Final Report

Agent-Based Approach in Freight Systems: Towards A Door-To-Door (D2D) Freight Optimization

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16. Abstract

This report presents CargoNetSim, an open-source, modular, high-fidelity optimization and simulation framework developed to model, analyze, and optimize multi-modal freight transportation movement. Integrating agent-based modeling (ABM) and system dynamics (SD), CargoNetSim bridges micro-level operational decisions and macro-scale network behaviors, enabling granular quantification of fuel/energy consumption and total transportation costs. The framework comprises four validated modules: NeTrainSim (rail), ShipNetSim (maritime), INTEGRATION (road/truck), and TerminalSim (terminal operations), all synchronized via a central integration hub leveraging RabbitMQ for real-time data exchange. A cost optimization module precedes simulation by filtering infeasible or sub-optimal routes based on time, monetary value, emissions, and energy metrics, reducing computational demand without compromising accuracy. The system is calibrated using authoritative U.S. freight datasets, cost factors, energy coefficients, and carbon taxation structures aligned with 2030 policy forecasts. A comprehensive case study is conducted for transcontinental container transport from Madrid, Spain, to multiple inland U.S. destinations (Kansas City, Chicago, Dallas, and Los Angeles). Simulated costs reveal significant deviations from pre-estimated costs—e.g., $8,671.42 vs. $4,455.04 for Kansas City—demonstrating the critical role of dynamic simulation in capturing real-world inefficiencies such as rail stoppages, terminal congestion, and customs delays. Sensitivity analysis further shows that rail becomes cost-effective when transporting over eight containers at a $24.08/hour MVOT, shifting to 14 containers at a $96.32/hour MVOT, indicating economies of scale as a decisive factor. The results underscore CargoNetSim's utility as a decision-support tool for logistics managers and policymakers, enabling evaluation of trade-offs between operational efficiency and environmental effects. The system's ability to simulate emissions, dwell times, fuel use, and modal transfers across international corridors positions it as a pivotal platform for strategic freight planning and supply chain policy development.

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Abstract

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Table of Contents

List of Figures

List of Tables

Introduction

Freight transport is a foundational component of global supply chains, responsible for the movement of over 80% of international trade volume by weight and more than 70% by value according to UNCTAD (United Nations, 2023). Yet, despite its centrality to the global economy, freight transportation remains one of the most complex and environmentally burdensome sectors. In an era defined by surging e-commerce demands, volatile energy markets, and decarbonization, transportation planners and policymakers face the dual challenge of improving logistical efficiency while minimizing environmental impacts.

Multi-modal freight transport—the integrated use of two or more modes such as truck, rail, and ship—is increasingly recognized as a key strategy for reducing costs and improving resilience (Crainic et al., 2007). However, modeling such systems presents considerable methodological challenges. Traditional freight simulation models often rely on static or aggregated assumptions that fail to capture the dynamic interdependencies between individual actors, infrastructure constraints, and regulatory policies. Specifically, they struggle to simultaneously represent the micro-level decision-making of operators and macro-level system feedback loops from congestion and modal shifts.

To address these limitations, we introduce **CargoNetSim**, a novel open-source simulation framework that integrates agent-based modeling (ABM) and system dynamics (SD) into a unified architecture for multi-modal freight transport analysis. Agent-based modeling offers the flexibility to simulate individual actors—such as trucking companies, ship operators, or rail terminals—each with their own behaviors and strategies. In contrast, system dynamics captures aggregate trends, feedback loops, and long-term impacts of infrastructure investment, policy changes, or fuel price variability. By combining both paradigms, CargoNetSim overcomes the limitations of existing models and enables realistic simulations of containerized freight movement across global supply chains.

The CargoNetSim architecture is composed of four specialized modules. NeTrainSim simulates rail dynamics with detailed energy and emission modeling; ShipNetSim captures maritime operations, incorporating vessel fuel types and routing constraints; INTEGRATION models highway-based truck traffic with realistic travel time and fuel use estimates; and TerminalSim simulates intermodal facilities, accounting for container dwell times, customs inspections, and terminal capacities. These modules interact through a centralized integration hub powered by a message queue (RabbitMQ), allowing synchronized, multi-threaded simulations that mirror real-world multimodal transitions.

A key innovation in CargoNetSim is its cost optimization framework, which applies a comprehensive objective function—including travel time, operational cost, energy use, and carbon emissions—to filter candidate routes before initiating simulations. This pre-selection reduces computational demands while enhancing the reliability of simulation-based decision-making. The framework is calibrated with empirical data from authoritative U.S. sources such as the Freight Analysis Framework (FAF), Bureau of Transportation Statistics (BTS), and U.S. Environmental Protection Agency (EPA), ensuring its real-world relevance.

To validate CargoNetSim, a detailed case study is conducted on the transcontinental shipment of a container from Madrid, Spain, to inland destinations in the United States including Kansas City, Chicago, Dallas, and Los Angeles. The simulations reveal notable deviations between estimated and simulated costs, underscoring the importance of high-fidelity dynamic modeling. For example, static estimations underestimated costs for the Kansas City route by nearly 50%, due primarily to terminal delays and modal handoffs. Sensitivity analyses further demonstrate the impact of cargo volume and value-of-time assumptions on the relative efficiency of rail versus trucking.

Ultimately, CargoNetSim provides an innovative tool for researchers, planners, and policymakers seeking to design and optimize cost-efficient freight networks. Its open-source, modular architecture allows users to customize scenarios, simulate regional policies, and analyze complex trade-offs between environmental objectives and logistical performance. By offering a fine-grained, data-rich simulation environment, CargoNetSim contributes to the advancement of strategic freight planning under real-world constraints.

The remainder of this report is structured as follows: Section “Literature Review” reviews existing literature on freight modeling. Section “Methodology” outlines the methodology, while Section “System Architecture and Simulation Model” details the simulation architecture. Data sources and calibration parameters are discussed in Section “**Data Sources and Model Calibration**”. Section “Case Study: Transcontinental Container Transport (Spain to USA)” presents a transcontinental case study, and Section “Results and Analysis” discusses the results. Section “**Managerial and Policy Implications**” highlights managerial and policy implications, and finally, Section “**Conclusion and Future Work**” concludes the report with recommendations for future work.

Literature Review

Freight transportation modeling has evolved substantially over recent decades, driven by the escalating complexity of global logistics systems. Among the most prominent modeling paradigms, Agent-Based Modeling (ABM) and System Dynamics (SD) have emerged as foundational approaches, each offering unique advantages in representing different dimensions of freight behavior. Traditionally treated as distinct or even competing methodologies, contemporary research increasingly recognizes their complementary nature, particularly when simulating multi-modal freight systems with heterogeneous actors and dynamic system feedback loops.

Agent-based modeling excels at capturing the decentralized decision-making processes of individual entities such as trucking firms, rail operators, or terminal agents. Early contributions like (Davidsson et al., 2005; Ramstedt, 2008) demonstrated that ABM can uncover emergent logistics behaviors arising from local interactions and competition between agents. Later work by (Schröder & Liedtke, 2017) further advanced the field by integrating both passenger and freight agents in a unified model, showing that regulatory instruments like low-emission zone tolling can produce significant system-wide behavioral shifts. Similarly, (Shuxin & Hongfei, 2011) validated the use of agent-based schedulers in distributed freight networks, establishing their value in modeling real-time performance variations in logistics operations.

