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BEYOND GREEN BORDERS: AN INNOVATIVE MODEL FOR SUSTAINABLE TRANSPORTATION IN SUPPLY CHAINS

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Abstract. Modern requirements necessitate the establishment of sustainable transportation systems, considering the substantial growth in transportation activities over recent years, which is expected to continue. Companies are facing the challenge of modeling their system transport to align with green principles. Sustainable transport relied on involving diverse stakeholders, particularly scientific research, in the development of this field. In light of this, maintaining sustainable transport quality involves conducting thorough investigations into an innovative study focusing on an uncertain interval programming model for a multi-stage, multi-objective, multi-product transportation challenge within budget constraints and safety measures in a green supply chain. Human languages often contain imperfect or unknown information, inherently lacking certainty; achieving precision in describing existing states or future outcomes is frequently unattainable. In probability theory, sufficient historical information is crucial for estimating probability distributions; while in fuzzy theory, determining a reliable membership function proves challenging; hence, there is often a hesitant estimation of the degree of belief in the occurrence of each condition. Addressing such uncertainties, the theory of uncertain intervals proves highly valuable. Given these considerations, the elements of the specified problem are recognized as uncertain intervals. To manage this lack of assurance, a fusion of interval theory and methods from uncertain programming is used to formulate two distinct models: an expected value model and a chance-constrained model. The equivalent deterministic models are then formulated and solved utilizing Weighted Sum Method, fuzzy programming, and goal programming. Following this, a numerical example is utilized to assess the model's performance, and the results obtained are compared. Finally, the document concludes with a sensitivity analysis and outlines future directions.

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1. Introduction

The Supply Chain, also known as the logistics chain, encompasses various activities aimed at planning, coordinating, and controlling the flows of products, information, and finances. Its mission extends from the warehouses of the initial supplier to the delivery at the final customer's location. Road freight transport serves as a traditional sector dedicated to enhancing the efficiency of coordinating physical movements throughout every stage of the logistics chain. The origins of the problem date to Hitchcock in 1941 [21], considering both the source and destination. Haley [19] introduced a third index that refers to modes of transport, in which a homogeneous product is transported from sources to destinations using various modes of transport, known as conveyances, including cargo flights, freight trains, trucks, etc.

Transportation problem (TP) knew considerable extensions and innovations to meet the market's demand. Hirsch and Danzig [20] introduced the concept of fixed charge (FCTP) that incorporates fixed charges or costs in addition to the variable transportation costs. Baidya and Bera [3] extended the framework of Solid Transportation Problem (STP) to incorporate budget constraints to limit the expenses and guiding resource allocation. Baidya and Bera [4] included safety factors in STP, which encompass measures aimed at ensuring secure transportation, risk avoidance, and compliance with safety regulations.

Real-world applications in engineering, economics, and logistics involve multi-objective aspects. The multi-objective problem presents a challenge for decision-makers, as they navigate between competing objectives, each with its own set of priorities and trade-offs. Balancing these multiple objectives requires a thoughtful and often complex decision-making process to arrive at the most suitable solutions that address these varied concerns. Gütmen *et al.* [18] provided an overview of weighted objective programming applied to a multi-objective transport problem. Akram *et al.* [1] addressed the complexity of handling multiple conflicting objectives. Khalifa and Kumar [23] employed a goal programming approach for solving multi-objective linear fractional problem with LR possibilistic variables. Yu *et al.* [40] applied an interactive approach for addressing the multi-objective transportation problem involving interval parameters.

Accurately analyzing past events or predicting the future is challenging due to uncertainties arising from unpredictable factors like weather, fluctuating traffic patterns and infrastructure problems. Various theories have been developed to address these uncertainties. Probability theory relies on historical data for estimating probability distributions, while applying fuzzy theory depends on establishing a reliable membership function, which poses a significant challenge. Liu [24] introduced uncertainty Theory, focusing on the assessment of belief degrees within human language. This theory provides a means to accurately evaluate the subjective beliefs held by experts through an uncertain measure. In the literature, there are many works done in the field of transportation problems under a lot of theories. Garg and colleagues [32] focused on addressing a fuzzy fractional two-stage transshipment challenge wherein all parameters are expressed using fuzzy numbers. Fathy [8] introduced an innovative approach to address the linear programming problem in the context of interval-valued intuitionistic fuzzy sets. Zhu and team [42] conducted investigations into a transportation problem with a fixed charge, focusing on the handling of fragile items in an uncertain environment. Ghosh *et al.* [9] tackled the challenges of waste management in the Department of Agriculture and Forestry by applying Pythagoras' hesitant fuzzy environment. Mardanya *et al.* [31] developed a Multi-Modal Transportation Problem by taking parameters in the form of rough intervals. Mardanya *et al.* [30] introduced a novel approach to address the multi-objective multi-item solid transportation problem using trapezoidal fuzzy numbers. Sifaoui and Aïder [36] addressed the uncertain interval multi-objective multi-product fixed charge solid transportation problem, incorporating a budget constraint and integrating a safety measure.

