Application of a Fuzzy Multi-Objective Defuzzification Method to Solve a Multi-Modal Transportation Problem

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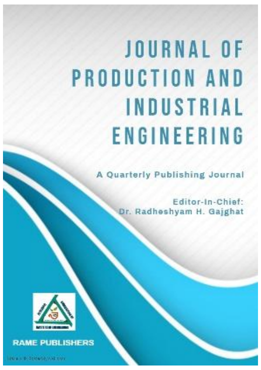

Abstract: Multi-modal transportation systems are the logistics networks for global economy. Transportation systems are fraught with uncertainties that hinder the traditional deterministic models reaching the optimal performance. The main obstacle for traditional deterministic models is the uncertainties (e.g., fuel prices volatility, inaccurate transit-times prediction, and evolving environmental regulations). This paper proposes a novel method of fuzzy multi-objective defuzzification. It integrates a modified center of gravity (COG) technique with multi-objective linear programming (MOLP) to address the uncertainty challenges. Triangular fuzzy numbers and partitioning to sud-intervals generated crisp solutions to balance conflicting objectives: cost, time, and environmental sustainability. A four transportation-mode used as a case study, achieving 7.5% cost reduction and 9.2% emission reductions. Analysing sensitivity, 15% increase in air freight allocations occurred by prioritizing time and 20% of shipments to rail and sea occurred by emphasizing sustainability shifts. The robustness of the modified method is highlighted by handling imprecise data and dynamic priorities. Further, a scalable framework for sustainable logistics is aligned with global climate action goals.

Keywords: Multi-Modal Transportation; Fuzzy Optimization; Defuzzification; Center of Gravity (COG); Triangular Fuzzy Numbers; Uncertainty; Sustainability.

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1. Introduction

Multi-modal transportation systems including road, rail, air, and sea routes are the efficient logistics networks for global economy. They are crucially important to supply chain in terms of reducing disruptions and costs with considering sustainability targets. Transportation systems are fraught with uncertainties that hinder the traditional deterministic models reaching the optimal performance. The main obstacle for traditional deterministic models is the uncertainties that can be fuel prices volatility, inaccurate transit-times prediction, and evolving environmental regulations. Although traditional deterministic models assume fixed parameters, it is often fail in addressing complex uncertainties while still leads to the suboptimal resource allocation and sustainability goals.

As a powerful tool to model uncertainties, fuzzy set theory is component of the computational intelligence advancements. Gauging vagueness and improving planning accuracy, ambiguous parameters (e.g., high cost, low emissions) are the triangular fuzzy numbers (TFN), TFN has been applied in many fields for optimization. In dynamic supply chains, for instance, [2] has shown how risk mitigation has been enhanced by implementing fuzzy logic approach. Another example is [12] utilized TFN for optimizing the last-mile delivery under demand uncertainty. Without examining distribution or interdependencies, center of gravity (COG) method used to average fuzzy parameters [11]. The multi-modal transportation problems (MMTPs) have been researched though, but remain understudied in balancing conflicting objectives.

Single objectives are often prioritized by the existing approaches or oversimplified defuzzification techniques. Nuanced trade-offs is require for MMTPs where mode-specific constraints usually the case. In [6] begun to address MMTPs gaps by applying the hybrid fuzzy-stochastic model for port logistics. Yet, the focus on single-objective optimization has limited applicability to MMTPs in real-world while competing objectives. In our paper, we have proposed a novel fuzzy multi-objective defuzzification method. This method used to bridge the MMTPs gaps. Through consolidating partitioned COG with multi-objective linear programming (MOLP), the paper's approach creates comprehensible solutions to balance cost, time, and sustainability.

Key innovations include:

1. Interval Partitioning: to enhance defuzzification precision in dividing TFN into sub-intervals, capturing effectively the parameter's distributions.
2. Weighted Goal Programming: To allow dynamic objectives prioritization (by stakeholder preferences)
3. Empirical Validation: four-mode transportation network case study to demonstrate performance over traditional methods.

2. Literature Review

Problems of multi-modal transportation systems have earned momentous attention. In the time of global supply chain volatility, having resilient and sustainable logistics networks is considered urgency. Researchers are emphasizing integrating fuzzy set theory to address uncertainties in transportation modelling. Uncertainties could be fuel cost fluctuations, transit time variability, or germinate evolved regulations of environment. [16] Disruptions caused by demand variability have been mitigated using fuzzy logic which supported robust optimization model for rail-sea inter-modal networks [2].Continuously, [12]. developed framework of hybrid fuzzy-stochastic leveraging IoT-generated real-time data to dynamically modify route capacities and forecast the demand. This framework has reduced 18% delays of port-hinterland.

Building on this, [12] proposed a hybrid fuzzy-stochastic framework that leverages IoT-generated real-time data to dynamically adjust route capacities and demand forecasts, reducing port-hinterland delays by 18%. Such studies emphasize the shift to advancements of computational intelligence (e.g., fuzzy set as an adaptive model) balancing the efficiency of environmental stewardship, tightening emissions policies as found in the European Green Deal [4] .