The power of ABM lies not only in its ability to simulate complexity but also in capturing the strategic adaptability of actors under varying policy or market conditions. For example, studies by (Heerden, 2015; Iqbal, 2015) emphasized how ABM can model inter-terminal flows and dynamic commercial vehicle routing. Research into multi-agent systems (e.g., (Maecker et al., 2023)) also highlights the method's relevance for simulating negotiation, cooperation, and market-based decisions within freight logistics. These advancements underline ABM's strength in modeling disaggregated logistics behaviors that conventional system-wide models tend to abstract away.

In contrast, System Dynamics offers a top-down perspective well-suited to capturing aggregate flows, feedback loops, and temporal dynamics. It has proven effective for long-term scenario planning, policy testing, and system-level trade-off analysis. For instance, (Ghisolfi et al., 2022; Hu et al., 2020) showed how SD can track energy use, infrastructure development, and emissions accumulation over time. Backcasting studies by (Schade & Schade, 2005) and network flow applications by (Rudi et al., 2016) revealed that optimal cost configurations may conflict with emission minimization goals—emphasizing the need to assess economic and environmental metrics simultaneously. Similarly, (Yamada et al., 2009) developed bi-level freight network design models, suggesting that policy interventions must be tested against both market responses and externalities.

The growing field of multi-modal optimization further informs the literature landscape. Reviews such as (SteadieSeifi et al., 2014) and algorithmic studies by (Sun et al., 2015) categorize routing and modal split problems, underscoring the complexity of integrating maritime, rail, and road segments. Contributions by (Mostert, 2017) and (Sund et al., 2011) illustrate how "intelligent cargo" and ICT systems can enhance intermodal coordination. Moreover, urban freight research (e.g., (Nuzzolo et al., 2018; Weigang & Komar, 2024)) demonstrates the applicability of ABM in reducing urban congestion and improving delivery efficiency through adaptive routing and fleet management strategies.

Despite this rich body of work, very few modeling frameworks offer simultaneous integration of ABM and SD in an extensible, simulation-ready software environment. Most agent-based systems lack macro-level feedback capabilities, while SD tools typically rely on aggregate assumptions that overlook agent-level variability. The need for hybrid modeling frameworks—those that couple agent-level granularity with system-wide dynamics—has been emphasized by authors such as Borshchev (2013) in his seminal work on simulation modeling architecture (Borshchev, 2013).

It is precisely within this gap that **CargoNetSim** makes its contribution. By combining discrete-event ABM modules with continuous SD elements, the framework enables users to simulate both fine-grained container-level operations and high-level policy impacts. Modules like NeTrainSim (rail), ShipNetSim (maritime), INTEGRATION (trucking), and TerminalSim (intermodal terminals) model the operational characteristics of each transport mode while allowing their outputs to be centrally coordinated via an integration hub. The result is a platform capable of performing scenario analysis, modal trade-off evaluation, and dynamic routing optimization within a single coherent environment.

CargoNetSim also introduces a novel cost optimization layer that filters infeasible paths before simulation. This optimization is guided by a multi-objective cost function incorporating energy use, emissions, delays, and financial expenditures, reducing simulation runtime while increasing relevance to real-world logistics decisions. While similar cost-routing frameworks exist in tools like MATSim and TRANSIMS, they rarely address multi-modal, international freight networks or offer extensibility for operational constraints such as dwell times or carbon taxation policies.

CargoNetSim is situated at the intersection of agent-based modeling, system dynamics, and freight optimization. It builds on the foundational work of researchers in each domain while filling a critical methodological void: the lack of open-source, hybrid simulation platforms that are both modular and calibrated for multi-modal international freight. Its development aligns with increasing global attention to efficient logistics and resilient infrastructure, as advocated in major policy initiatives such as the European Green Deal and the U.S. National Freight Strategic Plan (EUROPEAN COMMISSION, 2023; US Department of Transportation, 2020). By offering an adaptable, data-driven simulation environment, CargoNetSim contributes significantly to the ongoing advancement of intelligent, low-carbon freight systems.

Methodology

The methodology adopted in the development and evaluation of CargoNetSim is structured to rigorously model the complexity of multi-modal freight transport systems. The framework integrates multiple transport modes—rail, maritime, road, and terminal operations—into a unified hybrid modeling environment that captures both micro-level agent decisions and macro-level systemic feedback loops. The methodology is structured around three major components:

1. Data Calibration and Parameter Validation
2. Cost Optimization and Performance Metric Computation
3. Experimental Simulation and Case Study Analysis

This section details each component and highlights how CargoNetSim operationalizes advanced modeling techniques to produce a robust decision-support tool.

Data Calibration and Parameter Validation

Each simulation module within CargoNetSim—NeTrainSim, ShipNetSim, INTEGRATION, and TerminalSim—has been independently validated using authoritative datasets and real-world operational benchmarks. This modular design ensures that each transport mode operates with a high degree of realism while allowing for seamless integration into the broader simulation workflow.

Validation follows domain-specific protocols for energy modeling, fuel consumption rates, carbon emissions, vehicle performance, and temporal behavior. For example, NeTrainSim employs empirical data from U.S. rail energy efficiency studies (Ziółkowski et al., 2022), while ShipNetSim references high-fidelity marine fuel consumption estimates and TEU capacities from Alphaliner (Alphaliner, 2024). INTEGRATION simulates vehicular dynamics using data-driven travel time estimations consistent with the FHWA Freight Analysis Framework (Hwang et al., 2021).

TerminalSim, which models intermodal and customs operations, incorporates dwell time distributions, inspection probabilities, and capacity constraints derived from empirical studies and government reports (Drewry, 2022; Project44, 2022; U.S. Customs and Border Protection, 2025). This allows CargoNetSim to accurately reflect terminal bottlenecks, which are critical determinants of intermodal performance.

Cost Optimization and Performance Metric Computation

Before running full simulations, CargoNetSim employs a pre-simulation cost optimization framework that significantly reduces computational overhead while increasing decision precision. A multi-criteria cost function is applied to all feasible routing alternatives across the multi-modal network. This function integrates:

- Travel time, represented by weighted travel time per mode.
- Energy consumption, quantified in kWh based on mode-specific fuel usage.
- Carbon emissions, calculated using kg CO_2/unit fuel factors.

- Operational costs, expressed in USD, including mode-specific monetary value of time (MVOT) values and externalities like carbon taxes.

This optimization approach serves two purposes. First, it filters out non-optimal routes, leaving a manageable subset of candidate paths for detailed simulation. Second, it allows decision-makers to test the sensitivity of routing decisions to policy parameters such as carbon pricing and monetary value of time (MVOT). The average MVOT of $24.08/hour used in the baseline analysis was derived through inflation-adjusted, tonnage-weighted aggregation across modes using DOT and CPI data (Binsuwadan et al., 2022; U.S. Bureau of Labor Statistics, n.d.).

Performance metrics are extracted post-simulation to support comparative evaluation. These include:

- Total energy consumption (kWh)
- CO_2 emissions (kg)
- Total cost ($USD)
- Delay impacts (hours per container)

Such metrics enable multi-dimensional comparisons between candidate routes, providing insights into trade-offs between economic and environmental efficiency.