Indeed, the environmental impact of transportation cannot be overlooked. Transport stands as a substantial contributor to greenhouse gas emissions, making sustainability a pressing concern. Achieving global emission reduction targets necessitates significant reductions in emissions from freight and passenger transport.

Green supply chains offer a solution, merge logistics optimization with environmental responsibility. Companies must find a balance between environmental benefits and impacts in their logistics planning. In recent years, there has been a notable increase in the focus and significance given to the study of sustainable development.

Tseng *et al.* [39] conducted a comprehensive literature review focused on green supply chain management, during which they scrutinized current trends and identified upcoming challenges in the domain. Sheng *et al.* [35] presented a critical review that delved into the concept of green supply chain management as a means to promote sustainability in the manufacturing industry in China. Tian *et al.* [38] conducted a survey exploring various multi-criteria decision-making techniques applied in the context of green logistics and low-carbon transportation systems. Das *et al.* [7] addressed the multi-objective solid transportation-location problem, accounting for variable carbon emissions in inventory management.

Our article proposes an innovative model, an uncertain interval programming framework designed for a multi-stage, multi-objective, multi-product solid transportation challenge, incorporating budgetary and safety constraints within the context of a sustainable supply chain.

This research paper makes several key contributions, which can be outlined as follows:

- Development of an innovative Uncertain Interval Programming Model for a transportation problem involving multi-objective, multi-stage, multi-product solid fixed charge, budget constraints, and safety measures within a green supply chain.
- Integrating budget constraints and safety measures optimizes economic efficiency, minimizes risks, and introduces crucial trade-offs in transportation model performance. Strategic resource allocation and a global perspective ensure a balanced and sustainable transport system.
- Integrating Liu's uncertainty theory with interval-based programming methods to tackle the green supply chain characterized by uncertainties in parameters.
- Fusion of elements related to environmentally conscious logistics into the uncertain interval model for multi-objective, multi-stage, multi-product solid fixed charge, budget constraints, and safety measures, underscoring the importance of sustainability in supply chain management.
- Utilization of uncertain interval parameters to express the intrinsic uncertainty in the parameters of a multi-stage, multi-objective, multi-product fixed charge solid transportation problem within the framework of green logistics.
- Resolution of the deterministic model using diverse optimization techniques such as the Weighted Sum Method, fuzzy programming, and goal programming.
- Integration of environmental externalities and their potential impact on the quality of life for future generations into the problem formulation.
- Conducting a comparative study to analyze and compare the optimal solutions obtained using different approaches.
- Implementation and analysis of results to examine the effects of coefficient changes and determine the parameter value ranges.
- Illustration of the integration of budget constraints and safety measures into a transportation model.
- Demonstration of the practical relevance of the proposed model through an industrial problem, showcasing its applicability to multi-stage, multi-objective, multi-product fixed charge solid transportation problems with budget constraints in the uncertain interval context of green logistics.

The rest of the document is structured as follows: Section 2 provides a comprehensive summary of relevant literature. Section 3 offers the core principles of uncertain interval programming. Section 4 delves into the mathematical model, encompassing the notation. Section 5 devises uncertain programming utilizing methods of expected value and chance constraints within the proposed model. Section 6 establishes the deterministic equivalent of the analyzed models. Section 7 outlines three methods for addressing the models and introduces relevant theorems. Section 8 includes practical examples of application. Section 9 presents the results and discussions. Section 10 performs a sensitivity analysis of the acquired results. Section 11 concludes the manuscript and suggests directions for future research.

