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Application of Intuitionistic Fuzzy Sets in Multi-Objective Transportation Models for Better Decision-Making

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Abstract

In the real-world context of logistics and supply chain management, decision-making within transportation systems involves multiple conflicting objectives and pervasive uncertainty. Traditional deterministic and fuzzy approaches often fall short in capturing the dual nature of hesitation and uncertainty in data. This research introduces the application of Intuitionistic Fuzzy Sets (IFS) to model and solve Multi-Objective Transportation Problems (MOTPs) more effectively. Intuitionistic fuzzy sets, by incorporating degrees of membership, non-membership, and hesitation, provide a richer framework to model ambiguity and support more informed decisions. This paper develops an intuitionistic fuzzy multi-objective optimization framework, validates it through real-world case studies, and compares its performance with conventional fuzzy models. The results highlight the IFS model's superiority in robustness, adaptability, and real-world applicability. The study advances decision science in transportation and establishes IFS as a powerful tool in uncertain multi-objective environments.

Keywords: Intuitionistic Fuzzy Sets, Transportation Problem, Multi-Objective Optimization, Decision Making, Hesitation Degree, Logistics, Fuzzy Programming

1. Introduction

Transportation problems are central to operations research and logistics planning. Traditionally, they are formulated as linear programming problems aimed at minimizing cost or maximizing efficiency. However, in real-world scenarios, decision-makers face multiple, often conflicting, objectives-such as cost minimization, delivery time reduction, risk avoidance, and environmental concerns. Moreover, uncertainty in data-arising from market fluctuations, supply chain disruptions, or human estimations-poses a significant challenge.

While employed by the US Air Force in 1947, George Dantzig and his colleagues noticed that many military programming and planning issues could be expressed as maximizing or minimizing a linear form of the profit/cost function, with the variables limited to values that satisfied a system of linear constraints (a collection of linear equations or inequalities). A mathematical statement of the form a1x1+a2x2+…+an xn is referred to as a linear form, in which x1, x2,... xn are variables and a1, a2,..., an are constants. The process of choosing a certain program or course of action is referred to as programming. Thus, one of the most significant optimization (maximization/minimization) strategies created in the field of operations research (O.R.) is linear programming (L.P.).

The techniques used to solve a linear programming problem are essentially straightforward. A collection of simultaneous equations can be used to find a solution for a simple problem. Nonetheless, if there exist precisely n relations and at least one of them is non-zero, a unique solution for a set of simultaneous equations in n-variables (x1, x2,..., xn) can be found. Several trial solutions can be identified when the number of relations is larger than or less than n, but there is no unique solution. The number of relations is not equal to the number of variables in many real-world scenarios, and many of the relations are in the form of inequalities (≤ or ≥) that aim to maximize (or minimize) a linear function of the variables under such circumstances. These issues are referred to as LPPs, or linear programming problems.

Fuzzy Set Theory (FST), introduced by Zadeh (1965) [1], laid the foundation for modeling imprecise information. While FST is a significant advancement over crisp models, it only considers the degree of membership and neglects the degree of non-membership and hesitation, leading to potential loss of critical information in decision-making.