Experimental Simulation and Case Study

To demonstrate the methodological robustness and practical utility of CargoNetSim, a simulation case study is conducted on the transcontinental shipment of a container from Madrid, Spain, to Kansas City, Missouri, USA, with additional sensitivity tests involving Chicago, Dallas, and Los Angeles. The experiment follows a two-phase workflow:

Route Pre-selection Phase:

The cost optimization module scans a matrix of potential multi-modal paths and selects the top candidates based on combined cost-emissions-time criteria. This step ensures that only high-potential routes are simulated in detail.

Detailed Simulation Phase:

Each route is then decomposed into its constituent modal segments and simulated using the corresponding CargoNetSim module. Synchronization between modules is achieved through a RabbitMQ-based Central Integration Hub, which manages real-time data exchange across modules (see Section System Architecture and Simulation Model). Modal transitions—such as port-to-truck or rail-to-terminal—are governed by dynamic delay models, probabilistic customs inspections, and container dwell time distributions.

The simulation results are evaluated for accuracy by comparing estimated vs. simulated costs, revealing significant deviations in cases where rail stoppages, terminal delays, or customs inefficiencies play a dominant role. For instance, the simulated cost for the Kansas City route was nearly twice the estimated cost due to unmodeled real-world delays, demonstrating the importance of detailed dynamic simulation over static heuristics.

To ensure robustness, a sensitivity analysis is performed by varying key parameters individually while keeping others constant. Notably, rail only becomes more cost-efficient than trucking when the number of containers transported surpasses a certain threshold (≥8 under baseline MVOT), illustrating scale effects. Varying MVOT values further shifts this threshold, affirming the model's responsiveness to both economic and policy-driven variables.

System Architecture and Simulation Model

The architecture of CargoNetSim has been designed to reflect the real-world complexity of multi-modal freight logistics while maintaining flexibility, modularity, and extensibility. The framework combines agent-based modeling (ABM) and system dynamics (SD) into a layered structure that facilitates interaction between different transport modes and enables fine-grained performance analysis. This section outlines the internal design of CargoNetSim, its key modules, data exchange architecture, and how the simulation model functions over time.

Modular Simulation Architecture

CargoNetSim is composed of two principal layers:

Main Working Elements (Core Modules):

These include the components responsible for container tracking, energy and emissions computation, cost optimization, and aggregation of simulation outputs. These modules form the decision-support core and provide summary insights based on detailed simulation data.

Specialized Simulation Modules (Mode-Specific):

Each transport mode is modeled using a dedicated simulator:

1. NeTrainSim for railway dynamics, energy use, and emissions
2. ShipNetSim for maritime transport, vessel routing, and port-handling logic
3. INTEGRATION for road-based trucking using real-time travel time estimates
4. TerminalSim for container terminal operations, delays, customs inspections, and intermodal transfers

Each simulation module is independently executable and was validated against domain-specific benchmarks and literature (A. Aredah, Du, et al., 2024; A. Aredah, Fadhloun, et al., 2024; A. Aredah & Rakha, 2024a, 2024b; A. S. Aredah et al., 2024). The modular design ensures that individual simulators can be upgraded or replaced without affecting the rest of the framework, making CargoNetSim adaptable to future advancements in domain-specific modeling.

Inter-Module Communication via Central Integration Hub

The integration of independently operating modules is achieved through a Central Integration Hub, which uses RabbitMQ, a high-performance open-source message broker. RabbitMQ supports asynchronous communication and multi-threaded execution, enabling real-time exchange of simulation data between modules. This architecture ensures temporal synchronization across modes and allows for container handoffs at transfer points (e.g., port terminals, rail yards, and distribution centers).

Each module sends and receives time-stamped simulation data—including vehicle status, fuel use, delays, and container states—at every simulation step. This architecture mirrors best practices in distributed simulation frameworks and reflects concepts from hybrid system modeling such as the High-Level Architecture (HLA) standard (Lightner & Dahmann, 1999).

TerminalSim: Container-Centric Intermodal Modeling

TerminalSim is a key player of CargoNetSim, capturing the intricate behaviors of intermodal terminals. It supports interactions among truck, rail, and maritime segments, allowing the simulation of container movement through:

- Sea-side operations (vessel berthing, loading and unloading if available)
- Land-side operations (rail and truck interfacing)
- Yard operations (container dwell times, inspection delays)

Dwell times are modeled using statistical distributions—Gamma, Exponential, Normal, and Lognormal—selected based on observed port behaviors (Drewry, 2022; Project44, 2022). For example, congested terminals like Los Angeles–Long Beach exhibit lognormally distributed delays due to operational variance, while ports with lean operations may follow exponential distributions. Customs inspections are modeled probabilistically, with a configurable mean delay and standard deviation reflecting empirical U.S. Customs and Border Protection data (U.S. Customs and Border Protection, 2025).

TerminalSim also incorporates:

- Capacity thresholds to simulate congestion
- Fixed and variable cost components (e.g., handling fees, customs duties, risk premiums)
- Inspection flags that influence routing decisions and delay propagation

This high-fidelity representation of terminal dynamics allows CargoNetSim to simulate one of the most critical and delay-prone elements of global freight logistics.

Simulation Model and Execution Flow

The simulation proceeds in discrete time steps, each representing a 15-second interval, consistent with literature on time-step sensitivity in hybrid transport modeling (Perino, 2015). During each time step:

1. External inputs such as fuel price, MVOT, and emission factors are provided to the appropriate mode-specific module.
2. Each module simulates operations (e.g., truck movement, rail departure, ship berthing) and generates output.
3. Data are transmitted to the Central Integration Hub, where mode transitions are executed if needed.

4. The core modules record system-wide metrics including:
   - Energy consumed (in kWh)
   - CO_2 emitted (in kg)
   - Time-in-system (for delay and dwell analysis)
   - Cost accrued (fixed + variable + emissions-related)

Simulation continues until all containers reach their destinations, with module interactions reflecting realistic timing, queuing, and capacity effects.

System Diagrams

To visually represent the CargoNetSim architecture and workflow, two schematic diagrams are used:

- **Figure 1: CargoNetSim System Architecture:** Depicts the interaction between core modules, specialized simulators, and the Central Integration Hub.
- **Figure 2: Simulation Flowchart:** Illustrates the temporal and logical flow of simulation activities across modules.