2. Review of relevant literature

In the field of TP, the existing literature is large and covers a vast amount of work. The following four tables refer to recent reviews of various TP variations under conditions of uncertainty. Despite significant advances in this field, there are still notable gaps in the literature on transport problems. To the best of our knowledge, none of the previous studies has explored an interval-based programming model under uncertainty for a multi-stage, multi-objective, multi-product fixed charge solid transportation while taking into account budgetary constraints and safety measures as part of an environmentally-friendly supply chain. This paper presents a novel transportation problem that has not been previously explored.

The objective of the four tables presented below is to illustrate the comparative study:

Articles	Objective	Parameters	Sustainable	Stage	Contribution of the paper
Ghosh *et al.* [10]	Multi	Neutrosophic	Yes	Single	Integrating the solid transportation problem, budget constraints, and carbon emissions into the context of maximizing probable profits involves employing a neutrosophic environment. This approach incorporates neutrosophic linear programming, fuzzy programming, and the global criterion method to determine a compromise solution for the multi-objective transportation problem.
Ghosh *et al.* [9]	Multi	Hesitant Fuzzy	Yes	Single	This study explores the implications of implementing carbon emission reduction strategies in the optimization of multi-objective solid waste transportation within a Pythagorean Hesitant Fuzzy framework. This research employs a ranking approach to convert uncertain data into a deterministic form and utilizes both fuzzy programming and Pythagorean Hesitant Fuzzy programming to derive a Pareto-optimal solution.
Ghosh *et al.* [11]	Multi	Type-2 zigzag uncertain	Yes	Single	Developing a model for the multi-objective fixed-charge solid transportation problem involves introducing key criteria such as time window restrictions and preservation technology, with the parameters considered as type-2 zigzag uncertain variables. Employing the expected value operator to convert this uncertainty into a deterministic model, the approach utilizes fuzzy programming, Pythagorean hesitant fuzzy programming, and the global criterion method to identify Pareto-optimal solutions.
Mondal *et al.* [33]	Multi	Intuitionistic Fuzzy	No	Single	Present a model to promote sustainability in the context of a multi-objective, multi-product, multi-choice fixed-charge solid transport problem in a fuzzy intuitionistic environment. The model takes into account customer satisfaction and social aspects. To deal with the uncertainty in the problem, a ranking concept based on total integral values is developed. In addition, a new solution method, the intuitionistic fuzzy game theory method, is proposed to deal efficiently with deterministic models.

Articles	Objective	Parameters	Sustainable	Stage	Contribution of the paper
Bind *et al.* [5]	Multi	Triangular Intuitionistic	Yes	Single	Study of an approach that aims to maximize profits while simultaneously minimizing item breakage, carbon emissions, and transportation time within a multi objective, multi product, fixed charge solid transportation problem, the associated parameters are modeled using triangular intuitionistic fuzzy numbers, and a score function is applied to transform the intuitionistic fuzzy problem into a deterministic one. Subsequently, a comprehensive methodology is devised to solve the proposed model, accounting for various driving styles.
Mardanya and Roy [29]	Multi	Interval	Yes	Single	The focus of the study is the analysis of a time-variant multi-objective linear fractional transportation problem. The investigation incorporates interval-valued parameters, which are utilized to convert the problem into a deterministic form through a novel transformation technique. Subsequently, fuzzy programming is applied to solve the transformed problem.
Giri and Roy [13]	Multi	Neutrosophic	Yes	Single	The investigation is focused on minimizing transportation costs, carbon emissions, and delivery times within the Neutrosophic Multi-Objective Green Four-Dimensional Fixed Charge Transportation Problem including source, destination, vehicle type, and road condition, using (α, β, γ) cuts to transform the model into interval form, then two distinct approaches, Neutrosophic Programming (NP) and Pythagorean Hesitant Fuzzy Programming (PHFP), are employed to identify an optimal compromise solution.
Midya *et al.* [32]	Multi	Intuitionistic fuzzy	Yes	Multi	Introduce a multi-stage multi-objective fixed-charge solid transportation problem. Use the expected value operator to transform the proposed model into a deterministic one. Subsequently, apply weighted Tchebycheff metrics programming and min–max goal programming. These methodologies are designed to yield Pareto-optimal solutions.
Ghosh *et al.* [12]	Multi	Type-2 intuitionistic fuzzy	Yes	Multi	Introducing a model focused on optimizing sustainability factors in solid waste management. Utilizing a rank operator to establish a deterministic model, and then using neutrosophic linear programming and ϵ-constraint methodologies to obtain a compromise solution for the multi-objective transportation problem.
Ghosh *et al.* [9]	Multi	Pythagorean hesitant fuzzy	Yes	Multi	Developing a multi-objective solid transportation model targeting waste management challenges within the agriculture and forest department. Utilizing a ranking approach to convert uncertain data into deterministic form. Employing both fuzzy programming and Pythagorean hesitant fuzzy programming to attain Pareto-optimal solutions for complex problems.
Ghosh *et al.* [10]	Multi	Neutrosophic environment	Yes	Multi	Developing a model for the Fixed-Charge Solid Transportation Problem under budget constraints, considering carbon emissions. Therefore employing neutrosophic linear programming, fuzzy programming, and the global criterion method to obtain a compromise solution for the multi-objective transportation problem.