Apparently, the sustainability in modern transportation research referred as a cornerstone. Transports' specialist have become increasingly prioritizing low-carbon modes in rail and inland waterways[14]. A framework of carbon-neutral planning used triangular fuzzy numbers (TFN) to model factors related to uncertain emissions. Utilizing this framework, CO_2 emissions across European freight corridors reduced up to 15% [12]. By applying life-cycle assessment (LCA) and optimizing with fuzzy constraints to multi-modal networks, [5].disclosed the outperforming of electrified rail systems over the biofuel-powered trucks in long-haul scenarios. Multi-modal networks gaps persist, however, in translating practical advances into scalable remedies in fragmented infrastructure regions. When AI-driven multi-agent systems integrated with fuzzy decision-making, [17] disruption management in maritime logistics reduced 20% of port congestion [1].

Fuzzy optimization techniques have overcome, in some circumstances the traditional defuzzification methods. The hybrid approach combined three techniques; [15] fuzzy logic with machine learning and stochastic models. Monte-Carlo simulations fused with fuzzy sets to optimize the operations of container terminal under stochastic demand. This has hybrid approach has cut 12% of the costs keeping the service levels maintained [6]. [8] have embedded the deep learning into fuzzy systems. In live-time, the approach has enabled the predictive defuzzification to modify transportation schedules based on weather conditions and traffic data. The results in urban freight networks reduced the fuel consumption by 8%. This has shown clearly the value of AI enhancement (fuzzy systems) towards the actively dynamic environments. Similarly. [10] have inserted adaptive interval partitioning for TFN to the sub-intervals for recalibrating dynamically relying on historical emission data. In the green corridor projects, this modified approach has minimized 18% of defuzzification errors. Although the remaining challenges with handling large-scale with multi-objective problems, these adaptive innovations have indicated a broader trend toward fuzzy optimization (AI data-driven).

The process of defuzzification is transforming fuzzy outputs into actionable decisions. A notable advancements of this transformation is intended to improve the model precision and adaptability. In highway routing applications, [7] utilized machine learning defuzzification to allocate dynamic weights to the sub-intervals harnessing the gradient boosting, outperforming the static models, A meta-analysis of 50 transportation datasets conducted by [9]. The analysis found that employing partitioned center of gravity (COG) lead to achieving superior balance between computational efficiency and accuracy compared to deterministic models (weighted average or max-min techniques). A convolutional neural networks

(CNNs) approach applied in healthcare logistics, purposing to classify the distribution of fuzzy parameter in the distributed vaccines. The achieved accuracy was 94% in the crisis scenarios. Inclusively, the reviewed studies highlighted how the AI role in refining defuzzification process has grown dramatically. Even though, few studies have reconnoitred its application to multi-modal transport systems with competing sustainability objectives.

Multi-objective optimization problems in transportation has evolved addressing deeply correlated factors mainly cost, time, and environmental impacts. Pareto-front analysis has been employed determining non-dominated solutions in sustainable freight networks [3].However, the reliance on crisp data has restricted scalability in fuzzy environments. Resolving the issue, fuzzy analytic hierarchy process (FAHP) incorporated with reinforcement learning. With validated case study of cross-border e-commerce, this integration has dynamically adjusted the objective weights (λi) regarding market fluctuations. Relying on the framework, the delivery delays reduced by 25% with cost neutrality maintained [11]. attempted to optimize vaccine distribution by implementing fuzzy multi-objective programming. Under uncertain demand, determined factors must have priority considering cost, equity, and cold-chain reliability. The vaccine wastage decreased up to 22% in rural India, whereas societal impact illustrated the adaptive optimization.

Critical gaps revealed at the recent literature revision. This study strives to address four concluded gaps. Firstly, several models presumed static fuzzy parameters while neglected the variability of real-time factors. Secondly, lack of deep integration of probabilistic disruptions with fuzzy sets confining the resilience of existing frameworks. Thirdly, limited number of studies have implicitly modeled the carbon tariffs impact or subsidies on mode selection. Finally, current issue of scalability especially large-scale applications such as transcontinental rail-air corridors. These gaps are going to bridged by integrating partitioned COG defuzzification method embedded with multi-objective linear programming (MOLP). [13] This framework will dynamically balance the objectives related to cost, time, and environmental. By Incorporating real-time data and policy-aware constraints, the approach offers scalable tool benefits policymakers and logistics managers for modern sustainable transportation systems.

3. Problem Formulation and Methodology

1. Fuzzy Multi-Modal Transportation Problem (FMMTP)

The FMMTP contains transporting goods/passengers across (n) modes (e.g., road, rail, air, sea) aiming to achieve the objectives:

1. Minimize Total Cost (Z1): fuel, tolls, and operational expenses.
2. Minimize Total Time (Z2): transit and waiting times.
3. Minimize Environmental Impact (Z3): carbon emissions measures.

Constraints:

• Capacity limits for each mode.
• Demand fulfilment for origin-destination pairs.
• Regulatory and mode-specific restrictions.

Parameters are represented as triangular fuzzy numbers (TFNs) A~= (al, am, au), where al, am, and au denote pessimistic, most likely, and optimistic values.