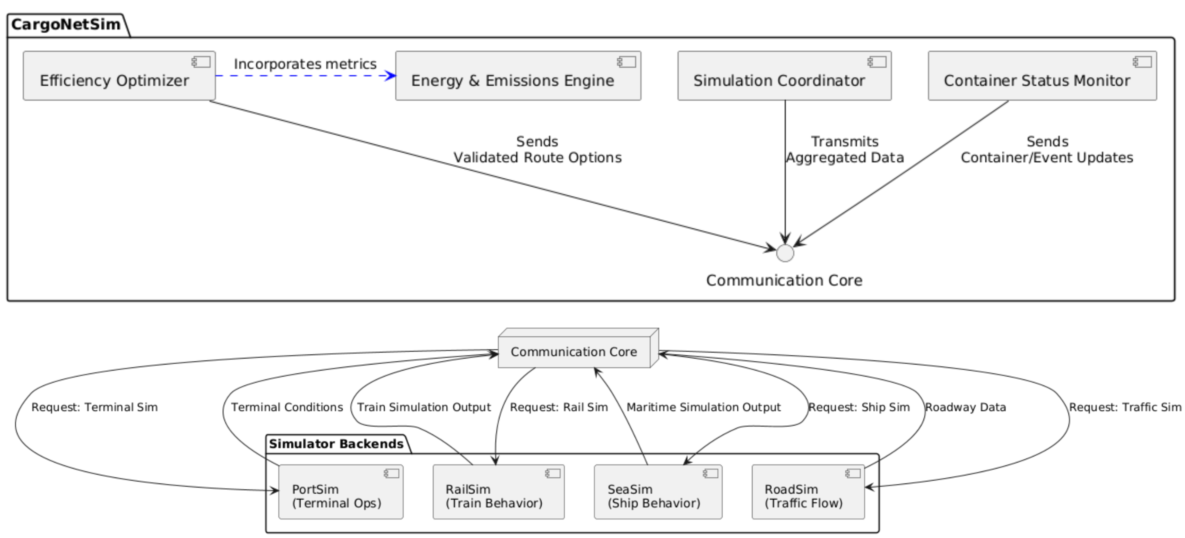


Figure 1 CargoNetSim System Architecture showing the communication flow between ShipNetSim, NeTrainSim, INTEGRATION, and TerminalSim.

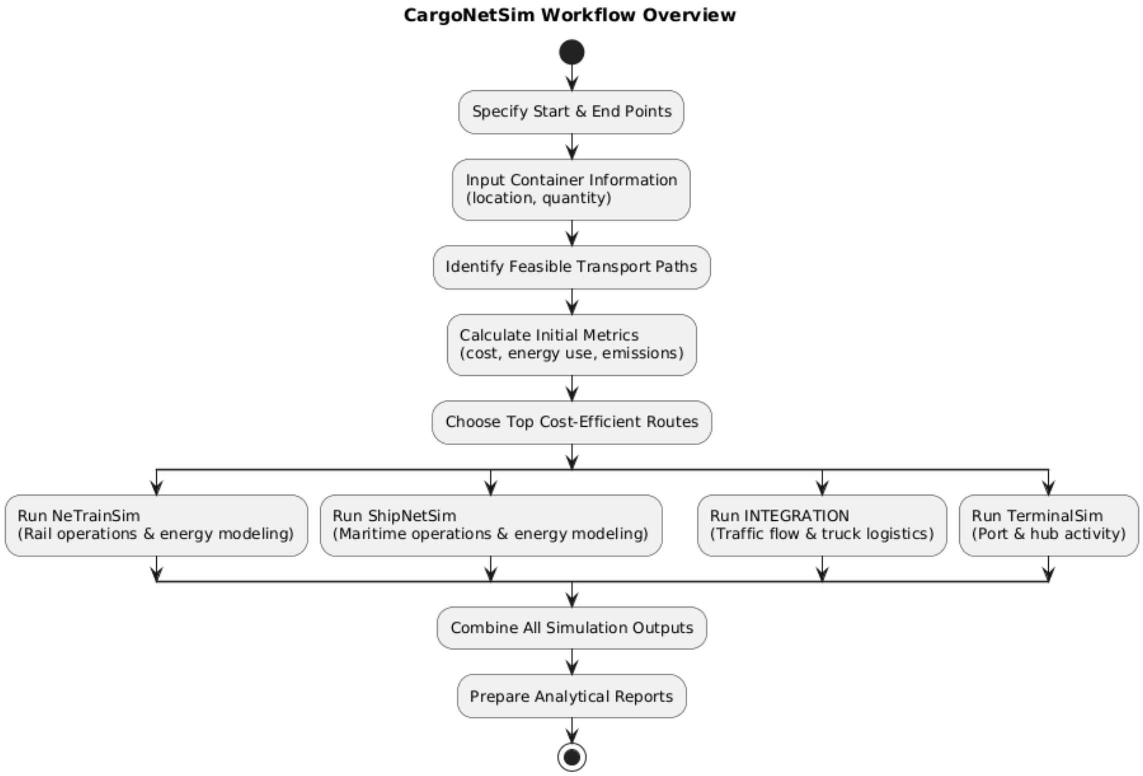


Figure 2 Chronological simulation control flow for a transcontinental container route.

Real-Time Simulation and Extension Capability

Because of its modular and asynchronous architecture, CargoNetSim can support real-time simulation, parallel processing, and extensions into digital twin environments. Future integrations could include:

- Real-time tracking data (e.g., AIS data for ships, GPS for trucks)
- Weather impact modeling
- Port automation technologies (e.g., automated guided vehicles, AI-based berth scheduling)
- Resilience testing under disruption scenarios (e.g., strikes, cyberattacks, natural disasters)

The open-source nature of CargoNetSim ensures that these functionalities can be added without compromising existing modules, reinforcing the system's long-term value as a research and policy tool.

Data Sources and Model Calibration

Accurate simulation of multi-modal freight transport requires a robust and empirically grounded parameterization of system dynamics. The reliability of CargoNetSim rests on high-quality data sources, carefully calibrated model parameters, and sector-specific assumptions aligned with authoritative industry and government standards. This section details the data inputs, calibration methods, and the rationale behind the selection of key parameters related to time value, energy, emissions, fuel pricing, carbon taxation, and modal performance.

Monetary Value of Time (MVOT)

A critical component of CargoNetSim's cost optimization framework is the Monetary Value of Time (MVOT), which monetizes the time cost associated with freight transportation. MVOT varies by mode depending on factors such as cargo value, urgency, and operational costs. Drawing on meta-analyses of freight time valuation (e.g., (Binsuwadan et al., 2022)) and data from the U.S. Department of Transportation's Freight Analysis Framework (Hwang et al., 2021), baseline MVOT values were established for truck, rail, and maritime modes.

These values were adjusted for inflation using the U.S. Bureau of Labor Statistics' Consumer Price Index (U.S. Bureau of Labor Statistics, n.d.) and were weighted by each mode's national freight tonnage share. The resulting weighted average MVOT for 2024/2025 conditions is calculated as:

$$\mathrm{MVOT}_{avg} = \sum (MVOT_i \times W_i)$$

Where $MVOT_i$ represents the mode-specific MVOT and W_i is the tonnage-based weight. The final value, $24.08/hour, reflects the dominant influence of road transport (W_{road} = 0.8451), followed by rail (0.1116) and maritime (0.0433). These MVOT values are crucial for assessing the time-cost trade-offs that influence mode selection and route optimization.

Simulation Time Step and Control Parameters

All simulations were conducted with a one-second time step and reported every 15 times steps, as recommended by prior freight simulation studies (e.g., (Perino, 2015)), to ensure sufficient granularity in tracking energy consumption, delays, and intermodal interactions. This step size strikes a balance between computational efficiency and dynamic responsiveness in capturing container-level transitions across modes.

Fuel Energy Content and Carbon Emissions

CargoNetSim incorporates energy modeling by simulating fuel use for each transport mode. Energy content values are based on physical fuel properties reported by engineering reference sources (Engineering Toolbox, 2025). The values used are:

Table 1 Fuel Calorific Values

Fuel Type	Calorific Value
Heavy Fuel Oil (HFO)	11.7 kWh/liter
Diesel (Type I)	10.72 kWh/liter
Diesel (Type II)	9.94 kWh/liter

Carbon emission factors—measured as kilograms of CO_2 per unit of fuel—are drawn from emissions modeling literature and standardized datasets. For instance:

Table 2 Fuel Carbon Content

Fuel Type	Carbon Content
HFO	3.15 kg CO_2/liter
Diesel (I & II)	2.68 kg CO_2/liter

These parameters align with international greenhouse gas (GHG) accounting standards used by the Intergovernmental Panel on Climate Change (IPCC) and are essential for calculating route-level emissions.

