

Choosing Multimodal Freight Mix: An Integrated Multi-Objective Multicriteria Approach

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How to cite this paper: Rahman, M.A. (2024) Choosing Multimodal Freight Mix: An Integrated Multi-Objective Multicriteria Approach. *Journal of Transportation Technologies*, 14, 402-422.
<https://doi.org/10.4236/jtts.2024.143024>

Received: April 17, 2024

Accepted: July 16, 2024

Published: July 19, 2024

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Abstract

Multimodal freight transportation emerges as the go-to strategy for cost-effectively and sustainably moving goods over long distances. In a multimodal freight system, where a single contract includes various transportation methods, businesses aiming for economic success must make well-informed decisions about which modes of transport to use. These decisions prioritize secure deliveries, competitive cost advantages, and the minimization of environmental footprints associated with transportation-related pollution. Within the dynamic landscape of logistics innovation, various multicriteria decision-making (MCDM) approaches empower businesses to evaluate freight transport options thoroughly. In this study, we utilize a case study to demonstrate the application of the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) algorithm for MCDM decision-making in freight mode selection. We further enhance the TOPSIS framework by integrating the entropy weight coefficient method. This enhancement aids in assigning precise weights to each criterion involved in mode selection, leading to a more reliable decision-making process. The proposed model provides cost-effective and timely deliveries, minimizing environmental footprint and meeting consumers' needs. Our findings reveal that freight carbon footprint is the primary concern, followed by freight cost, time sensitivity, and service reliability. The study identifies the combination of Rail/Truck as the ideal mode of transport and containers in flat cars (COFC) as the next best option for the selected case. The proposed algorithm, incorporating the enhanced TOPSIS framework, benefits companies navigating the complexities of multimodal transport. It empowers making more strategic and informed transportation decisions. This demonstration will be increasingly valuable as companies navigate the ever-growing trade within the global supply chains.

Keywords

Multimodal Freight Transport, MCDM, TOPSIS, Entropy Technique, COFC

1. Introduction

In today's interconnected global economy, efficient freight transport is crucial. Businesses involved in international markets rely on real-time tracking, optimized route planning, and improved logistics to remain competitive. The rise of containerized shipping, along with multimodal and intermodal transport, has significantly improved supply chain efficiency, boosted national economies, and contributed to global GDP growth. The selection of freight transport modes and understanding of the selection criteria are critical for seamless material flow. Businesses import goods from suppliers, transport them to the manufacturing facilities, and finally deliver them to the retailers or consumers. Unimodal transport (using a single mode like truck) can be expensive for certain situations. Businesses consider multimodal, and intermodal as open options for transportation of goods. Multimodal transportation utilizes multiple modes of transport, such as truck, rail, and ship, within a single journey under one contract. This logistics company acts as a single point of contact that handles all documentation, contracts, and insurance and gets goods from origin to destination using various modes. In intermodal shipping, a business contracts with different carriers for each leg of the journey (trucking company, rail operator, etc.) until the final destinations. The business is responsible for coordinating between contracts and handling any issues during transfers. In multimodal, a single bill of lading contract (a document listing cargo details) covers the entire journey. Meanwhile, intermodal requires separate bills of lading for each transport mode used. Many businesses find the single point of contact with multimodal transportation is convenient, more secure, and easy to handle. In many countries, the road mode accounts for more than 75% of total inland freight transportation [1]. Due to their flexibility, trucks, and trailers are the most common freight shipment modes in many situations. However, the environmental impact of road transport, including congestion, accidents, and substantial CO₂ emissions, is a growing concern for many corporations. This has led to a push towards greener practices in the industry, with companies increasingly adopting eco-friendly transportation modes and investing in sustainable logistics solutions to reduce carbon emissions and improve efficiency. Companies realize that the appropriate selection of freight carriers by evaluating the right policy attributes reduces transportation costs, increases reliability, and minimizes harmful emissions while speeding up delivery to the end customer. Multimodal transportation has the potential to be less expensive and more sustainable than unimodal road transportation [2]. Trains, barges, and ships have lower costs and emissions per ton/km than trucks. Businesses are considering more efficient transportation

modes, such as intermodal and multimodal, to reduce environmental impact and costs.

The share of GDP attributed to freight transportation varies across the regions. In the US, it accounts for approximately 6% of the GDP, with the value of imports and exports projected to grow from 18.907 trillion dollars in 2017 to \$20.328 in 2023 and is expected to reach almost \$36.283 trillion in 2050 [3]. In Europe, the transport sector contributes around 5% to the EU’s GDP, supporting over 10 million jobs [4]. Rapidly developing economies like China have an even higher percentage than the developed economy. In the fourth quarter of 2023 alone, GDP from transport in China increased to 578.198 billion CNY from the previous quarter’s 431.239 billion CNY. This sector includes the freight and logistics market and passenger transport. The China freight and logistics market is projected to reach approximately USD 1.224 trillion in 2024, with a predicted growth rate of 6.39% annually through 2030, reaching 1.78 trillion in 2030 [5]. The market size expanded steadily due to the country’s strong economic growth, increasing international trade, and the development of e-commerce. The rise of e-commerce platforms like Alibaba has significantly impacted this growth. Like China, other developing Asian economies have a significant share of freight transportation in their GDP. Latin America’s intra-regional trade lags other major regions [6]. Freight transport contribution to Latin America’s GDP growth can help with better infrastructure and transportation logistics. Figure 1 shows a comparative value of major inter-regional trades.