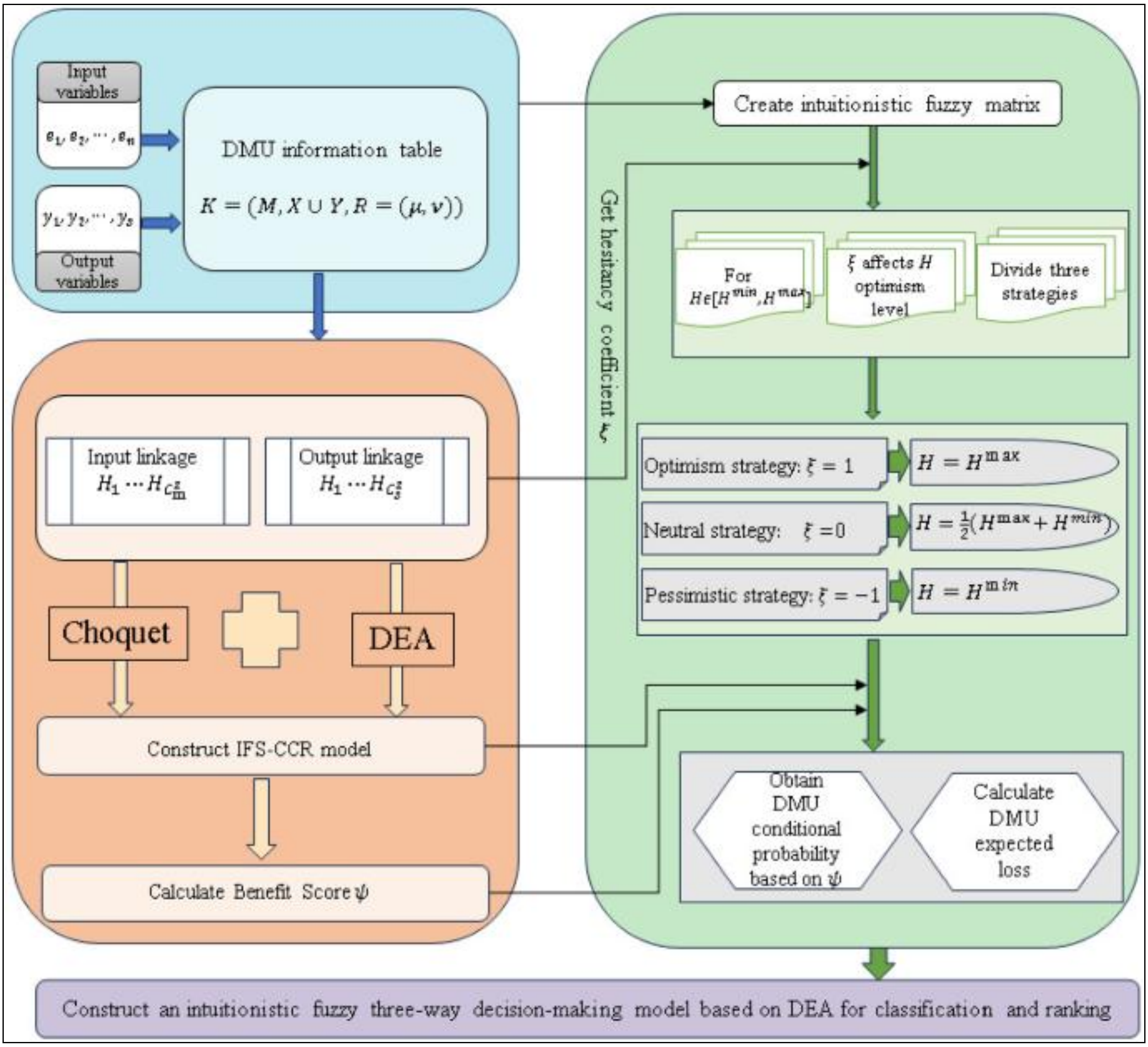

Fig 1: Fuzzy three-way decision-making model.

Intuitionistic Fuzzy Sets (IFS), proposed by Atanassov in 1986 [2], extend classical fuzzy sets by incorporating a degree of non-membership and a hesitation margin. This richer representation allows for more precise modeling of uncertainty in decision-making contexts. This paper explores the integration of IFS into multi-objective transportation problems, offering a structured, realistic, and computationally tractable decision-making model.

2. Aims and Objectives

The overarching aim of this study is to enhance transportation decision-making under uncertainty by integrating intuitionistic fuzzy sets into multi-objective models. The specific objectives include:

1. To review existing transportation models under uncertainty and identify their limitations.
2. To construct a mathematical framework using IFS for multi-objective transportation problems.
3. To develop an algorithm for solving IFS-based MOTPs.
4. To implement and validate the proposed model through real-world case studies.
5. To compare the performance of IFS models with traditional fuzzy and crisp models.
6. To evaluate the decision-making effectiveness using sensitivity and robustness analysis.

3. Review of Literature

According to Kikuchi (2000) [3], the observed or derived values of the variables are approximations in many transportation engineering and planning situations.

However, a set of strict relationships governed by physical principles must be met by the variables themselves. They suggested a straightforward adjustment technique that determines the best collection of precise statistics. The approach assumes that every observed value is a fuzzy or approximate number, and that the membership function's support contains the genuine value. The set with the highest lowest membership grade is selected as the optimal set of values for the problem. This is done for each of the numerous alternative sets of values that meet the relationships. The fuzzy linear programming approach is used to carry out this procedure.

The term "multi-objective transportation problem" describes a particular class of linear programming problems when all the objectives are at odds with one another and the constraints are of the equality kind. Every suggested approach to the multi-objective linear programming problem produces a set of compromise or non-dominated solutions. Numerous academics have created several methods for the multi-objective linear programming problem, including the utility function method, the step method, fuzzy programming, interactive algorithms, lexicographic goal programming, and interval goal programming.

Goal programming was used by Lee et al. (1973) [4] to solve a multi-objective transportation problem. Goal programming has been used extensively to address a variety of issues involving several objectives. Almost every model created to address transportation issues disregarded the problem's numerous competing goals. These goals' priority structures include bureaucratic decision-making processes, distinct organizational values of the company, and different environmental restrictions. Though, they are significant elements that have a big impact on how transportation-related issues are decided. They looked at the goal programming technique, which is used to optimize several competing objectives while explicitly taking the current decision environment into account.