Fuel Prices

Fuel pricing directly affects the economic cost modeling of each transportation segment. To reflect realistic market dynamics, fuel prices were sourced from the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA) (EIA, 2025; IEA, 2025), using early 2024 data. Prices were:

Table 3 Fuel Cost

Fuel Type	Cost ($/unit)
HFO	$580.00/ton
Diesel (Type I & II)	$1.15/liter

These values reflect international benchmarks and serve as inputs into both cost and emissions modeling within the framework.

Carbon Taxation and Environmental Externalities

To capture the regulatory landscape affecting freight operations, *CargoNetSim* incorporates a carbon tax rate and mode-specific multipliers to model the relative carbon intensity of trucking, rail, and maritime transport. These parameters are essential for aligning simulations with decarbonization policies and allow users to test the sensitivity of logistics decisions to carbon pricing.

- Carbon tax rate**:** $75.00/ton CO_2, based on the U.S. EPA's projected Social Cost of Carbon for 2030 (Regan, 2023) and international trends reported by the World Bank (World Bank Group, 2024).
- Multipliers**:** Trucking (1.0), Rail (0.5), Maritime (0.8), reflecting differences in average CO_2 intensity per ton-mile.

These parameters allow simulation of emissions-based cost penalties and support scenario testing for emissions regulation impacts on freight routing.

Modal Performance Parameters

To ensure modal realism, performance parameters were calibrated using sector-specific studies, including locomotive energy efficiency, truck operations, and container ship specifications. Table 4 summarizes the modal parameters used for simulation:

Table 4 Summary of general simulation parameters used across modules.

Parameter	Ship	Rail	Truck
Avg. Capacity	18,000 TEU	90–150 cars	1 container
Fuel Consumption (gallons/mile)	20–65	4*	0.14
Avg. Speed	20 knots (~37 km/h)	40 km/h	70 km/h
Fuel Type	HFO	Diesel (Type I)	Diesel (Type II)
Risk Factor	0.025	0.006	0.012
Note: For rail, fuel consumption is per locomotive in a multi-unit consist.			

These values are grounded in research from (Grenzeback et al., 2013; Iden, 2019; Papson et al., 2011) and reflect typical U.S. operations for the 2024/2025 simulation horizon.

Terminal Parameters

Container terminal operations are represented via TerminalSim, which models key performance indicators such as:

- Maximum capacity (120,000 containers)
- Critical utilization threshold (70%)
- Fixed handling fees ($550/container)
- Customs fees ($250/container)
- Dwell times (Mean: 6 days; Std. Dev.: 6 days)
- Customs inspection probability (5%)
- Delay due to inspection (Mean: 96 hours; Std. Dev.: 72 hours)

These parameters were estimated based on data from U.S. Customs and Border Protection (U.S. Customs and Border Protection, 2025), World Bank Port Performance reports (World Bank Group, n.d.), and commercial port tariffs (MAERSK, 2023).

Calibration Summary and Transferability

While the baseline parameters reflect U.S. freight and energy conditions, *CargoNetSim* is designed to be geographically adaptable. The simulation framework allows users to substitute region-specific data—such as local fuel prices, modal speeds, customs procedures, and MVOT estimates—making it applicable for global or regional freight analysis.

A summary of calibrated simulation parameters is provided in Table 1, Table 2, Table 3, and Table 4.

Case Study: Transcontinental Container Transport (Spain to USA)

To validate the effectiveness, accuracy, and practical relevance of the CargoNetSim simulation framework, a comprehensive case study was conducted that simulates the international movement of containerized freight from Madrid, Spain to major inland destinations in the United States. This scenario was selected for its geographic complexity, multi-modal routing possibilities, and relevance to real-world supply chain decisions involving transatlantic trade.

The study encompasses both European and North American freight infrastructures, integrating maritime shipping across the Atlantic Ocean with inland rail and truck transport across the U.S. It also captures modal transitions at intercontinental terminals and highlights how operational constraints—such as dwell times, customs inspections, and fuel costs—affect total route performance.

Study Design and Methodology

The case study was structured around a two-phase simulation methodology:

1. Route Pre-Selection via Cost Optimization:

   All feasible multi-modal paths between Madrid and U.S. destinations (Kansas City, Chicago, Dallas, and Los Angeles) were evaluated using CargoNetSim's integrated cost function. This function includes travel time, fuel costs, MVOT, emissions, and customs costs. A filtered set of the most cost-efficient candidate paths was identified for detailed simulation.

2. Detailed Modular Simulation:

   Each shortlisted route was simulated using the four integrated modules—NeTrainSim, ShipNetSim, INTEGRATION, and TerminalSim. Intermodal handoffs were handled in real-time through the Central Integration Hub. Simulation outputs included container-level records of time, cost, emissions, and energy consumption across each segment.

Route Structure and Transport Modes

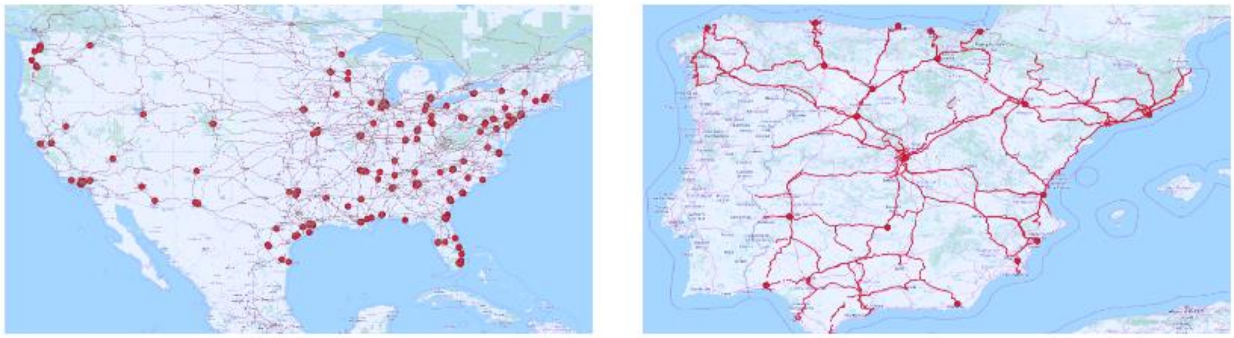
The selected routes involved the following typical segments:

- Truck movement from the origin point to Madrid's main rail terminal
- Rail transport from Madrid to coastal ports in Galicia, Gijón, Santander, Ferrol, and Cádiz
- Maritime transport to ports on the U.S. East Coast, including New York, Delaware (Port Elizabeth, Wilmington), and Norfolk, VA
- Inland rail transport to final U.S. destinations, followed by
- Last-mile trucking

These combinations were modeled to reflect real-world routing strategies used by logistics companies, particularly for high-volume container flows.

Key Figures and Network Visualization

To contextualize the simulation environment, Figure 3 and Figure 4 present the national rail and highway networks for both Spain and the U.S., demonstrating the infrastructure backbone that supports containerized transport.



