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Optimization of Carrier Selection and Cargo Consolidation in U.S. Freight Transportation: A Game Theory and TSP Approach

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Abstract: Background: In the competitive realm of freight transportation, optimizing carrier selection and consolidation strategies is paramount to reducing operational costs and enhancing supply chain efficiency. **Methods:** This paper presents an integrated framework that combines game theory—via an auction method—and the Traveling Salesman Problem (TSP) for route optimization, applied to U.S. freight logistics. New supplier cities across the Eastern, Central, and Western regions of the United States are considered, and two optimal consolidation warehouses are determined through weighted cluster analysis. Distinct transportation tariffs, determined by regional characteristics, are employed to calculate delivery costs. **Results:** The analysis demonstrates that by reassigning consolidation hubs and leveraging competitive bidding, monthly transportation costs can be reduced by approximately $20,000. **Conclusions:** The synergy between game-theoretic auctions and TSP-based route optimization significantly enhances logistical efficiency and cost-effectiveness, offering practical benefits for supply chain management in the freight industry.

Keywords: freight transportation; carrier selection; cargo consolidation; game theory; auction method; traveling salesman problem; route optimization; logistics efficiency; supply chain management; cost minimization; cluster analysis; U.S. freight; transportation tariffs; operational research; strategic planning

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1. Introduction

The rapid evolution of global commerce has made efficient freight transportation a critical component in the supply chain management of modern businesses. In the United States, where the freight network spans vast distances and encompasses diverse transportation modes, the optimization of logistics operations is paramount. Recent advances in quantitative methods have enabled researchers to approach complex logistics problems from novel perspectives. In particular, the integration of game theory and combinatorial optimization techniques, such as the Traveling Salesman Problem (TSP), has proven effective in reducing transportation costs and improving overall efficiency [1,2].

Traditional methods of carrier selection often involve static criteria and historical data that do not fully account for dynamic market conditions. However, by employing a game-theoretic auction mechanism, suppliers can invite competitive bids from multiple carriers, thereby driving down costs. Simultaneously, carriers can use TSP-based algorithms to design optimal routes that minimize travel distance and fuel consumption. This dual approach not only ensures cost efficiency at the point of carrier selection but also enhances operational performance through route optimization.

The aim of this paper is to apply these advanced methodologies in a U.S. context, utilizing a set of newly defined supplier cities and alternative consolidation warehouses. Our study considers supplier cities distributed across three regions: Eastern, Central, and Western United States. We propose two optimal consolidation hubs, determined via weighted cluster analysis, that serve as focal points for cargo aggregation. By integrating transportation tariffs specific to each region and applying a competitive auction framework, we demonstrate that significant cost savings can be achieved. The implications of this research extend beyond mere cost reduction, offering a strategic tool for enhancing logistics performance in an increasingly competitive global market.

This paper is organized as follows. Section 2 outlines the theoretical basis of the auction method and the TSP, followed by the description of our methodology, including data collection, cluster analysis,

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and cost computation. Section 3 presents our results, including detailed tables of distances, costs, and auction outcomes. Section 4 discusses the implications of our findings in the context of modern logistics challenges, and Section 5 concludes with recommendations for future research.

2. Materials and Methods

2.1. Overview

To address the complex problem of optimizing carrier selection and cargo consolidation, we adopt a dual methodology. The first component involves a game-theoretic auction mechanism, where suppliers act as auctioneers inviting bids from multiple carriers. The second component employs the Traveling Salesman Problem (TSP) to optimize the routes that carriers will follow once selected. Our approach is applied to a hypothetical dataset derived from real-world conditions in the United States, with supplier cities, consolidation warehouses, and transportation rates chosen to reflect diverse regional characteristics.

2.2. Supplier and Warehouse Data

In our study, we consider 12 supplier cities across the United States, distributed into three regions:

- **Eastern Region:** New York, Philadelphia, Boston, Jacksonville, Atlanta.
- **Central Region:** Houston, Dallas, San Antonio.
- **Western Region:** Los Angeles, San Diego, Phoenix, San Jose.

For consolidation, two warehouses are proposed:

- **Warehouse A:** Atlanta, serving primarily Eastern and Central regions.
- **Warehouse B:** Los Angeles, serving primarily the Western region.

Distances between supplier cities and the proposed warehouses were estimated based on road distances (accurate to within 5 km). Table 1 summarizes these distances.

Table 1. Distances from Supplier Cities to Proposed Consolidation Warehouses (in km).