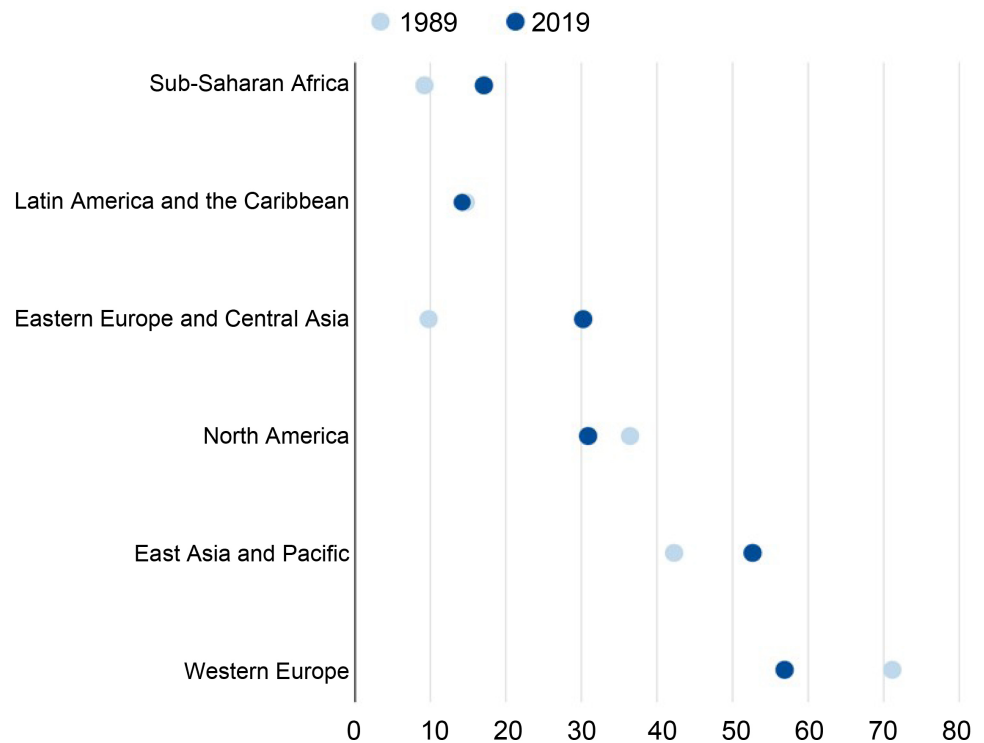


Figure 1. Intra-regional trade among major regions. Source: Picture; data from IMF, Direction of trade statistics; and IMF staff calculations [4].

Given the trade growth and logistics challenges, many governments implemented policies to promote the development of the logistics industry while ensuring environmental safety. Companies increasingly embrace eco-friendly transportation and sustainable logistics solutions to reduce carbon emissions and improve efficiency [7]. Multimodal transportation is a promising avenue, offering economic viability and environmental sustainability. Imagine an imported shipment arriving in Southern California and destined for a Chicago suburb. Multimodal transport offers an efficient and environmentally friendly solution. The long-haul portion can be covered by a trailer or a train (using a container on a flatbed—COFC) or a cargo plane for about 2200 miles. Upon reaching a rail terminal or the cargo airport near Illinois, a truck completes the final short-distance delivery. Businesses will investigate which long-haul transport mode and truck will be cost-effective for the final leg delivery.

Multicriteria Decision Making (MCDM) methods influence route selection and mode of transport choice. This study integrates MCDM techniques and intermodal cost models to help companies swiftly respond to customer demands and adapt to market changes. Businesses require a robust approach to selecting the proper freight transport mode to minimize costs, improve competitiveness, and enhance customer satisfaction. This study proposes an integrated multicriteria modeling framework that evaluates service quality, cost, and environmental impact, optimizing freight flows on a multimodal transportation network. It offers a user-friendly alternative to expensive software or complex mathematical models, allowing managers to create a simple criteria-based matrix for route selection. The proposed model is a practical decision-making tool for businesses to navigate the complex world of freight transport. By considering service quality, cost, and environmental impact, companies can select the most suitable multimodal or intermodal transportation option while optimizing their supply chains.

The organization of the rest of the paper is as follows: Section 2 is the literature on multicriteria decision-making models for transportation selection. Section 3 demonstrates a case study of multimodal transport related to multimodal transport cost functions, modal selection matrix, and the background of the entropy model and TOPSIS algorithm. Subsequently, Section 4 proposes the numerical results of this proposed method for modal selection using the TOPSIS model integrated with the entropy technique. Section 5 provides the conclusion, a discussion of future research direction, and concluding remarks.

2. Literature Review

In the globalized economy, the success of a business relies upon efficient decision-making in selecting the transport carrier and orchestrating distribution across the supply chain connections designed to meet the company's specific requirements. Several factors influence this decision, including a facility's location relative to intermodal infrastructure, reliability of a transport logistics com-

pany, transport cost, greenhouse gas emissions, and government regulations. Researchers have explored how companies can evaluate and select freight transport models using multicriteria decision-making (MCDM) methods. These methods help compare multiple transport options based on various factors, allowing businesses to choose the best route that balances cost, speed, safety, and environmental impact. Over the years, the adoption of multicriteria decision models has risen due to their user-friendly solution approaches and the capability to integrate subjective expert judgments into the decision-making process. One prominent MCDM approach is the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS). This fact-based model prioritizes feasible alternatives while minimizing conflicting objectives. It can handle qualitative and quantitative data, considering factors like reducing cost and maximizing service reliability. Transport selection requires many different types of factors, such as cost, delivery speed, safety, and environmental impact, and sometimes ranking these factors needs to be more explicit. Fuzzy techniques offer a valuable approach when precise data is difficult to obtain. Fuzzy logic assigns “fuzzy scores” to reflect the importance of various factors, such as delivery speed or safety. This approach has been used with methods like Fuzzy AHP (Analytic Hierarchy Process) and Fuzzy TOPSIS for transport selection. Authors use fuzzy techniques to incorporate fuzzy numbers as a set of discrete values assigned to linguistic variables when it is difficult or impossible to assign a numerical value to the criteria [8]. The fuzzy AHP (Analytic Hierarchy Process) method helps establish by comparing factors in pairs and assigning fuzzy scores to reflect importance. The fuzzy TOPSIS method identifies the transport option closest to an ideal scenario based on all criteria. A fuzzy analysis network process (FANP) is used to avoid ambiguity in selecting a transportation mode between two countries [9], and a hybrid Fuzzy-Analytic Network Process is used in the supplier evaluation process [10]. Further study implemented the fuzzy TOPSIS method to obtain a sustainable solution for a transportation system [11]; the TOPSIS approach for solving multicriteria decision-making problems with interval data considering environment-friendly and sustainable factors [12]; and an extended TOPSIS to solve multi-objective nonlinear-programming-problems [13].