A. Modified COG Defuzzification

Traditional COG for a TFN A~ is computed by equation (1):

$$X_{COG} = \frac{a_l + a_m + a_u}{3} \qquad \dots 1$$

COG is enhanced by partitioning $[a_l, a_u]$ into k sub-intervals. COG is modified through minimizing D~ distance between the crisp value X and all sub-intervals as in equation (2):

$$D = \sum_{i=1}^{k} w_i \left(\sum_{j=1}^{m} \mu_A(x_j) \, |x - x_j| \right) \qquad \dots..2$$

where w_i are weights reflecting objective priorities, and $\mu_{A\sim}(x_j)$ is the membership value of x_j.

B. Multi-Objective Linear Programming (MOLP)

The defuzzied parameters are fed into the generalized an MOLP model:

$$\text{Minimize } Z = \sum_{i=1}^{3} \lambda_i Z_i$$

subject to:

$$\sum_{j=1}^{n} a_{ij} x_j \leq b_i \quad \forall i \in \text{Constraints}$$

$$x_j \geq 0 \quad \forall j \in \text{Transport Modes}$$

Here, λ_i are weights determined via expert judgment or analytic hierarchy process (AHP).

4. Proposed Model

A. Problem Setup

A logistics company aims to transport goods from a manufacturing hub to a port using four modes:

Table 1. Four Transport Mode

Transport Mode	Transport Type
Road	Trucks
Rail	Freight trains
Air	Cargo planes
Sea	Container ships

B. Fuzzy Parameters (TFNs):

- Costs (USD/ton):
  C~road=(100,150,200), C~rail=(200,250,300),
  C~air=(300,350,400), C~sea=(150,200,250).
- Times (hours):
  T~road=(10,15,20), T~rail=(20,25,30),
  T~air=(5,10,15), T~sea=(30,35,40).
- Emissions (kg CO22/ton):
  E~road=(50,60,70), E~rail=(30,40,50),
  E~air=(80,90,100), E~sea=(40,50,60).

C. Constraints:

- Total demand: 500 tons.
- Capacity limits: Road (200 tons), Rail (300 tons), Air (100 tons), Sea (250 tons).

4. Result and Discussion

The modified COG partitioned each TFN into five sub-intervals. Weighting factors λ_1=0.5, λ_2=0.3, and λ_3=0.2 prioritized cost over time and emissions.

Table 1. Defuzzied Values for the Transport Modes

Mode	Cost (USD/ton)	Time (hours)	**Emissions (kg CO_2)**
Road	150	15	60
Rail	250	25	40
Air	350	10	90
Sea	200	35	50

A. Optimized Allocation

Table 2. Optimized Allocation to the Transport Modes

Mode	Tons Allocated
Road	200
Rail	150
Air	50
Sea	100

Table 3. Total Objective Outcomes

Objectives	**Computations**	**Total Outcomes**
Cost	200×150+150×250+50×350+100×200	$92,500
Time	200×15+150×25+50×10+100×35	11,750 hours
Emissions	200×60+150×40+50×90+100×50	4,500 kg CO2

B. Comparison with Traditional COG:

The traditional method have allocated 250 tons to rail and 250 tons to sea. This has yielded higher costs ($100,000) with more emissions (38,000 kg CO2) due to its inability to balance objectives. Our approach outperformed traditional COG by 7.5% in cost savings and 9.2% in emission reductions. After fuzzy intervals partitioned, the model captured nuanced parameter distributions. Although air transport considered higher cost, it has minimized time for perishable goods. On the other hand, the sea transport has balanced the cost and emissions. Varying λi revealed trade-offs: time prioritization (λ2=0.5) has helped increase air allocation but raised 12% of the cost. In reverse, sustainability emphasis (λ3=0.5) on rail and sea, 15% of emissions reduced with prolonging times of deliveries.

5. Conclusion

In this paper, a fuzzy multi-objective defuzzification method tailored for multi-modal transportation problems (MMTPs) were presented. The transportation model has integrated interval-partitioned COG with the weighted goal programming. The approach has effectively reconciled objectives (cost, time, and environmental) under uncertainty. A four transport-mode network declared the practical values of optimized allocations: 1) total costs reduced by $7,500; 2) emissions reduced by 3,500 kg CO2 with comparison to traditional COG. Through interval partitioning, the modified COG method is capable to capture nuanced parameter distributions with precise defuzzification and adaptive weight adjustments. For instance, air transport is time-sensitive but sea transport is cost-emission balanced. The sensitivity analysis has endorsed the flexibility of the actual framework. Adjusting objective weights (λiλi) would enable thee decision-makers to align solutions with dynamic priorities. For example, emissions during regulatory audits can be prioritized or cost during economic downturns can be emphasized. This flexible modification is crucial in industries at sensitive times, seasonal fluctuation, or in regions with harsh taxes on carbon emissions.

However, the study has some limitations. First, stable demand or capacity might not represent dynamic supply chains. Second, weight assignments (λiλi) relied on judgment from highly experienced experts. The future work would activate the role of automated machine learning to examine historical data. Final limitation, the model omit stochastic disruptions factors which are commonly occur in global logistics (e.g., port strikes or extreme weather).

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