically important market. The study develops solutions using Mixed Integer Linear Programming (MILP) and the Clarke–Wright Savings Algorithm to minimize operational costs while incorporating Boil-Off Gas (BOG) losses as a novel constraint in maritime CVRP formulations. Through analysis of five vessel capacity configurations (125,000–180,000 m^3) across eight representative Japanese terminals, this research demonstrates that 180,000 m^3 vessels achieve optimal performance with a three-vessel fleet deployment and 80.2% average utilization. When operational consistency constraints require a minimum 80% target utilization, the optimal configuration shifts to 170,000 m^3 vessels, achieving 84.9% average utilization with significantly reduced variability (3.6% standard deviation versus 15.8% unconstrained). The research validates MILP optimality for medium-scale instances while establishing metaheuristic alternatives for larger operational deployments. Beyond operational efficiency, the optimized routing demonstrates significant environmental benefits through reduced fuel consumption and BOG emissions, with potential annual CO_2 emission reductions of approximately 8–12% compared to non-optimized routing patterns.

Keywords: Capacitated Vehicle Routing Problem, Maritime Logistics, LNG Distribution Optimization, Mixed Integer Linear Programming, Boil-Off Gas Integration, Fleet Capacity Analysis

INTRODUCTION

Japan's position as the world's second-largest LNG consumer, importing over 70 million tonnes annually through 37 operational terminals, presents a unique and understudied optimization challenge in maritime logistics (Song, 2024). The archipelagic nation's extensive 29,000-kilometer coastline creates natural conditions for domestic LNG distribution that could benefit significantly from systematic route optimization, yet this critical component of global energy infrastructure has received no dedicated academic attention (International Energy Agency, 2024).

The significance of this research gap becomes particularly pronounced when considering Japan's current market dynamics (Huang et al., 2024; Ren et al., 2024). Recent analysis reveals that the country's four largest LNG utilities—JERA, Tokyo Gas, Osaka Gas, and Kansai Electric—face over-contracting issues totaling approximately 12 million tonnes of surplus capacity (Reynolds & Doleman, 2024). This surplus situation creates substantial economic incentives for optimized inter-terminal transfers, flexible coastal distribution arrangements, and sophisticated fleet deployment strategies that traditional international shipping models do not address.

The Capacitated Vehicle Routing Problem (CVRP), introduced by Dantzig and Ramser in 1959, has evolved into one of the most extensively studied NP-hard combinatorial optimization problems. However, its application to maritime LNG logistics represents a significant theoretical and practical advancement that addresses multiple research gaps simultaneously. Traditional CVRP formulations assume static cargo quantities and conventional transportation constraints, neither of which adequately capture the unique characteristics of LNG maritime distribution. In maritime LNG contexts, additional complexities such as boil-off gas, time-dependent inventory, and split deliveries require extensions of the classical CVRP (Eriksen et al., 2022). Some small-scale LNG distribution models embed CVRP formulations into mixed-integer programs, integrating routing decisions with inventory and fleet-mix selection (Budiyanto et al., 2023). Moreover, hybrid heuristics combining CVRP structures with greedy or metaheuristic approaches have been proposed to deal with LNG routing under maritime constraints (Wijharnasir et al., 2019; Shao et al., 2024). Recent works further extend the CVRP paradigm by including transshipment or intermediate storage nodes in LNG delivery networks, effectively blending CVRP with maritime inventory routing to capture real supply chain flexibility (Li & Schütz, 2023).

LNG transportation presents three fundamental challenges that distinguish it from conventional CVRP applications. First, the cryogenic nature of LNG at -162°C results in inevitable Boil-Off Gas (BOG) losses averaging 0.10–0.15% of cargo volume daily (Mokhatab et al., 2014). This time-dependent cargo degradation directly impacts both delivered quantities and route economics, creating a dynamic constraint environment that requires sophisticated mathematical modeling. Second, LNG terminals operate under strict berth scheduling protocols, safety requirements, and weather constraints that create complex time windows significantly more restrictive than typical distribution networks (Rakke et al., 2011). Third, the capital-intensive nature of LNG carriers—with construction costs exceeding $200 million per vessel—combined with Japan's unique geographic and regulatory environment, necessitates optimization frameworks that balance economic efficiency with operational resilience.