Researchers have explored several other MCDM methods. One study implemented the Markov Decision Process (MDP) method to compare transportation options based on cost, carrier, and inventory levels [14]. The author used MDP to transport materials in a JIT (just-in-time) based production system. A freight transport modal selection method combining MCDM and geographic information systems used transport price, transport time, congestion time, CO₂ emissions, accident risk, and noise as their criteria for container transport route selection [15]. A study of a decision support model using an analytic hierarchy process (AHP) and zero-one goal programming (ZOGP) determined an optimal multimodal transportation route. In a hybrid model, one study used AHP to determine the weights of the factor, relying on expert judgments and integrating

with the ZOGP model to generate the optimal route. The model combined the MCDM with geographic information systems (GIS) for route selection, considering congestion time and CO₂ emissions [16]. A study on the multicriteria model with blockchain concept resolved synchronized transportation (using trains, ships, and trucks together) to find the best balance by balancing cost, speed, emissions, and blockchain costs and ranked the best options in the context of security, efficiency, and eco-friendly way to move things [17]. There are certain limitations that researchers have tried to overcome, such as situation selection factors being interrupted and new data becoming continuously available as the activity progresses. Several recent studies provide in-depth analyses of multicriteria decision models integrating Bayesian analysis to improve the selection process and satisfy customer needs. Fuzzy models can become complex, especially with many criteria. The fuzzy method's limitation is evident in determining the relative importance or weight of different criteria in multicriteria decision-making (MCDM). The entropy method uses information theory to determine each criterion's weights based on the data objectively. It is beneficial in reducing subjectivity and providing a more data-driven approach to weight determination. A study on the entropy method demonstrated the weight factors using quantitative information to rate each alternative based on criteria in the data matrix [18]. The entropy method enumerates the weights of various attributes without directly involving decision makers' subjective choice for weight selection [19]. **Table 1** presents a brief model description of primary MCDM methods and their origin.

Although MCDM methods offer valuable tools, complexities arise with models like fuzzy logic when dealing with numerous criteria. The entropy method tackles this by objectively assigning data-driven weights to each criterion, minimizing bias, and promoting a data-centric approach. By integrating the entropy weight coefficient method with the TOPSIS algorithm, we create a powerful MCDM tool. This combined approach refines the TOPSIS platform, enabling us to evaluate the ideal transportation mode among various multimodal and intermodal options (truck-rail, air-truck). This blended method enhances multicriteria decision-making (MCDM) by minimizing conflicting objectives when selecting optimal transportation modes and carriers. Based on a comprehensive set of criteria, this technique accurately evaluates the best options among various multi/intermodal combinations, ultimately aiding businesses in strategically choosing transportation methods that align with customer demands and enhance their overall performance. This decision-making process is crucial for freight companies to identify and select the most efficient and effective transport planning strategies.

3. Case Study: Selecting Multimodal Carrier

In the realm of business, transportation preferences are often shaped by service commitments, costs, and customer service standards. This case study demonstrates how a company can choose the best carrier among a few multimodal

Table 1. Origin of major MCDM methods.

Method [Original Source]	Brief Model Description
AHP (Analytical Hierarchical Process) [20]	Prioritize alternate pairwise based comparisons
DEA (Data Envelopment Analysis) [21]	Assesses relative efficiency of alternatives using mathematical modeling
TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [22]	Identifies closest alternative to an ideal solution
FST (Fuzzy Set Theory) [23]	Framework for dealing with uncertainty and vagueness
Goal Programming (GP) [24]	Achieves a set of goals with minimal deviations using mathematical programming
GRA/GRM (Grey Relational Analysis/Grey Relational Model) [25]	Evaluates alternatives with limited data using grey system theory
ANP (Analytic Network Process) [26]	ANP extends AHP by allowing for dependence and feedback loops between criteria.
CBR (Case-Based Reasoning) [27]	Solves new problems by adapting solutions from similar past cases.
PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluate) [28]	Ranks alternatives based on pairwise outranking comparisons.
ELECTRE (Serbian for Multicriteria Optimization and Compromise Solution) [29]	Multi-criteria decision analysis methods that emphasize outranking relationships.
VIKOR (French for Elimination and Choice Expressing Reality) [30]	Multi-criteria decision-making method focused on ranking and selecting from alternatives.

transport alternatives implementing the TOPSIS algorithm integrated entropy weight coefficient method. Multimodality involves employing multiple transportation modes to move goods, while intermodalism emphasizes seamless transfer using standardized loading units such as containers (Intermodal Transportation Units, or ITUs). Despite the prevalence of multimodal options, unimodal road transport still plays a substantial role in long-haul continental freight movement [31]. This persistence is attributed to factors like cost-effectiveness, flexibility in pick-up and delivery, and inadequate infrastructure for intermodal transfers in certain regions. Multimodality can involve any combination of transport methods, such as rail, road, air, and sea. This case study focuses on transporting a large quantity of lightweight backpacking equipment. The journey starts from a warehouse near a West Coast maritime terminal and ends at

the company's Midwestern warehouse. The analysis will determine the most suitable transportation mode(s) for this specific scenario. Employing the entropy method for assigning weights to evaluation criteria ensures a more objective evaluation process. By considering all relevant criteria and their importance, this method empowers decision-makers to identify the multimodal solution closest to the ideal state, ultimately selecting the best carrier for their specific needs. The efficacy of each transport mode hinges on performance criteria and empirical data samples. Managers examine available transportation options with pertinent facts and quantifiable data to effectively compare and rank alternatives. **Figure 2** details the steps involved in this combined TOPSIS-entropy framework.