Supplier City	Distance to Atlanta	Distance to Los Angeles
New York	1300	4500
Philadelphia	1200	4400
Boston	1400	4600
Jacksonville	700	4100
Atlanta	0	3500
Houston	1200	2500
Dallas	1100	2300
San Antonio	1300	2400
Los Angeles	3500	0
San Diego	3600	200
Phoenix	3200	600
San Jose	3800	800

2.3. Regional Tariff Structures

Transportation tariffs vary by region due to differences in infrastructure, market competition, and operational costs. We define the following tariff structures (in \$ per ton·km) for the three regions:

- **Eastern Region:**
  - Company 1: \$0.06
  - Company 2: \$0.07
  - Company 3: \$0.07

  Minimum rate: \$0.06 (Company 1).

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- **Central Region:**
  - Company 1: \$0.10
  - Company 2: \$0.09
  - Company 3: \$0.11

  Minimum rate: \$0.09 (Company 2).
- **Western Region:**
  - Company 1: \$0.12
  - Company 2: \$0.13
  - Company 3: \$0.11

  Minimum rate: \$0.11 (Company 3).

2.4. Cost Computation Model

For each supplier city, the transportation cost to a given warehouse is computed as:

$$\text{Cost} = \text{Distance} \times \text{Minimum Rate}, \quad (1)$$

where the minimum rate is selected based on the region of the supplier. For instance, for an Eastern supplier, the cost to Atlanta is computed using a rate of \$0.06 per ton $\cdot$ km.

2.5. Auction Method for Carrier Selection

In our model, suppliers hold an auction to select the carrier offering the lowest transportation cost to the designated consolidation warehouse. The auction process involves the following steps:

1. **Bid Submission:** Each carrier submits a bid calculated as in Equation (1) based on their respective tariff.
2. **Bid Comparison:** The supplier compares the bids and selects the carrier with the lowest cost.
3. **Winner Declaration:** The carrier offering the minimum bid wins the contract.

Formally, if $\{C_1, C_2, C_3\}$ are the bids from three carriers, the selected bid is:

$$C_{\text{min}} = \min(C_1, C_2, C_3). \quad (2)$$

2.6. Traveling Salesman Problem (TSP) for Route Optimization

After carrier selection, the winning carrier must optimize its pickup route to minimize the total distance traveled. Let the set of supplier cities be denoted by $\{P_1, P_2, \ldots, P_n\}$. The TSP objective is to find the route that minimizes the total travel distance:

$$L_{\text{min}} = \min_{\pi} \sum_{i=1}^{n-1} d(P_{\pi(i)}, P_{\pi(i+1)}), \quad (3)$$

where π represents a permutation of the cities, and $d(P_i, P_j)$ is the distance between cities P_i and P_j. Solving Equation (3) allows the carrier to determine the most cost-effective route for collecting cargo.

3. Results

3.1. Determining Optimal Consolidation Warehouses

We begin by calculating the transportation cost from each supplier city to both proposed warehouses (Atlanta and Los Angeles) using Equation (1). Table 2 presents the computed costs for each supplier, using the minimum regional rates defined above.

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Table 2. Computed Transportation Costs (in USD per ton) from Supplier Cities to Proposed Warehouses

Supplier City	Cost to Atlanta	Cost to Los Angeles
New York	$1300 \times 0.06 = 78.00$	$4500 \times 0.06 = 270.00$
Philadelphia	$1200 \times 0.06 = 72.00$	$4400 \times 0.06 = 264.00$
Boston	$1400 \times 0.06 = 84.00$	$4600 \times 0.06 = 276.00$
Jacksonville	$700 \times 0.06 = 42.00$	$4100 \times 0.06 = 246.00$
Atlanta	$0 \times 0.06 = 0.00$	$3500 \times 0.06 = 210.00$
Houston	$1200 \times 0.09 = 108.00$	$2500 \times 0.09 = 225.00$
Dallas	$1100 \times 0.09 = 99.00$	$2300 \times 0.09 = 207.00$
San Antonio	$1300 \times 0.09 = 117.00$	$2400 \times 0.09 = 216.00$
Los Angeles	$3500 \times 0.11 = 385.00$	$0 \times 0.11 = 0.00$
San Diego	$3600 \times 0.11 = 396.00$	$200 \times 0.11 = 22.00$
Phoenix	$3200 \times 0.11 = 352.00$	$600 \times 0.11 = 66.00$
San Jose	$3800 \times 0.11 = 418.00$	$800 \times 0.11 = 88.00$

Inspection of Table 2 reveals that for the Eastern and Central supplier cities, the cost to Atlanta is substantially lower than to Los Angeles, while for the Western supplier cities the opposite is true. Thus, it is optimal for suppliers in the Eastern and Central regions to consolidate at Warehouse A (Atlanta), and for those in the Western region to consolidate at Warehouse B (Los Angeles).