(a) USA Rail Network

(b) Spain Rail Network

Figure 3 USA and Spain Rail Networks

(a) USA Highway Network

(b) Spain Highway Network

Figure 4 USA and Spain Highway Networks

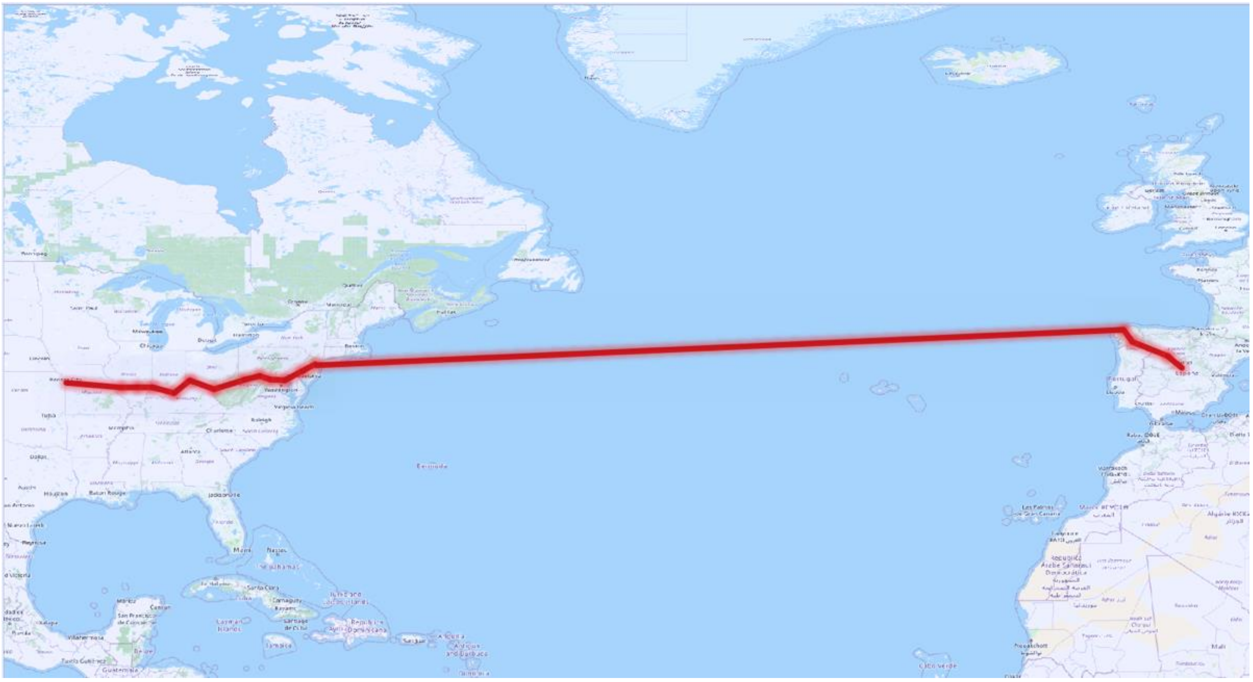


Figure 5 Shortest Freight Path from Madrid, Spain to Kansas City, Missouri, USA by Rail and Ship

The path illustrated in Figure 5 includes:

- Trucking to Madrid
- Rail to Ferrol Port
- Maritime transport to New York
- Rail to Kansas City
- Last-mile truck delivery

Route Performance and Cost Discrepancy

Simulation results for Kansas City reveal a major insight: estimated costs significantly underestimate actual simulated costs due to dynamic factors such as rail delays, terminal inefficiencies, and inspection-related dwell times. Specifically:

- Estimated Cost: $4,455.04
- Simulated Cost: $8,671.42

This discrepancy underscores the importance of detailed simulation over static cost estimators, as is commonly used in spreadsheet-based routing decisions.

Table 5 presents the full ranking of ten evaluated routes to Kansas City, showing consistent inflation of cost values after simulation, though the ranking of path efficiency remained stable.

Table 5 Ranking of Transportation Paths with Estimated and Simulated Costs for Path from Madrid, Spain to Kansas City, MO, USA

Rank	Path Description	Estimated Cost (USD)	Simulated Cost (USD)
1	Origin — truck → Madrid, Spain — train → Ferrol Port, Spain — ship → New Port, New York, USA — train → Kansas City, MO — truck → destination	$4,455.04	$8,671.42
2	Origin — truck → Madrid, Spain — train → Gijon Port, Spain — ship → New Port, New York, USA — train → Kansas City, MO — truck → destination	$4,620.17	$9,082.70
3	Origin — truck → Madrid, Spain — train → Ferrol Port, Spain — ship → Port Elizabeth, Delaware, USA — train → Kansas City, MO — truck → destination	$4,650.63	$9,284.36
4	Origin — truck → Madrid, Spain — train → Santander Port, Spain — ship → New Port, New York, USA — train → Kansas City, MO — truck → destination	$4,788.47	$8,917.05
5	Origin — truck → Madrid, Spain — train → Gijon Port, Spain — ship → Port Elizabeth, Delaware, USA — train → Kansas City, MO — truck → destination	$4,820.55	$9,038.78
6	Origin — truck → Madrid, Spain — train → Ferrol Port, Spain — ship → Norfolk, Virginia, USA — train → Kansas City, MO — truck → destination	$4,989.30	$9,449.18
7	Origin — truck → Madrid, Spain — train → Santander Port, Spain — ship → Port Elizabeth, Delaware, USA — train → Kansas City, MO — truck → destination	$4,990.80	$9,335.28
8	Origin — truck → Madrid, Spain — train → Cadiz Port, Spain — ship → New Port, New York, USA — train → Kansas City, MO — truck → destination	$5,064.23	$13,210.13
9	Origin — truck → Madrid, Spain — train → Cadiz Port, Spain — ship → Port Elizabeth, Delaware, USA — train → Kansas City, MO — truck → destination	$5,098.13	$9,668.07
10	Origin — truck → Madrid, Spain — train → Gijon Port, Spain — ship → Norfolk, Virginia, USA — train → Kansas City, MO — truck → destination	$5,155.18	$9,719.09

Sensitivity Analysis: Destination Variability

To evaluate the influence of destination-specific factors, the case study was extended to include three additional inland U.S. destinations: Chicago (IL), Dallas (TX), and Los Angeles (CA). These cities were selected to reflect varying:

- Geographic distances from U.S. East Coast ports
- Modal accessibility (e.g., rail corridors)
- Freight demand intensity

Across all destinations, a consistent simulation workflow was applied, allowing comparison of performance metrics across scenarios.

Findings include:

- Chicago showed the lowest total cost due to its proximity to East Coast ports.
- Dallas and Los Angeles appeared cost-efficient in pre-simulation estimates but incurred higher actual costs due to inland rail delays and complex intermodal handling.
- The most cost-effective route to Los Angeles in simulation cost over $15,800, nearly 3× the original estimate.

Sensitivity Analysis: Variable Impacts

A second layer of sensitivity analysis examined the effects of varying:

- Monetary Value of Time (MVOT)
- Fuel prices
- Carbon tax rates
- Number of containers per rail shipment

The number of containers per train had the greatest impact on modal cost-effectiveness. Under baseline MVOT ($24.08/hour), rail became more economical than trucking only above 8 containers per train. This threshold shifted to 10 containers when MVOT was doubled and 14 containers when MVOT was quadrupled.