Japan's LNG infrastructure presents unique characteristics that make it an ideal case study for advanced maritime routing optimization. The country's integrated utility system, featuring major terminals in Tokyo Bay (Sodegaura, Negishi, Ohgishima, Futtsu), Osaka Bay (Senboku, Himeji), Nagoya (Chita), and Kyushu (Tobata, Hibiki), creates complex inter-terminal transfer requirements that existing international routing models do not address. This research, *Navigating a Greener Horizon: Route Optimization of LNG Shipping*, addresses four primary objectives: (1) develop BOG-integrated CVRP formulations, (2) establish optimal fleet configuration parameters, (3) validate solution methodology performance, and (4) demonstrate Japanese market applicability. The achievement of these objectives offers substantial benefits for both academic knowledge advancement and industrial practice. Theoretically, this work extends CVRP methodology into the maritime LNG domain by integrating physical phenomena (BOG losses) with operational constraints, thereby enriching the optimization literature. Practically, the findings provide actionable fleet deployment strategies that can reduce operational costs by 8–12% while simultaneously decreasing environmental emissions, directly addressing Japan's energy security and sustainability challenges. The broader implications extend to other archipelagic nations and regional LNG markets, where similar distribution networks could benefit from adapted optimization frameworks. Thus, the novelty of this research lies in the first application of the BOG-integrated CVRP framework to Japan's domestic distribution network, which bridges the gap between large-scale international route models and under-recognized domestic logistics needs.

The academic literature surrounding maritime LNG optimization reveals a fundamental paradox: while extensive research exists on international LNG inventory routing problems, domestic distribution networks—particularly within major consuming nations like Japan—remain virtually unexplored. The Vehicle Routing Problem emerged from practical necessity in the late 1950s, when Dantzig and Ramser (1959) formulated *The Truck Dispatching Problem* to address real-world logistics challenges. Clarke and Wright's (1964) savings algorithm remains one of the most widely applied constructive heuristics, calculating savings $s_{ij} = c_{0i} + c_{0j} - c_{ij}$for merging routes while respecting capacity constraints.

The adaptation of VRP methodologies to maritime contexts required fundamental reconceptualization of constraint structures and objective functions. The critical breakthrough for LNG-relevant modeling emerged through Christiansen and Nygreen's (1998) work, which introduced Maritime Inventory Routing Problems (MIRPs). Their work addressed the fundamental challenge of combining vessel routing decisions with inventory management at both loading and discharge ports.

Grønhaug et al.'s (2010) work in *Transportation Science* established the first dedicated LNG optimization model, developing branch-and-price methods that explicitly incorporated BOG losses of 0.1–0.15% daily into routing optimization. The most comprehensive LNG routing framework emerged from Rakke et al.'s (2011) rolling horizon heuristic for creating annual LNG delivery programs. Recent advances by Shao et al. (2014) employed arc-flow formulations with Dantzig–Wolfe decomposition to handle 365-day planning horizons with daily discretization.

Regional distribution networks provide the most relevant examples for domestic LNG routing optimization, yet published research remains limited. Budiyanto et al.'s (2023) analysis of Indonesian archipelagic distribution employed CVRP with greedy algorithms to optimize four distribution clusters. Zhao et al.'s (2022) analysis of Chinese domestic LNG networks demonstrated 9.87% annual cost reduction through optimized deployment of a 10-vessel fleet across three routes.

The comprehensive literature analysis reveals five fundamental gaps that this research addresses: (1) limited Japanese market analysis, (2) insufficient pure CVRP applications, (3) BOG integration complexity, (4) operational constraint integration, and (5) methodological framework limitations.

METHOD

This research employs a comprehensive methodological framework designed to address the complex, multi-dimensional nature of maritime LNG routing optimization while maintaining rigorous academic standards and practical applicability. The methodology integrates exact mathematical programming with sophisticated heuristic approaches, enabling both theoretical analysis and practical implementation across varying operational scales.

Mathematical Model Formulation

The core mathematical model employs a node-based formulation with explicit consideration of vessel capacity, BOG losses, and operational constraints specific to Japanese LNG terminal operations. The model's theoretical foundation builds upon established CVRP frameworks while introducing novel constraint structures.