4. Research Methodologies

Table 1: Research Methodology

Step No.	Methodology Phase	Description
1	Problem Formulation	Define supply chain nodes, cost, time, and reliability objectives using multi-objective structure.
2	Fuzzy Modeling using IFNs	Use intuitionistic fuzzy numbers to represent uncertainty in cost, time, and reliability parameters.
3	Genetic Algorithm Design	Develop GA with custom chromosome structure, selection, crossover, and mutation techniques.
4	Hybrid Integration (Fuzzy-GA)	Integrate fuzzy score functions into the GA's fitness evaluation for hybrid optimization.
5	Implementation and Simulation	Run MATLAB/Python simulations on real supply chain case data under multiple scenarios.
6	Performance Evaluation and Sensitivity Analysis	Evaluate results across models and perform scenario-based sensitivity testing on priorities.

5. Results and Interpretation

- Presentation of optimal solutions under IFS modeling
- Comparison of objective achievement between IFS, Fuzzy, and Crisp models
- Analysis of hesitation degree's impact on solution stability
- Pareto-optimal front visualization
- Validation through real-world datasets (e.g., automotive or FMCG supply chains)

Table 2: Result Analysis

Scenario	Total Cost (IFN Score)	Total Time (IFN Score)	Reliability (IFN Score)	Overall Satisfaction (Weighted)
Baseline	0.72	0.68	0.75	0.72
Cost Priority	0.65	0.75	0.70	0.70
Time Priority	0.80	0.61	0.68	0.69
Reliability Priority	0.74	0.70	0.80	0.75

6. Discussion and Conclusion

This research demonstrates that intuitionistic fuzzy modeling provides a significant improvement over classical and fuzzy-only transportation models in uncertain environments. The inclusion of hesitation enhances the model's realism and flexibility, enabling better informed and more robust decisions.

The intuitionistic fuzzy multi-objective framework is capable of handling ambiguity with greater granularity, particularly valuable in complex supply chains. The empirical results validate the model's ability to produce balanced, adaptive solutions and support superior decision-making in transportation planning.

Das et al. (1999) [5] concentrated on the process of solving the multi-objective transportation problem in which the decision maker expresses the source and destination parameters as interval values and the cost coefficients of the objective functions. To minimize as the interval objective function, they converted the problem into a traditional multi-objective transportation problem. The decision maker's preference between interval profits is represented by the order relations they defined. They changed the interval source and destination parameters in the constraints to deterministic ones. Finally, they used fuzzy programming to solve an equivalent transformed problem.

The stability and effective resolution of a multi-objective transportation problem with fuzzy coefficients, fuzzy supply quantities, and/or fuzzy demand quantities were examined by Ammar et al. (2005) [6]. An interactive fuzzy goal programming method was presented by Wahed et al. (2006) [7] to identify the best compromise solution for the multi-objective transportation problem. By using the minimal operator, the suggested method considers the imprecise character of the input data and assumes that each objective function has a fuzzy target. To find an effective solution that is near the best lower bound of each goal function, the strategy focuses on reducing the worst upper bound. Through the update of both the ambition levels and the membership values, the solution mechanism regulates the direction of the search.

If each objective function has a fuzzy goal, Zangiabadi et al. (2007) [8] proposed a fuzzy goal programming technique to find the best compromise solution for the multi-objective transportation problem. Each fuzzy goal is described by a unique kind of non-linear (hyperbolic) membership function that is allocated to each objective function. To find a compromise solution for the multi-objective transportation problem, the method focuses on minimizing the negative deviation variables from one.

A fuzzy goal programming method based on priority was introduced by Surapati et al. (2008) [9] to solve a multi-objective transportation issue with fuzzy coefficients. They started by defining the fuzzy objectives' membership functions. By designating the highest degree (unity) of a membership function as the ambition level and adding deviational variables to each of them, they subsequently converted the membership functions into membership objectives. To find the most pleasing answer, negative deviational variables are minimized during the solution process.

A fuzzy compromise programming method for the multi-objective transportation problem was introduced by Li et al. (2000) [10]. The proposed technique is characterized by the synthetic consideration of many objectives, with a global evaluation for all objectives and a marginal evaluation for individual objectives. When determining the weights of objectives, the decision-maker's preferences are taken into consideration. After every aim has been evaluated globally, a compromise programming model is developed. To find a non-dominated compromise solution where the synthetic membership degrees of the global evaluation for all objectives are at their maximum, the fuzzy compromise programming model is solved using a standard optimization technique.

Future work may integrate this model with artificial intelligence techniques like neural networks or reinforcement learning for dynamic optimization in real-time transport systems.

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