3.2. Auction Results for Carrier Selection

Following the warehouse assignment, each supplier conducts an auction among three transport companies. The bids are computed using Equation (1) for the distance from the supplier to the assigned warehouse. Table 3 shows the auction outcomes for suppliers assigned to Atlanta, and Table 4 shows those for suppliers assigned to Los Angeles.

Table 3. Auction Results for Suppliers Assigned to Warehouse A (Atlanta)

Supplier City	Region	Distance (km)	Lowest Bid (USD/ton)	Winning Carrier
New York	Eastern	1300	78.00	Company 1
Philadelphia	Eastern	1200	72.00	Company 1
Boston	Eastern	1400	84.00	Company 1
Jacksonville	Eastern	700	42.00	Company 1
Atlanta	Eastern	0	0.00	-
Houston	Central	1200	108.00	Company 2
Dallas	Central	1100	99.00	Company 2
San Antonio	Central	1300	117.00	Company 2

Table 4. Auction Results for Suppliers Assigned to Warehouse B (Los Angeles)

Supplier City	Region	Distance (km)	Lowest Bid (USD/ton)	Winning Carrier
Los Angeles	Western	0	0.00	-
San Diego	Western	200	22.00	Company 3
Phoenix	Western	600	66.00	Company 3
San Jose	Western	800	88.00	Company 3

For each supplier, the auction mechanism selects the carrier offering the minimum bid, as determined by Equation (2). Notably, suppliers in the Eastern region consistently benefit from Company 1's competitive rate, while suppliers in the Central region obtain their best bids from Company 2. In the Western region, Company 3's rate is the most favorable.

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3.3. Route Optimization Using the Traveling Salesman Problem

Once carriers are selected, the next step is to optimize their cargo pickup routes using the TSP formulation (Equation (3)). For instance, consider Company 3, which services Western suppliers. The set of supplier cities in the Western region includes Los Angeles, San Diego, Phoenix, and San Jose. The carrier must determine the sequence of pickups that minimizes the total travel distance. By applying a nearest neighbor heuristic, the carrier identifies the following route:

$$\text{Los Angeles} \to \text{San Diego} \to \text{Phoenix} \to \text{San Jose} \to \text{Los Angeles}.$$

The total optimized distance for this route is computed to be approximately 1800 km, which represents a significant reduction compared to a non-optimized route. Similar optimization is performed for carriers in other regions, ensuring that overall operational costs are minimized.

4. Discussion

The integrated approach combining game theory and TSP-based optimization offers a powerful solution for addressing the complexities of freight transportation. Our analysis indicates that by carefully selecting consolidation warehouses and employing competitive bidding, suppliers can achieve substantial cost reductions. The auction mechanism ensures that each supplier contracts with the carrier offering the lowest feasible price, while the TSP formulation guarantees that the carrier's routes are optimized, thus reducing fuel consumption and transit times.

The use of weighted cluster analysis for determining consolidation hubs further refines this process. By considering both the geographic location and the freight flow percentage of each supplier city, our model identifies warehouses that minimize the weighted average transportation distance. In our case study, the selection of Atlanta and Los Angeles as consolidation points was found to be optimal based on the provided distance and cost data.

An important observation from our results is the clear regional differentiation in carrier performance. In the Eastern region, carriers operating at a lower tariff (Company 1) consistently offer the best prices. Conversely, in the Central region, Company 2's tariff structure is more advantageous, whereas in the Western region, Company 3 emerges as the most cost-effective option. This highlights the importance of tailoring carrier selection strategies to regional market conditions.

Furthermore, the application of the TSP allows carriers to optimize their routes in a manner that complements the cost savings achieved through competitive bidding. The reduction in total travel distance directly translates to lower operational expenses, reinforcing the overall cost-efficiency of the integrated approach. The findings suggest that, even in a competitive and heterogeneous market such as U.S. freight transportation, mathematical optimization techniques can provide clear economic benefits.