Sets and Indices:

- N = {1, 2, ..., 8}: Set of LNG terminals representing major Japanese facilities
- K = {1, 2, ..., m}: Set of available vessels with varying capacity configurations
- i, j ∈ N: Terminal indices for routing decisions
- k ∈ K: Vessel index for fleet assignment decisions

Parameters:

- d_i: Base demand at terminal i (m^3)
- Q_k: Capacity of vessel k (m^3), analyzed across five scenarios (125,000-180,000 m^3)
- c_{ij}: Travel cost from terminal i to j (USD)
- p_i: Port charges at terminal i (USD)
- t_i: Total time at terminal i (days)
- β = 0.0015: Daily BOG loss rate (0.15%)
- d_i^{eff} = d_i × (1 - β × t_i): Effective demand incorporating BOG losses

Decision Variables:

- x_{ijk} ∈ {0,1}: Binary routing variable indicating vessel k travels from terminal i to j
- y_{ik} ∈ {0,1}: Binary assignment variable indicating terminal i is served by vessel k
- z_k ∈ {0,1}: Binary fleet variable indicating vessel k is utilized
- u_i ≥ 0: Auxiliary variable for subtour elimination

Objective Function:

Minimize: Z = ΣΣΣ c_{ij} x_{ijk} + ΣΣ p_i y_{ik} + Σ FC_k z_k

Subject to:

1. Service Coverage: Σ y_{ik} = 1 ∀i ∈ N
2. Capacity Constraint with BOG: Σ d_i^{eff} y_{ik} ≤ Q_k z_k ∀k ∈ K
3. Flow Conservation: Σ x_{ijk} = Σ x_{jik} = y_{ik} ∀i ∈ N, k ∈ K
4. Operational Efficiency: Σ y_{ik} ≥ 2 × z_k ∀k ∈ K
5. Subtour Elimination (MTZ): u_i - u_j + n × x_{ijk} ≤ n - 1 ∀i,j ∈ N, i ≠ j, k ∈ K

Solution Methodology

The research employs a multi-method approach combining exact optimization with proven heuristic techniques. MILP implementation utilizes PuLP library with CBC solver backend and Google's OR-Tools with SCIP solver. Both implementations employ identical mathematical formulations with 300-second time limits.

The heuristic component incorporates three complementary approaches:

1. **Greedy Construction Heuristic:** Rapid solution construction through iterative terminal selection based on efficiency metrics (demand/cost ratio).
2. **Clarke-Wright Savings Algorithm:** Classical approach calculating merger benefits s_{ij} = d_{0i} + d_{0j} - d_{ij} for terminal pairs while respecting capacity constraints.
3. **Genetic Algorithm:** Sophisticated search with population size 50, 100 generations, tournament selection (size=3), mutation rate 0.1, and fitness function f(x) = 1/(total_cost + penalty × underutilization).

Data Collection

The empirical component utilizes demand data from eight representative LNG terminals within Japan's domestic distribution network, selected to capture diversity and operational characteristics. The terminal dataset encompasses facilities across Tokyo Bay, Osaka Bay, Nagoya Area, and Kyushu terminals, with demand range 25,300 to 80,000 m³ per terminal (total system demand: 429,300 m³), port charges $150,000 to $200,000 per call, and operational efficiency of 23-29 hours laytime.

Validation Framework

The research employs comprehensive validation including: (1) input data integrity verification, (2) route feasibility analysis, (3) completeness and coverage assessment, (4) mathematical constraint compliance, (5) business logic verification, (6) optimality assessment, (7) sensitivity analysis, and (8) risk evaluation.

RESULTS AND DISCUSSION

Optimal Fleet Configuration Analysis

The systematic analysis of vessel capacity configurations from 125,000 to 180,000 m³ reveals critical insights into the relationship between fleet composition, operational efficiency, and risk management in maritime LNG distribution.

Table 1. Comprehensive Capacity Performance Comparison

Capacity (m³)	Fleet Size	Avg Utilization	Utilization Range	Risk Assessment
125,000	4 vessels	86.6%	45.2%	High
145,000	4 vessels	74.7%	59.8%	Medium-High
150,000	4 vessels	72.2%	55.7%	Medium-High
180,000	**3 vessels**	**80.2%**	**38.5%**	**Low**

Source: Results of primary data processing using MILP and Clarke-Wright Algorithm, 2024

The analysis reveals that the 180,000 m³ capacity configuration achieves optimal performance across multiple evaluation criteria. This configuration demonstrates superior balance between operational efficiency and risk management, requiring the minimum fleet size while maintaining reasonable utilization levels.

Table 2. Detailed Optimal Solution Analysis (180,000 m³ Configuration)

Vessel	Route	Cargo (m³)	Utilization	Cost (USD)
1	Depot → G → C	155,000	86.9%	$344,000
2	Depot → D → B → F	171,500	96.1%	$495,000
3	Depot → H → E → A	102,800	57.6%	$582,000

Source: MILP-PuLP optimization output with CBC solver, 2024

The optimal routing configuration exhibits sophisticated load balancing and geographic optimization. The multi-terminal route (D → B → F) achieves 96.1% utilization, demonstrating effective capacity utilization while maintaining a critical 3.9% safety margin necessary for operational reliability.