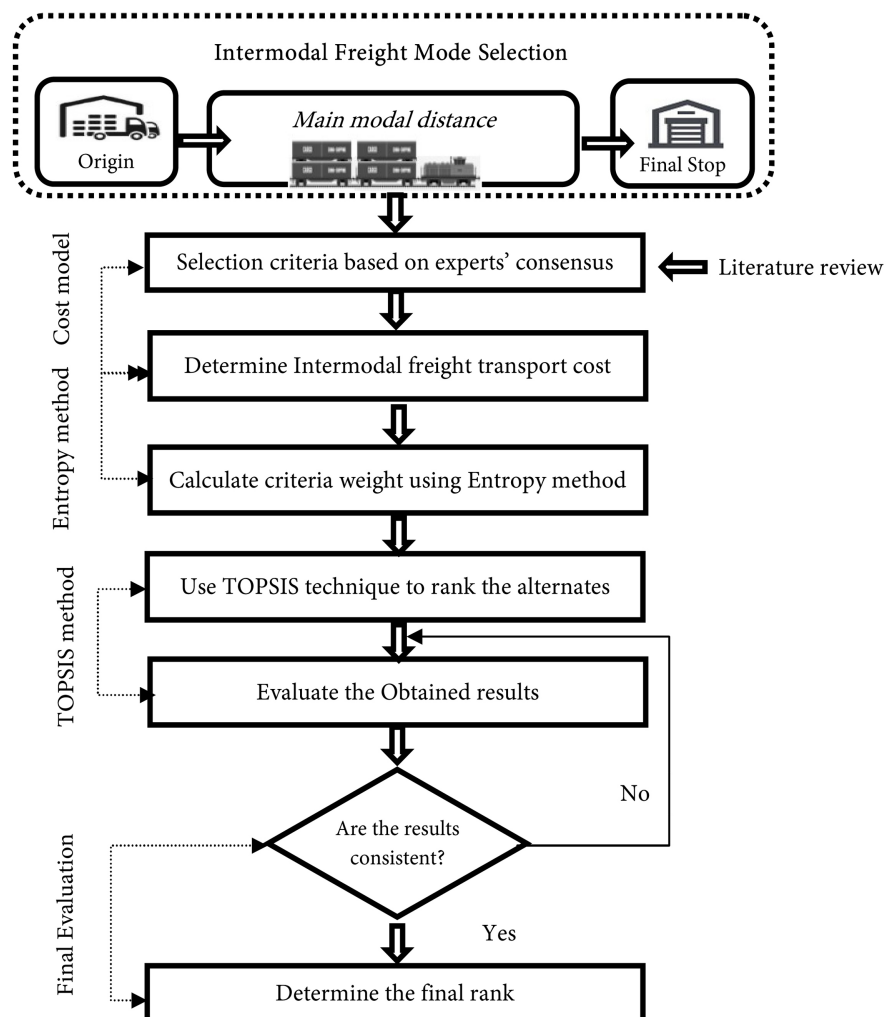


Figure 2. Unimodal and multimodal freight selection.

3.1. Carrier Alternatives

The study evaluates four distinct modes of transportation: 1) a unimodal transport chain involving trailer transport from the origin to destination, and two multimodal transport chains utilizing; 2) rail/truck and 3) air/truck and an in-

termodal 4) container on flat car (COFC)/Truck for the transport. Therefore, the four potential carrier alternates are considered: A_1 (All along trailer), A_2 (Rail/Truck combination), A_3 (Air/Truck combination), and A_4 (Container on Flat Car (COFC) intermodal and truck). The configurations of alternative multimodal freight transportation are visually depicted in **Figure 3**.

Definition: An intermodal becomes a multimodal when it operates under a single freight transportation contract.

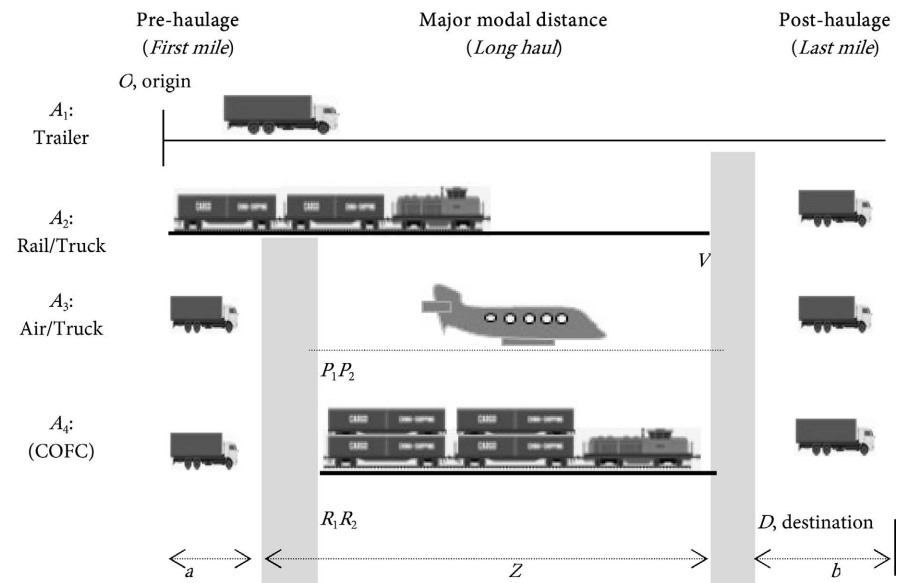


Figure 3. Multimodal transports between points of origin (O) to the destination (D).

Modal transportation offers a powerful tool for businesses to optimize their supply chains. By combining different modes of transport (truck, rail, ship), multimodal systems leverage the strengths of each to achieve greater efficiency and cost-effectiveness compared to traditional single-mode options [32]. As illustrated in **Figure 3**, most modal systems involve three key stages:

Pre-Haulage (First Mile): Trucks are typically the most efficient way to move goods short distances from factories or warehouses to the initial transport hub (port, rail yard). Businesses often use their own trucks for this leg due to the proximity of facilities to these hubs.

Long-Haul (The Main Event): The long-distance journey utilizes the most suitable mode (rail, ship, air) or even a combination of modes depending on cost, speed, and distance. Trailers on flatcars (TOFC) and containers on flatcars (COFC) are commonly used for efficient rail transport.

Post-Haulage (Last Mile): Like pre-haulage, trucks are often the best choice for final delivery to urban centers, warehouses, and distribution centers. This “last mile” delivery is often referred to as drayage.

The distance between the main modal starts and ends is Z miles. Here, pre-haulage distance, a is considered from the origin (facility) to the main modal start point. The post-haulage distance b is from the main modal start point to

the destination. Therefore, total transport travel distance = $Z + (a + b)$.

Intermodal transport offers a strategic advantage when the total costs (including pre and post-haulage) become competitive with traditional trucking for the entire distance. **Figure 4** presents pre-haulage, long haulage, and post-haulage transport cost functions.