Articles	Objective	Parameters	Sustainable	Stage	Contribution of the paper
Mardanya *et al.* [31]	Single	Rough interval	No	Multi	Develop a Multi-Modal Transportation Problem by taking parameters in the form of rough intervals. Then use rough chance-constrained programming and the expected value operator to handle these rough intervals.
Mardanya *et al.* [30]	Multi	Fuzzy	No	Single	Investigating the Multi-Objective Multi-item Solid Transportation Problem in a fuzzy environment, then using Grzegorzewski's conversation rule [17] to transform trapezoidal fuzzy numbers into nearly approximation interval numbers. Fuzzy programming and interval programming techniques are applied to solve the converted model.
Das *et al.* [7]	Multi	Deterministic	Yes	Multi	Aims to address the multi-objective solid transportation-location problem, accounting for variable carbon emissions in inventory management, using a hybrid approach. This innovative methodology relies on an alternating locate-allocate heuristic and intuitionistic fuzzy programming to achieve the Pareto-optimal solution for the proposed formulation.
Mondal *et al.* [7]	Multi	Intuitionistic fuzzy	Yes	Single	tackles a sustainable multi-objective multi-product multi-choice step fixed-charge solid transportation problem. It introduces an innovative defuzzification technique employing total integral values and transforms models into deterministic forms *via* binary variables. Additionally, it introduces the intuitionistic fuzzy game-theoretic method as an effective approach for solving these deterministic models.
Goli *et al.* [16]	Multi	Robust optimization	Yes	Multi	Focuses on designing a sustainable supply chain network capable of managing multiple products across different time periods. It leverages Internet-of-Things (IoT) technology and integrates both forward and reverse logistics systems. To handle uncertainties in the demand parameter, the study adopts a robust optimization approach employing a single-objective model through Goal Programming (GP) methodology.
Goli *et al.* [15]	Multi	The credibility theory	No	Multi	Introduces a mathematical model that utilizes possibilistic programming to design an organ transplant supply chain while considering uncertainty. To address this uncertainty, a simulation-based optimization method is incorporated into the model, leveraging credibility theory.
Goli *et al.* [14]	Multi	The credibility theory	No	Multi	Investigates the development of a closed-loop supply chain system suitable for perishables, prioritizing sustainability covering, multi-level, multi-products and to solve the problem, a new hybrid algorithm based on the Whale Optimization Algorithm (WOA) and the Genetic Algorithm (GA) is used.
Maity *et al.* [27]	Multi	Interval	Yes	Single	This research delves into the examination of a multi-objective transport problem characterized by time variation and pollution minimization, where the model parameters are presented as intervals. To address this, a function, depends on time, is employed, ensuring the value falls within the interval [0,1]. This serves to transform the interval-valued cost parameter into a real-valued parameter. Subsequently, Goal Programming is employed to solve the deterministic model.