Boil-Off Gas Integration Impact

The integration of BOG considerations into the CVRP formulation demonstrates material impact on routing decisions and operational performance. Quantitative analysis shows: base system demand of 429,300 m³, BOG-induced decrease of 3,704 m³ (0.86%), average BOG impact per terminal of 463 m³, and maximum single-terminal impact of 672 m³ at Terminal F.

Table 3. Sensitivity Analysis of BOG Rate Variations

BOG Rate (daily)	Effective Volume (m³)	Decrease from Base
0.10%	428,055	0.29%
0.15%	425,608	0.86%
0.20%	423,161	1.43%

Source: Sensitivity analysis results from MILP optimization model with varying BOG parameters, 2024

The 180,000 m³ optimal configuration maintains feasibility across all BOG rate scenarios, with maximum route utilization remaining below 97% even under the highest BOG rate assumption. This robustness validates the configuration's suitability for operational implementation where BOG rates may vary due to weather conditions, vessel characteristics, or operational procedures.

Operational Constraint Analysis

When operational policies require minimum 80% target utilization with ±5% tolerance, the optimal configuration shifts significantly to 170,000 m³ capacity.

Table 4. Constrained Optimization Results (170,000 m³)

Vessel	Route	Utilization	Cargo Volume (m³)	Route Cost (USD)
1	D → H → E	84.8%	143,000	$562,000
2	G → B → A	89.3%	150,800	$519,000
3	C → F	80.5%	135,500	$340,000

Source: MILP optimization results with 80% minimum utilization constraint using OR-Tools SCIP solver, 2024

Performance characteristics show average utilization of 84.9% (within 0.1% of target), standard deviation of 3.6% (77% reduction from unconstrained 15.8%), and utilization range of 8.8% (77% reduction from unconstrained 38.5%). The 77% reduction in both standard deviation and utilization range represents substantial operational benefit through improved predictability.

Sensitivity Analysis

Comprehensive sensitivity analysis validates the optimal solutions' robustness under parameter variations. Testing under ±10% demand variations reveals differential robustness: 125,000 m³ under +10% demand shows 95.3% maximum utilization (exceeds safe operational limits), 150,000 m³ shows 79.4% average utilization (acceptable), while 180,000 m³ maintains 88.2% average utilization (optimal balance maintained). Additional testing across operational parameters confirms solution robustness with ±2 hour laytime variations showing no impact on optimal routing configuration, ±$20,000 port charge adjustments causing minimal impact, and ±0.5 day voyage time variations resulting in routes remaining optimal with utilization changes <2%.

Strategic Implications

The identification of optimal 170,000-180,000 m³ vessel capacity range provides actionable guidance for fleet investment decisions. Given Japan's current over-contracting situation with 12 million tonnes of surplus capacity, optimized domestic routing could significantly improve economic efficiency while enhancing supply chain flexibility. The successful integration of BOG considerations and validation of hybrid optimization approaches establish frameworks applicable to Japan's evolving LNG market, potentially enabling the country to leverage its extensive infrastructure more effectively while reducing operational costs and environmental impact.

CONCLUSION

This study advances maritime logistics optimization by developing a comprehensive CVRP framework tailored to Japan’s domestic LNG distribution, integrating Boil-Off Gas (BOG) dynamics into routing formulations using $d_i^{eff} = d_i(1 - \beta t_i)$, which balances theoretical rigor with practical applicability. Results indicate that 180,000 m³ vessels offer optimal performance under unconstrained conditions with 3-vessel deployment and 80.2%

average utilization, while operational consistency favors 170,000 m³ vessels achieving 84.9% utilization and substantially lower variability (3.6% vs. 15.8% standard deviation). The framework achieves full compliance with feasibility criteria, addressing Japan's 12 million tonnes over-contracting challenge and revealing the operational significance of a 0.86% system-wide BOG impact at high utilization. Beyond LNG, the methodology holds value for diverse maritime logistics contexts. Future research should explore stochastic CVRP formulations, multi-period and inventory-integrated planning, multi-depot and multi-commodity extensions, environmental objective integration, hybrid and machine learning-based algorithms, and real-time optimization capabilities, while addressing current model limitations involving deterministic assumptions, single-commodity focus, static routing, and computational constraints.

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