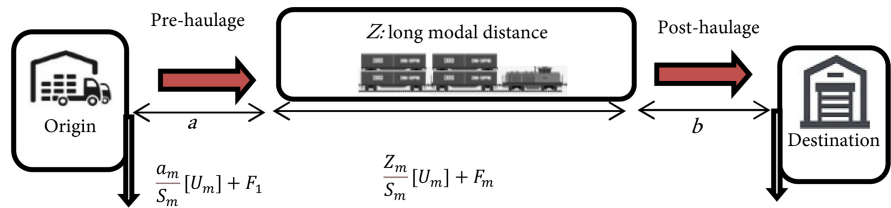


Figure 4. Intermodal: pre-haulage (“first mile”), long-haulage, and post-haulage (“last mile”).

Total Cost:

$$TC_m = \left(\frac{a_m}{S_m}[U_m] + F_1 \right) + \left(\frac{Z_m}{S_m}[U_m] + F_m \right) + \left(\frac{b_m}{S_m}[U_m] + F_2 \right) + w_m \times U(k)$$

Here, subscript m is modal: truck, Rail/Truck, Air/Truck, COFC/Truck etc.

where

TC_m : Total cost for modal transportation

$\frac{Z_m}{S_m}[U_m] + F_m$: Main modal transport cost (\$)

$\frac{a_m}{S_m}[U_m] + F_1$: Pre-haulage transport cost (\$)

$\frac{b_m}{S_m}[U_m] + F_2$: Post-haulage transport cost (\$)

$W_{R/T}$: Transshipment cost

Z : Distance, (mile)

a_m : Pre-haulage distances (road transport) (miles)

b_m : Post-haulage distances (road transport) (miles)

S_m : Transport speed (transport mode) (mile/hour)

F_m : Main transport tariff, (\$/Container mile)

k : Transshipment time at the intermodal terminal (hours)

U : Value of time (by transport mode) (\$/Container/hour)

$U(k)$: Transship time: Time to transfer container at modal terminal

W : Transship cost: Cost for modal transport (\$/Container)

F_1 : Pre-haulage tariff (\$/Container mile)

F_2 : Post-haulage tariff (\$/Container mile)

Freight transportation modeling requires fixed and variable expenses related to transport modes, vehicle types, product groups, origin-destination data, route networks, and terminal information for transferring containers between transport modes. In **Figure 3**, A_1 is unimodal freight transport by trailer; A_2 is (Rail/Truck) and there is no pre-haulage, so the distance is travelled by rail

transport as the main mode and truck for the post-haulage transport. The corresponding equation for the main mode of rail freight and truck for the post-haulage transport is below.

$$TC_{R/T} = Z_R \times \left(\frac{\beta_R}{h_R} + \tau_R \right) + b_T \times \left(\frac{\beta_T}{h_T} + g_2 \right) + w_m + \beta(r)$$

3.2. MCDM Freight Selection Model

The TOPSIS method with entropy weighting helps select the best carrier among discrete performance data by objectively assigning weights to criteria (e.g., cost, time) and ranking alternatives based on their closeness to an ideal scenario. The entropy method is useful when policymakers conflict with the values of weights [19]. This approach reduces bias from subjective weighting and helps businesses find the most efficient carrier for cost savings and market advantage. The procedure involves ranking alternative carriers structured into a series of systematic steps.

Step 1: Identify Alternatives and Evaluation Criteria

Determine potential transport routes and measurable characteristics, forming a decision matrix of discrete choices between alternatives and criteria. A decision maker identify n selection criteria $C = (C_j | j = 1, 2, \dots, n)$ through which m alternative transportation modes $A = (A_i | i = 1, 2, \dots, m)$. The data is expressed in a $(m \times n)$ matrix, representing the discrete choices between the criteria and alternatives. The Freight selection MCDM matrix is shown in **Table 2**:

Table 2. Freight selection MCDM matrix.

FSM Matrix	C_1	C_2	...	C_n
A_1	\tilde{x}_{11}	\tilde{x}_{12}	...	\tilde{x}_{1n}
A_2	\tilde{x}_{21}	\tilde{x}_{22}	...	\tilde{x}_{2n}
A_3	\tilde{x}_{31}	\tilde{x}_{32}	...	\tilde{x}_{3n}
A_m	\tilde{x}_{m1}	\tilde{x}_{m2}	...	\tilde{x}_{mn}

Matrix element, \tilde{x}_{ij} is the performance rating of criteria C_j for each alternative mode A_i . The normalized value P_{ij} is calculated as

$$P_{ij} = x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2}, \quad i \in (1, 2, \dots, m), \quad j \in (1, 2, \dots, n) \tag{1}$$

where x_{ij} represents the numerical evaluation of alternative A_i for criterion C_j . The squared normalization of the data eliminates the differences of measurement units and inconsistent scale.

Step 2: Entropy Coefficient Method to Evaluate Weight Criteria

Apply the entropy method to determine the weight $W = (\tilde{w}_j | j = 1, 2, \dots, n)$ for each criterion, $C_j (j = 1, 2, \dots, n)$. Using the normalized decision matrix, q_{ij} , the entropy weight coefficient E_j is calculated as follows:

$$E_j = -k \sum_{j=1}^n q_{ij} \ln(q_{ij}) \tag{2}$$

where $q_{ij} = x_{ij} / \sum_{i=1}^m x_{ij}$, and $k(\text{constant}) = 1/\ln(m)$.

The larger the entropy within the criteria the more likely it is to be an important criterion. Note, q_{ij} and P_{ij} are not same. The measurement of dispersion D_j for a criterion is calculated as, the following:

$$D_j = 1 - E_j. \quad (3)$$

The higher D_j value indicates the importance of the criterion in the decision matrix. The weight w_j for each attribute C_j is calculated by using the following formula:

$$w_j = \frac{D_j}{\sum_{k=1}^n D_k} \quad (4)$$

$w_j = \tilde{w}_1, \tilde{w}_2, \dots, \tilde{w}_n$, where \tilde{w}_j is the weight of j th criterion C_j .