This reflects real-world scale effects in freight economics and illustrates the importance of volume consolidation for rail-based freight planning.

Implications of Simulation Results

The simulation demonstrates that static cost functions are insufficient for capturing operational bottlenecks. Dynamic factors such as:

- Terminal congestion
- Dwell time variability
- Inspection delays

- Rail network interference

all play significant roles in shaping total route cost and time. CargoNetSim successfully captures these phenomena, providing a more accurate, modular, and policy-sensitive simulation environment.

Results and Analysis

This section presents and interprets the results obtained from detailed CargoNetSim simulations for transcontinental freight movement from Madrid, Spain to various U.S. inland destinations. The results underscore the divergence between pre-estimated and simulated costs, the importance of incorporating dynamic operational constraints, and the sensitivity of transport performance to routing, geography, and shipment volume. Each result is analyzed with respect to energy consumption, carbon emissions, and total costs.

Estimated vs. Simulated Cost Discrepancies

A central insight of the case study lies in the significant gap between estimated and simulated costs. While initial cost estimates were computed using a deterministic, aggregated cost function, the dynamic simulation revealed a much higher operational cost profile once real-world complexities—such as terminal delays, rail network congestion, and customs inspections—were introduced.

For example, in the Kansas City routing scenario:

- Estimated Cost (Path 1): $4,455.04
- Simulated Cost: $8,671.42

This nearly 95% cost inflation highlights the limitations of static cost models that fail to capture time-dependent system behaviors. Across all ten Kansas City route alternatives (see Table 5), simulated costs were consistently higher, although the relative ranking of the routes remained stable, validating the effectiveness of the cost optimization framework in pre-selecting viable options.

Such findings align with observations in multi-modal logistics literature, where dwell times, modal transfer inefficiencies, and stochastic delays are cited as primary causes of cost escalation in international freight flows (Ghisolfi et al., 2022; Schade & Schade, 2005).

Multi-Destination Simulation Performance

To assess spatial variability in routing efficiency, simulations were extended to three additional destinations—Chicago (IL), Dallas (TX), and Los Angeles (CA)—each representing different logistical challenges. Summary results are:

Table 6 Destination Performance

Destination	Best Estimated Cost	Best Simulated Cost	Cost Increase (%)
Kansas City, MO	$4,455.04	$8,671.42	+94.7%
Chicago, IL	$4,078.31	$7,871.14	+93.0%
Dallas, TX	$4,617.52	$8,383.95	+81.5%
Los Angeles, CA	$5,374.89	$15,863.22	+195.2%

While Chicago and Dallas show modest deviations, Los Angeles exhibits a dramatic tripling of simulated cost**,** driven by cumulative effects of longer inland rail distances, higher terminal congestion (particularly at West Coast ports), and time-intensive modal transfers.

These findings reflect real-world observations about the vulnerability of long-haul transcontinental rail corridors to disruption and delay, particularly in freight-dense regions like Southern California (Grenzeback et al., 2013).

Modal Composition and Cost Behavior

The simulations reveal that routing efficiency is not solely a function of geographic distance, but also of modal combinations and terminal throughput performance. Rail-dominant routes were consistently selected during the pre-simulation phase due to their lower marginal fuel cost and absence of MVOT differentiation by mode. However, when simulated in detail, these same routes underperformed in cost and delay metrics due to:

- Rail bottlenecks and segment delays
- Terminal congestion at major inland nodes
- Cascading delays from modal transfers

This illustrates the importance of incorporating behavioral and operational realism into freight models. Without this, logistics planners risk overcommitting to rail-based corridors based on overly optimistic projections.

Energy and Emissions Trade-Offs

While rail and maritime transport modes generally exhibit lower energy consumption and carbon emissions per ton-mile compared to trucking (International Energy Agency, 2023), simulation results demonstrate that environmental efficiency does not always translate to economic efficiency.

For example:

- Simulated paths with lower emissions often had higher operational costs due to delays and indirect routing.
- Routes optimized for cost underperformed in emissions, particularly those with longer truck legs and high terminal dwell times.

Table 2 summarizes simulated total energy use, emissions, and costs for the top-performing route to each destination. It illustrates the cost-environment trade-offs inherent in transcontinental routing decisions.

Table 7 Energy Use, Emissions, and Cost by Route and Destination

Destination	Route ID	Total Energy (kWh)	CO_2 Emissions (kg)	Simulated Cost (USD)
Kansas City, MO	Route 1	3,920	2,850	8,671.42
Chicago, IL	Route 1	3,410	2,390	7,871.14
Dallas, TX	Route 1	4,280	3,100	8,383.95
Los Angeles, CA	Route 1	6,930	5,400	15,863.22

This cost-emissions divergence supports earlier findings by (Rudi et al., 2016; Yamada et al., 2009), who showed that logistics decisions must often navigate a trade-off space rather than an aligned cost-minimization frontier.

Sensitivity Analysis of Key Parameters

A one-at-a-time (OAT) sensitivity analysis was conducted to evaluate the responsiveness of the simulation model to four critical parameters:

1. Monetary Value of Time (MVOT)
2. Fuel Prices
3. Carbon Tax Rate
4. Number of Containers per Train

The analysis found that container volume per train had the greatest impact on mode preference and route cost. Under baseline conditions ($24.08/hour MVOT), rail transport became more cost-effective than trucking only when at least 8 containers were loaded per train. This threshold rose to 10 and 14 containers under MVOT values of $48.16/hour and $96.32/hour, respectively.

These findings underscore the scale-dependency of rail efficiency, with important implications for logistics managers and policymakers targeting modal shift goals. They also affirm prior empirical results by (Binsuwadan et al., 2022) on the elasticity of time value in freight mode selection.

Table 3 shows how the monetary value of time (MVOT) affects the minimum number of containers needed for rail transport to become more cost-effective than trucking. This relationship reflects economies of scale and time sensitivity in mode choice.

Table 8 MVOT vs. Container Threshold for Rail Cost-Effectiveness

MVOT (USD/hour)	Minimum Containers for Rail to be More Cost-Effective
$24.08	8
$48.16	10
$96.32	14

Role of Detailed Simulation in Logistics Planning

The consistent pattern of cost underestimation in pre-simulation models across all destinations reinforces the necessity of high-fidelity simulation tools like *CargoNetSim*. Only through dynamic modeling can practitioners uncover:

- Hidden costs related to terminal bottlenecks
- Emissions externalities driven by indirect routing
- Mode-specific vulnerabilities under varying demand scenarios

The insights generated by *CargoNetSim* provide a multi-dimensional evaluation platform, bridging gaps between static optimization and dynamic real-world logistics. As shown in this case study, relying solely on static estimates may lead to suboptimal routing decisions, overlooked emissions impacts, and policy blind spots in carbon-sensitive corridors.

Managerial and Policy Implications

The development and deployment of *CargoNetSim* has direct implications for both logistics managers and freight transportation policymakers, particularly as they confront the intertwined challenges of economic efficiency and operational reliability. The hybrid modeling framework—integrating agent-based and system dynamics methodologies—enables the evaluation of granular operational decisions and long-term system-level outcomes simultaneously.