Articles	Objective	Parameters	Sustainable	Stage	Contribution of the paper
Sifaoui and Aïder [37]	Multi	Interval-valued fuzzy	Yes	Single	Investigates a multi-objective, multi-product solid transport problem with a time-variant factor, emphasizing pollution minimization. Parameters are represented as interval-valued trapezoidal fuzzy numbers. To enhance the model, a temporal-dependent function confines values within [0,1], converting the interval-valued cost parameter to a real-valued one. The research employs a hybrid method with various membership functions to achieve a compromise solution.
Sifaoui and Aïder [36]	Multi	Uncertain Interval	No	Single	Proposes uncertain interval programming models for a multi-objective, multi-product fixed charge solid transportation problem featuring budget constraints and safety measures. The study employs interval theory and uncertain programming techniques to develop an Expected Value Model and a Chance-Constrained Model. Additionally, equivalent deterministic models are formulated and solved using a linear weighted method, fuzzy programming method, and goal programming method.
Midya *et al.* [32]	Multi	Intuitionistic fuzzy	Yes	Multi	Focuses on an exploration of a multi-stage, multi-objective fixed-charge solid transportation problem within the framework of a green supply chain network, incorporating an intuitionistic fuzzy environment. The study employs the expected value operator to transform the initial intuitionistic fuzzy model into a deterministic representation. Subsequently, uses weighted Tchebychef metrics programming and min–max goal programming to yield Pareto-optimal solutions.
The proposed study	Multi	Uncertain interval	Yes	Multi	Introduces an uncertain interval programming model to tackle a diverse transportation challenge within a green supply chain. This intricate problem involves multiple stages, objectives, and products, all while considering budget constraints and safety measures. The study utilizes a fusion of interval theory and uncertain programming to formulate two models – an expected value model and a chance-constrained model. To achieve a Pareto-optimal solution, the research employs the Weighted Sum Method, fuzzy programming, and goal programming.

After a thorough examination of the tables above, it becomes clear that the models formulated in previous studies had inherent limitations. However, our proposed study takes a considered approach to addressing and overcoming these limitations with a clear objective. We aim to address and improve the following aspects.

– Utilizing uncertain intervals acknowledges the inherent variability, randomness, and incomplete information prevalent in the world, providing a more realistic and practical means to describe and comprehend real-life situations. It is noteworthy, according to conducted studies, that within the domain of transportation, there is a scarcity of research specifically addressing this type of uncertainty.
– Previous studies have not addressed an uncertain Interval Programming Model for a transportation problem involving multi-objective, multi-stage, multi-product, conveyance, fixed charge, budget constraints, and safety measures within a green supply chain. This proposed model aims to fill this gap by considering these diverse factors in a unified framework, presenting a novel and comprehensive approach to transportation problem resolution within the context of a green supply chain.
– Integrating safety measures and budget constraints into the supply chain is a challenge that hasn't been tackled, according to the tables above. Nevertheless, it remains a vital component of modern business,

encompassing safety standards, regulatory adherence, and operational continuity, necessitating innovative approaches within supply chain management.

- This study introduces a novel approach by integrating Liu's uncertainty theory with interval-based programming methods to tackle uncertainties in green supply chains, focusing on hesitations in decision-making and uncontrollable factors, which have not been extensively studied in existing literature. This innovative framework aims to offer a comprehensive strategy for optimizing operations in unpredictable environments, providing a unique contribution to the field of supply chain management.
- The integration of carbon emission charges within an Uncertain Interval Programming Model for complex transportation problems, spanning multiple objectives, stages, products, and encompassing conveyance, fixed charges, budget constraints, and safety measures, stands pivotal in ensuring transport sustainability. Remarkably, prior literature analyzed in the tables above has yet to comprehensively address this critical aspect of sustainable transportation.
- In the realm of supply chain management, prior studies have primarily focused on efficiency and cost reduction, neglecting a deep exploration of profit maximization. This uncharted territory presents an exciting opportunity to investigate how fine-tuning various supply chain components – from procurement to distribution – could directly influence overall profitability. By unraveling the intricate relationships among these elements, novel strategies might emerge, paving the way for substantial improvements in the financial performance of supply chains across diverse industries.
- Our proposed methodology for optimizing Green supply chain is currently theoretical. However, the fundamental principles we've established could potentially be adapted to other real-life problems.

3. Preliminary

Definition 3.1 ([37]). For any uncertain variable χ, we can associate an uncertain interval denoted as $[\chi_L, \chi_R]$, which can also be represented as $\langle \chi_M, \chi_W \rangle$. Here, $\chi_M = \frac{1}{2}(\chi_L + \chi_R)$ and $\chi_W = \frac{1}{2}(\chi_R - \chi_L)$ depicting the ambiguous midpoint and radius of the interval, respectively.