Step 3: Construct Weighted Normalized Decision Matrix

Update the matrix elements by multiplying the entropy-derived weights with normalized performance ratings as follows:

$$\tilde{V}_{ij} = \tilde{P}_{ij} \times \tilde{w}_j \quad (5)$$

where \tilde{w}_j is weight. \tilde{V}_{ij} , $i \in (1, 2, \dots, m)$, $j \in (1, 2, \dots, n)$ element in decision matrix.

Step 4: Determine Intuitionistic Positive and Negative Ideal Solution.

This step is to identify the positive ideal reference point V^+ and the negative ideal reference point V^- . Among the evaluation criteria, J_b ($J \in J_b$) is the set of benefit criteria, and J_c ($J \in J_c$) is the set of cost criteria. The V^+ and V^- are obtained as follows.

$$V^+ = \left\{ \left(\max_i V_{ij} \mid J \in J_b \right), \left(\min_i V_{ij} \mid J \in J_c \right) \right\} = \{V_1^+, V_2^+, \dots, V_n^+\} \quad (6a)$$

$$V^- = \left\{ \left(\min_i V_{ij} \mid J \in J_c \right), \left(\max_i V_{ij} \mid J \in J_b \right) \right\} = \{V_1^-, V_2^-, \dots, V_n^-\} \quad (6b)$$

Step 5: Determine the Separation Measures between the Alternatives

The distance of each alternative from the positive ideal reference point (S_i^+ from V^+) and negative ideal reference point, (S_i^- from V^-) is obtained as follows:

$$\text{Positive Ideal Separation: } S_i^+ = \sqrt{\sum_{j=1}^n d(V_{ij} - V_j^+)^2}, i = 1, 2, \dots, m \quad (7a)$$

$$\text{Negative Ideal Separation: } S_i^- = \sqrt{\sum_{j=1}^n d(V_{ij} - V_j^-)^2}, i = 1, 2, \dots, m \quad (7b)$$

Here, $d(V_{ij} - V_j^+)$ represents the distance between a given element and the maximum value. S_i^+ denotes the distance of an alternative from V^+ (the positive ideal solution), while S_i^- indicates the distance of the alternative from V^- (the negative ideal solution).

Step 6: Obtain the Closeness Co-efficient to Rank the Alternatives.

The TOPSIS method assigns a closeness index (U_i) to each carrier, indicating its proximity to the ideal option. The value of U_i is obtained as follows:

$$U_i = \frac{S_i^-}{S_i^+ + S_i^-}, \quad i = 1, 2, \dots, m; 0 \leq U_i \leq 1. \quad (8)$$

A U_i closer to 1 signifies a higher priority carrier, as it's closer to the best possible scenario and furthest from the worst.

4. Numerical Results

This example illustrates the use of the TOPSIS method with entropy weighting to select the optimal carrier for shipping lightweight backpacking equipment from a West Coast warehouse to the Midwest. The method evaluates various multimodal options, with entropy weighting providing an objective basis for assigning importance to different criteria, thus reducing bias. The selection process integrates expert opinions from logistics professionals and findings from a literature review, focusing on key factors such as cost, time, emissions, risk, reliability, and environmental impact. These criteria are applied to assess the different transportation options, as depicted in **Figure 5**, ensuring a comprehensive evaluation of the entire transport chain.

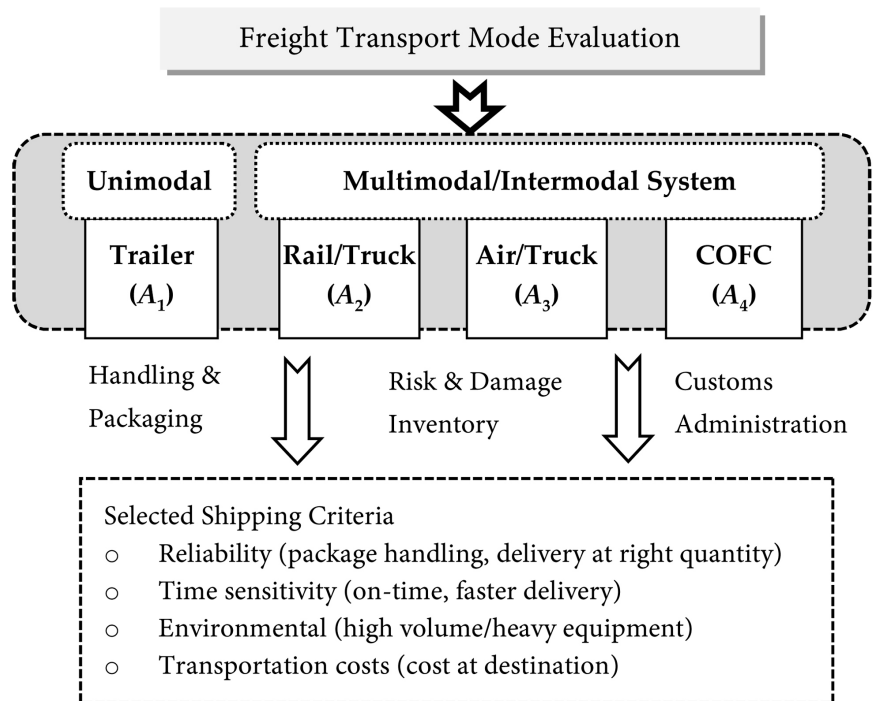


Figure 5. Alternative freight transports and selected criteria.

These options represent different combinations of transport modes:

A_1 : Unimodal Truck: This option involves using a single trailer for the entire journey from origin to destination.

A_2 : Rail-Truck (Multimodal): This multimodal option combines rail transport for a portion of the journey with final delivery by truck.

A_3 : Air-Truck (Multimodal): This multimodal option utilizes airfreight for a

faster but potentially more expensive leg, followed by truck delivery.

A_4 : COFC/Truck (Intermodal): This intermodal option leverages a container on a flatcar (COFC) for efficient rail transport, followed by truck for final delivery.