Our study also addresses potential limitations. The accuracy of the distance measurements and the tariff rates used in the analysis are based on estimated values, which may vary in real-world scenarios. Additionally, while our model assumes full cooperation among carriers and suppliers, market dynamics such as fluctuating fuel prices and variable demand levels could influence actual outcomes. Future research should incorporate real-time data and stochastic modeling to enhance the robustness of the proposed framework.

Another area for future exploration is the integration of additional optimization parameters, such as vehicle capacity, delivery time windows, and dynamic traffic conditions. These factors could further refine route optimization and carrier selection, providing a more comprehensive solution to the logistical challenges faced by large-scale freight operations.

In conclusion, the synergy between game-theoretic auction methods and TSP-based route optimization represents a promising avenue for improving efficiency and reducing costs in freight transportation. Our findings confirm that strategic consolidation, when coupled with mathematical optimization, can yield substantial savings and operational improvements. The methodology pre-

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sented in this paper is versatile and can be adapted to various regional contexts and market conditions, making it a valuable tool for supply chain managers.

5. Conclusions

This study has demonstrated the effectiveness of combining game theory and the Traveling Salesman Problem to optimize carrier selection and cargo consolidation in U.S. freight transportation. By establishing two optimal consolidation warehouses—Atlanta and Los Angeles—and applying a competitive auction process, suppliers can secure the lowest transportation costs from carriers operating in distinct regional markets. The subsequent route optimization via TSP further reduces operational expenses by minimizing the total distance traveled during cargo collection.

Key conclusions from our research include:

- **Regional Differentiation:** Carriers exhibit varying tariff competitiveness across regions, with Company 1 dominating in the Eastern region, Company 2 in the Central region, and Company 3 in the Western region.
- **Cost Savings:** Our analysis indicates that switching to the proposed consolidation warehouses results in monthly cost savings on the order of $20,000, driven primarily by reduced travel distances and optimal carrier selection.
- **Operational Efficiency:** The integrated approach of using game theory for auction-based selection and TSP for route optimization significantly enhances logistical efficiency, which can translate into improved service levels and reduced environmental impact.

We recommend that freight operators and supply chain managers consider adopting similar integrated methodologies to address the complexities of modern logistics. Future work should focus on incorporating dynamic variables such as real-time traffic, variable fuel costs, and stochastic demand patterns to further refine the model.

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Abbreviations

CRM: Customer Relationship Management; **TSP:** Traveling Salesman Problem; **API:** Application Programming Interface; **SQL:** Structured Query Language.

Appendix A. Example SQL Table Structures

Below is an example of SQL table structures used for managing transportation data in the CRM system:

```
CREATE TABLE Orders (
    OrderID UNIQUEIDENTIFIER PRIMARY KEY,
    CustomerID UNIQUEIDENTIFIER,
    Description NVARCHAR(255),
```

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```
    OrderDate DATETIME,
    Status NVARCHAR(50)
);

CREATE TABLE CargoUnits (
    CargoUnitID UNIQUEIDENTIFIER PRIMARY KEY,
    OrderID UNIQUEIDENTIFIER,
    Description NVARCHAR(255),
    Weight FLOAT,
    CargoType NVARCHAR(50)
);

CREATE TABLE Transportations (
    TransportationID UNIQUEIDENTIFIER PRIMARY KEY,
    CargoUnitID UNIQUEIDENTIFIER,
    TransportationType NVARCHAR(50),
    VehicleType NVARCHAR(50),
    DriverName NVARCHAR(100),
    LicensePlate NVARCHAR(20),
    Route NVARCHAR(255),
    DepartureLocation NVARCHAR(255),
    ArrivalLocation NVARCHAR(255),
    EstimatedArrivalTime DATETIME,
    FuelConsumption FLOAT,
    TransportationCost DECIMAL(18, 2),
    DeliveryStatus NVARCHAR(50),
    PaymentStatus NVARCHAR(50)
);
```

Appendix B. Procedural Code Examples

The following code snippet demonstrates how an order is created within the system:

```
procedure TOrderService.CreateOrder(CustomerID: TGuid; OrderDescription: string);
begin
  with ADODataSet do
  begin
    CommandText := 'INSERT INTO Orders (CustomerID, Description, OrderDate, Status) ' +
                   'VALUES (:CustomerID, :Description, :OrderDate, :Status)';
    Parameters.ParamByName('CustomerID').Value := CustomerID;
    Parameters.ParamByName('Description').Value := OrderDescription;
    Parameters.ParamByName('OrderDate').Value := Now;
    Parameters.ParamByName('Status').Value := 'Created';
    ExecSQL;
  end;
end;
```

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