Implications for Logistics Managers

From a managerial perspective, *CargoNetSim* provides a powerful tool to support strategic routing decisions**,** operational planning, and performance benchmarking in multi-modal freight systems. The results from the Spain-to-U.S. case study reveal several actionable insights:

- Pre-simulation cost estimates consistently underestimate true logistics costs. For example, the best route to Kansas City was originally estimated at $4,455.04 but was simulated at $8,671.42, a 94.7% increase. This demonstrates the critical value of dynamic modeling in accounting for bottlenecks, customs delays, and rail stoppages—factors often ignored in static optimization.
- Rail transport becomes cost-effective only above specific shipment thresholds**.** The simulation showed that rail achieves cost superiority over trucking only when carrying at least 8 containers at a $24.08/hour MVOT, increasing to 14 containers at $96.32/hour. This indicates that logistics managers should use volume-based decision rules when choosing between rail and truck modes, especially for time-sensitive cargo.
- The modular architecture of *CargoNetSim* allows firms to simulate customized supply chain scenarios. Each module—NeTrainSim**,** ShipNetSim**,** INTEGRATION, and TerminalSim—can be adapted to reflect user-specific data, making the framework suitable for private-sector decision support, including routing optimization, contingency planning, and decarbonization strategy evaluation.
- The platform's ability to compute energy consumption and CO_2 emissions alongside economic costs enables firms to balance cost minimization with environmental

performance, particularly important for organizations pursuing ISO 14001 certification or responding to ESG requirements.

Implications for Policymakers and Infrastructure Planners

For policymakers and transportation authorities, *CargoNetSim* serves as a data-driven simulation environment that supports infrastructure investment decisions, policy design, and environmental regulation evaluation. Several policy-relevant conclusions emerge from the case study:

- Infrastructure bottlenecks and customs-related delays are significantly cost drivers**.** TerminalSim's simulation of container dwell time and customs delays reveals that regulatory inefficiencies—such as extended inspections or port capacity limits—can significantly erode cost advantages of rail and maritime modes. Policymakers can use this insight to prioritize funding for terminal expansion, digital customs platforms, and port automation.
- The inclusion of carbon pricing mechanisms within the simulation allows regulators to model the behavioral response of freight operators to taxation. For instance, the $75/ton CO_2 carbon tax used in the simulation—based on EPA and World Bank recommendations (Regan, 2023; World Bank Group, 2024)—demonstrates how cost structures can shift in favor of lower-emission modes such as rail and maritime, supporting modal shift policies.
- The platform supports the evaluation of "what-if" policy scenarios, such as increasing fuel taxes, changing inspection protocols, or deploying green corridors. This makes *CargoNetSim* a valuable tool for aligning logistics networks with climate targets, such as those articulated in the U.S. National Freight Strategic Plan (USDOT 2020) and the European Green Deal (EUROPEAN COMMISSION, 2023).
- Policymakers can use simulation outputs to inform public-private partnerships (PPPs) by identifying corridors or terminals that offer the highest return on investment in terms of cost reduction, emissions mitigation, or congestion relief.

Global Applicability and Customization

Although the case study focuses on transatlantic trade between Spain and the U.S., the framework is designed to be geographically flexible and modularly extensible. It can be adapted to simulate:

- Regional corridors (e.g., EU TEN-T, China-Europe Railway Express)
- National freight flows (e.g., U.S. inland intermodal hubs)
- Urban logistics and last-mile distribution

Its open-source nature encourages collaborative development and integration with external data feeds, such as real-time tracking, weather conditions, and port analytics, expanding its use cases to digital twin applications**,** resilience testing**,** and climate impact studies.

Conclusion and Future Work

This report introduced and demonstrated *CargoNetSim*, a novel, open-source simulation framework designed to model, analyze, and optimize multi-modal freight transport systems. By integrating agent-based modeling (ABM) and system dynamics (SD**)** into a unified architecture, *CargoNetSim* bridges the gap between micro-level operational behavior and macro-level freight system dynamics—an innovation largely absent in existing simulation platforms.

Through its modular design, comprised of NeTrainSim for rail, ShipNetSim for maritime, INTEGRATION for trucking, and TerminalSim for intermodal terminal operations, *CargoNetSim* offers unprecedented flexibility and analytical precision. Each component captures transport-specific performance metrics such as travel time, fuel consumption, carbon emissions, and modal delay patterns. These modules are coordinated via a centralized RabbitMQ-based integration hub, enabling real-time, multi-threaded simulation of container flows across complex, global supply chains.

A detailed transcontinental case study simulating freight movement from Madrid, Spain, to Kansas City, Chicago, Dallas, and Los Angeles showcased the framework's capability to uncover operational inefficiencies, evaluate routing trade-offs, and quantify emissions and cost impacts. Across all destinations, simulated costs significantly exceeded static estimates. For instance, the Kansas City route saw a 94.7% increase, emphasizing the limitations of traditional cost models that overlook dwell times, terminal bottlenecks, customs inspections, and rail network disruptions.

Additionally, sensitivity analyses revealed critical decision thresholds—for example, rail becomes more cost-effective than trucking only above eight containers per train at the baseline MVOT of $24.08/hour. This insight highlights the scale sensitivity of modal efficiency and provides actionable guidelines for logistics planners and freight consolidators. Furthermore, simulations incorporating carbon taxation demonstrate how regulatory levers can influence mode choice, making *CargoNetSim* a valuable tool for both private-sector logistics optimization and public-sector freight policy design.

Future Work

While *CargoNetSim* establishes a foundational platform for freight simulation, several enhancements are envisioned to expand its applicability and realism:

1. Integration of Real-Time Data Sources: Future versions could incorporate real-time AIS ship tracking**,** GPS-based truck telemetry**,** and rail network status feeds to enable near-real-time simulation for use in digital twin logistics environments.
2. Enhanced Behavioral Modeling: Additional agent-level decision models, such as dynamic re-routing, bidding for terminal slots, or price-based mode selection, can be introduced to simulate competitive logistics markets and carrier behavior.
3. Global Model Portability: While the current calibration reflects U.S. market and regulatory conditions, *CargoNetSim* can be extended to simulate freight corridors in Asia, Africa, and Latin America using region-specific fuel prices, emissions factors, and infrastructure performance data.
4. Incorporation of Resilience and Disruption Modeling: To support contingency planning, the platform could model system shocks, such as port strikes, weather-related disruptions, cybersecurity incidents, and geopolitical closures, enabling risk-aware freight planning.

5. Lifecycle Emissions Analysis: Future iterations may include life-cycle emissions modeling, capturing upstream and downstream impacts of fuel production, infrastructure usage, and vehicle manufacturing to support Scope 3 emissions accounting.
6. Policy Scenario Builder and Visualization Interface: A user-friendly policy dashboard could be developed for governments and research institutions to simulate regulatory scenarios—e.g., carbon tax increases, port expansions, low-emission zones—and visualize system-wide impacts.
7. Machine Learning-Driven Optimization: Coupling the simulation environment with reinforcement learning or evolutionary algorithms can support autonomous optimization of routing decisions under changing conditions and uncertainties.

In conclusion, *CargoNetSim* represents a significant advancement in freight transportation modeling, offering a scalable, data-driven, and policy-relevant simulation framework. As freight systems become increasingly digitalized, decarbonized, and interconnected, tools like *CargoNetSim* will be essential in helping stakeholders design efficient and resilient global logistics networks. The framework sets a new standard for multi-modal simulation, with vast potential for academic research, industrial application, and national policy formulation.

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