In transportation logistics, the assessment of carrier selection transcends mere point-to-point shipment movement. Businesses are interested in the quality of physical handling, dispatch, reception, planning, and control activities on the freight's trajectory from origin to destination. The study guides a step-by-step logistic pathway for this specialized backpacking equipment, a substantial volume of lightweight backpacking equipment, from a West Coast company to a company-owned warehouse nestled in a Midwestern city in the United States. The priority of transport modal option is based on service reliability, time sensitivity, environmental commitment, and transportation costs. Businesses review the selected performance criteria and collect sample data to rank the best transport mode for an instant. Four key criteria to assess potential carriers:

- **Transport Cost** (C_1): This indicates the total cost associated with moving goods from origin to destination.
- **Time Sensitivity** (C_2): Prioritizes on-time delivery, considering urgency, road infrastructure, product types, and transport availability. Time sensitivity is a major criterion that affects the freight selection decision. The primary valuation of this criterion is on-time delivery. The constraints that directly affect transportation time include urgency and speed by which the goods are to be delivered, road infrastructure, types of products, and availability of transport.
- **Carbon Footprint** (C_3): Carbon footprint assesses the environmental impact of each mode produces per cargo unit moved and other pollution and waste. Environmental impact is an essential criterion for transport mode selection.
- **Service Reliability** (C_4): Ensures material handling and preserves product quality during transport. The selected modes are suitable to carry the commodity groups (products) and have the capacity to maintain product quality during transportation.

4.1. Determining Transportation Cost

The illustrative case is a data-driven approach that offers the selecting most suitable carrier for the specific freight scenario. The numerical findings of the case study illustrate the practical application of the TOPSIS method integrated with the entropy weight coefficient technique, facilitating the thorough analysis of carriers' selection from a range of multimodal/intermodal transportation alternatives. The total cost of transportation for each modal includes pre-haulage, main modal, and post-haulage transport costs, along with transshipment costs. The distance between the point of origin and destination, equivalent to California and Midwest city (Chicago), is assumed to be 2000 miles. **Table 3** provides the comparative intermodal cost elements.

Table 3. Comparative intermodal cost elements.

Variables	Road	Rail/Truck	Air/Truck	COFC
z : Distance, (mile)	2000	1970	1950	1960
a : Pre-haul distance, (mile)	n/a	n/a	25	n/a
b : Post-haul distance, (mile)	n/a	30	25	40
r : Transshipment time (hours)	n/a	2	3	1
w : Transshipment costs, (\$/container)	n/a	25	50	15
τ : Transport tariff, (\$/Container mile)	1.1	0.5	1.1	0.7
h : Transshipment speed (mile/hour)	40	50	300	50
g : Post-haul tariff, (\$/Container mile)	0.0	3	3	3
β : Value of time (\$/Container/hour)	1	1	1	1

The distance traveled by a primary transport mode is $Z + (a + b)$, where Z is the long haulage distance and a and b are the pre-haulage and post-haulage distance, respectively. Road transport only uses pre- and post-haulage. Freight transportation costs fluctuate over time due to fuel prices, infrastructure maintenance, and market conditions. The context for cost evaluation includes the average freight transportation prices (percent/ton-mile) across different modes are \$2.50 for the railway, \$25.08 for truck/motorway, \$0.73 for water/seaway, and \$58.75 for airway. Total transport cost is represented by the cost derived using Equation (1). The transport cost comparison of the selected freight transport mode is shown in **Table 4**.

Table 4. Transport cost comparison of selected freight transport modes.

Mode	Total cost
TC (Trailer)	\$1840.00
TC (Rail/Truck)	\$1151.85
TC (Air/Truck)	\$2280.00
TC (COFC)	\$1361.80

4.2. Rank the Multimodal Transports

Following Step 1, the performance rate of each carrier alternative and the corresponding criteria are presented in **Table 5**. The freight carrier alternatives A_j ($j = 1, 2, \dots, 4$), evaluated against the selected attributes C_i ($i = 1, 2, \dots, 4$), the data is expressed in a (4×4) matrix that represents the discrete choice between the attributes and alternatives.

Squred normalization value $P_{ij} = x_{ij} / \sqrt{\sum_{i=1}^m x_{ij}^2}$, presented in **Table 6**.

Table 5. Data matrix to evaluate transportation mode by criteria.

	Freight Cost	Time-sensitive	Carbon Footprint	Reliability	
<i>Transport Mode</i>	C_1	C_2	C_3	C_4	Sum
A_1 : Trailer	5	7	5	8	25
A_2 : Rail/Truck	9	6	8	6	29
A_3 : Air/Truck	4	9	6	9	28
A_4 : COFC*	8	6	8	5	27

COFC* = Container on Flat Car, (Rail-Truck).

Table 6. Normalized value in decision matrix.

<i>Transport Mode</i>	C_1	C_2	C_3	C_4
A_1	0.3666	0.4925	0.3637	0.5574
A_2	0.6599	0.4222	0.5819	0.4180
A_3	0.2933	0.6332	0.4364	0.6271
A_4	0.5866	0.4222	0.5819	0.3484

For weight calculation using the entropy method, we used normalized method such that $p_{ij} = x_{ij} / \sum_{i=1}^m x_{ij}$. Here, the number of criteria, $m = 4$. Following is the entropy weight coefficient discussed in Step 2, presented in **Table 7**.

Table 7. Criteria weight using is determined as follows.

Entropy weight method	C_1	C_2	C_3	C_4
$E_j = -k \sum_{i=1}^n q_{ij} \ln(q_{ij})$	0.9863	0.9919	0.8823	0.9086
$D_j = 1 - E_j$	0.0155	0.0155	0.00350	0.0137
$W_j = D_j / \sum_{j=1}^n D_j$	0.2046	0.1520	0.4630	0.1804

In **Table 7**, Row 1, the value E_j is calculated using Equation (2), $E_j = -k \sum_{j=1}^n q_{ij} \ln(q_{ij})$. Therefore, the value of P_i for $T_{j=1}$ with respect to attributes A_1, A_2, A_3 and A_4 are 5/25, 7/25, 5/25, and 8/25, respectively.

$E_{j=1}$ is calculated as follows: $-(0.20 \times \ln 0.20 + \dots + 0.32 \times \ln 0.32) / \ln 4 = 0.9863$. High entropy suggests that criteria with considerable variation across options play a more crucial role in decision-making.

In **Table 7**, Row 2, following Equation (3), $D_j = 1 - E_j = 1 - 0.9863 = 0.0155$.

In **Table 7**, Row 3, the weight, W_j using Equation (4).

$\sum_{j=1}^n D_j = 0.0155 + 0.0155 + 0.00350 + 0.0137 = 0.0757$. Thus, $W_j = 0.0155 / 0.0757 = 0.2046$.

To construct the weighted normalized decision matrix, as described in Step 3, the weight factors (determined in Step 2 and listed in the last row of **Table 7**) multiplied with the normalized value P_{ij} (obtained in Step 1 and listed in **Ta-**

ble 6) to produce the results shown in Table 8.

Table 8. Weighted normalized decision matrix.

Transport Mode	C ₁	C ₂	C ₃	C ₄
A ₁	0.0750	0.0749	0.1684	0.1006
A ₂	0.1350	0.0642	0.2694	0.0754
A ₃	0.0600	0.0963	0.2021	0.1131
A ₄	0.1200	0.0642	0.2694	0.0629

In Table 8, we calculate the following equation: $\widetilde{V}_{ij} = \widetilde{Q}_{ij} \times \widetilde{w}_j$. Using values in Table 6 and Table 7, the cell, $V_{11} = A_1 \times C_{w1} = 0.3666 \times 0.2046 = 0.0821$, given A₁ (Trailer) and C₁ (Cost). The reference points discussed in Step 4 are the Positive Ideal Reference Point (v^+) and Negative Ideal Reference Point (v^-). From Table 8, the v^+ and v^- are the maximum and minimum values corresponding to each criterion, shown in Table 9.

Table 9. Ideal reference points (positive, v^+ and negative, v^-).

Ideal reference points	C ₁	C ₂	C ₃	C ₄
v^+	0.1232	0.1424	0.1594	0.0978
v^-	0.0821	0.0791	0.0996	0.2201

Criteria 2-3 are benefit criteria meaning the highest value is preferred. Criteria 1 is a cost criterion meaning the lowest value is preferred. Calculation in Step 5 represents the distance from the ideal reference points. The S_i^+ and S_i^- follows the Equation (7a) and Equation 7(b).

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (v_{ij} \text{ from Table 6, and } v_j^+ \text{ from Table 7})$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (v_{ij} \text{ from Table 6, and } v_j^- \text{ from Table 7})$$

The relative closeness of the alternate transport modes concerning S^+ and S^- has been defined in Equation (8) as $U_i = \frac{S_i^-}{S_i^+ + S_i^-}$ for $i = 1, 2, \dots, m$; $0 \leq U \leq 1$.

Since $S^+ > 0$ and $S^- > 0$, the relative closeness index, $C_i \in [0, 1]$. The S_i^+ and S_i^- and closeness index U_b in Step 6 for each alternate carrier mode ranking, is presented in Table 10.

The selection of freight involves optimizing delivery time, cost, and the ability to transport products effectively. Factors like cost, timeliness, and damage prevention are key when choosing freight. As shown in Table 8, the Rail/Truck combo mode ranks number one, being the most economical, widely used, reliable, and flexible option with on-time service. In this numerical study, the COCF (Container on Container Freight) mode ranks second best, presenting a viable alternative to the Rail/Truck mode. As companies grow within their supply

Table 10. S_i^+ and S_i^- for each transport carrier (distance from v_j^+ and v_j^-).

<i>Transport Mode</i>	S_i^+	S_i^-	C_i	<i>Rank</i>
A_1 : Trailer	0.1252	0.0223	0.1512	3
A_2 : Rail/Truck	0.0345	0.1314	0.7922	1
A_3 : Air/Truck	0.1127	0.0465	0.2922	4
A_4 : COFC	0.0354	0.1278	0.7830	2

chain industries, they increasingly recognize the benefits of managing transportation processes through strategic contract negotiations and optimizing costs, reliability, time sensitivity, and carrier capabilities.

5. Conclusions

Modern trade requires extensive transportation links between producers and consumers for the seamless flow of goods to create value. This study explores using multimodal transportation for better logistics coordination. The TOPSIS method with entropy weighting helps choose the best carrier objectively. This approach is simple to understand yet reduces subjective decision-making in identifying weight priority in pursuing the best alternative along a network of facilities. The entropy method offers a promising alternative to address the limitations of fuzzy techniques in weight determination for transport selection.

Transporting goods across the continent or interstate may use any primary mode of transportation, *i.e.*, trailers, rail, air, or COFC options, depending on geographical location and customer service levels. The freight by rail/truck or COFC may be much cheaper but takes longer, necessitating companies to hold relatively large amounts of inventory in WIP to buffer against the resulting longer lead times and the inherent uncertainty associated with the carrier. In the illustrative example, the rail/truck option is preferable for freight moving. The solution takes advantage of modal flexibility and rail's long-haul economic benefit.

With the increasing computational power of computers, MCDM methods have become more accessible and user-friendly. This accessibility empowers various entities, from business corporations to logistics providers, to apply these methods in carrier selection. These methods enable businesses to identify the best option in terms of price, reliability, time, and flexibility, leading to significant cost savings and improved customer service. The flexibility of these methods allows businesses to align the criteria with their policies, market dynamics, customer demands, quality standards, and competitive advantages. The decision maker should consider the service capabilities of the carrier and their perspective weights, as services can vary widely between carriers. The preference rating of the criteria is based on the company values, historical data, and unbiased subjective assessment while developing the framework of the decision matrix. Other selection criteria and variables can be used, such as trip distances, the maximum

legal capacity of transportation modes, infrastructures, cargo weight, operational cost, the total number of available vehicles, demand, and ability to accommodate product size or a particular product to obtain more precise results.

Multimodal transportation leverages multiple forms of transport, holds the promise of being a cost-effective and environmentally friendly alternative to solo trailers. However, it faces challenges in growth, maintaining quality, and ensuring smooth operations across different transport modes. A future exercise could involve a sensitivity analysis of variables such as energy usage and fuel consumption (ton-miles per gallon of fuel), infrastructure, availability, and transport accessibility in the freight selection process.

Acknowledgements

The author thanks the anonymous reviewers whose suggestions improved this paper and appreciates the support from the editor.

Conflicts of Interest

The author declares no conflicts of interest to report regarding the publication of this paper.

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