Definition 3.2. Let $\chi_A = [\chi_{a_L}, \chi_{a_R}]$ and $\chi_B = [\chi_{b_L}, \chi_{b_R}]$ be two intervals, denoted as A and B, and let $a \in \mathbb{R}$ be a scalar. Employing set-theoretic definitions and acknowledging that interval numbers are ordered sets of real numbers, the ensuing four formulas can be derived:

– Addition:

$$\chi_A + \chi_B = [\chi_{a_L}, \chi_{a_R}] + [\chi_{b_L}, \chi_{b_R}] = [\chi_{a_L} + \chi_{b_L}, \chi_{a_R} + \chi_{b_R}]. \tag{1}$$

– Subtraction:

$$\chi_A - \chi_B = [\chi_{a_L}, \chi_{a_R}] - [\chi_{b_L}, \chi_{b_R}] = [\chi_{a_L} - \chi_{b_R}, \chi_{a_R} - \chi_{b_L}]. \tag{2}$$

– Scalar Multiplication:

$$a\chi_A = k[\chi_{a_L}, \chi_{a_R}] = \begin{cases} [a\chi_{a_L}, a\chi_{a_R}] & \text{if } a \geq 0 \\ [a\chi_{a_R}, a\chi_{a_L}] & \text{if } a < 0. \end{cases} \tag{3}$$

– Multiplication:

$$\begin{aligned} \chi_A \times \xi_B &= [\chi_{a_L}, \chi_{a_R}] \times [\chi_{b_L}, \chi_{b_R}] \\ &= [\min\{\chi_{a_L}\chi_{b_L}, \chi_{a_L}\chi_{b_R}, \chi_{a_R}\chi_{b_L}, \chi_{a_R}\chi_{b_R}\}, \max\{\chi_{a_L}\chi_{b_L}, \chi_{a_L}\chi_{b_R}, \chi_{a_R}\chi_{b_L}, \chi_{a_R}\chi_{b_R}\}]. \end{aligned} \tag{4}$$

– Division:

$$\frac{\chi_A}{\chi_B} = \chi_A \times \frac{1}{\chi_B} = [\chi_{a_L}, \chi_{a_R}] \times \left[\frac{1}{\chi_{b_R}}, \frac{1}{\chi_{b_L}}\right], \text{ provided that } 0 \notin [\chi_{b_L}, \chi_{b_R}]. \tag{5}$$

Definition 3.3. For any two intervals

$$\chi_A = [\chi_{a_L}, \chi_{a_R}] = \langle \chi_{a_M}, \chi_{a_W} \rangle \quad \text{and} \quad \chi_B = [\chi_{b_L}, \chi_{b_R}] = \langle \xi_{b_M}, \xi_{b_W} \rangle, \tag{6}$$

$$\chi_A \preceq \chi_B \text{ if and only if } \begin{cases} \chi_{a_M} < \chi_{b_M} & \text{for } \chi_{a_M} \neq \chi_{b_M} \\ \chi_{a_W} \geq \chi_{b_W} & \text{for } \chi_{a_M} = \chi_{b_M}. \end{cases} \tag{7}$$

Furthermore,

$$\chi_A \prec \chi_B \text{ if and only if } \chi_A \preceq \chi_B \text{ and } \chi_A \neq \chi_B.$$

Definition 3.4 ([26])**.** An uncertainty distribution $\varphi(x)$ is considered regular if it is a continuous and strictly increasing function with respect to x and satisfies the following conditions:

$$\begin{cases} 0 < \varphi(x) < 1, \\ \lim_{x \to -\infty} \varphi(x) = 0, \\ \lim_{x \to +\infty} \varphi(x) = 1. \end{cases} \tag{8}$$

Definition 3.5 ([25])**.** Let χ be an uncertain variable with a regular uncertainty distribution $\varphi(x)$. Then, the inverse function $\varphi^{-1}(\gamma)$ is referred to as the inverse uncertainty distribution of χ.

Definition 3.6. The uncertain variables $\chi_1, \ldots, \chi_n$ are said to be independent if:

$$M\left\{\bigcap_{i=1}^{n} (\chi_i \in \gamma_i)\right\} = \bigwedge_{i=1}^{n} M\{\chi_i \in \gamma_i\}. \tag{9}$$

Definition 3.7 ([24])**.** The expected value of the uncertain variable χ is defined as:

$$E[\chi] = \int_0^{+\infty} M\{\chi \geq x\} \, \mathrm{d}x - \int_{-\infty}^{0} M\{\chi \leq x\} \, \mathrm{d}x \tag{10}$$

provided that at least one of the two integrals is finite.

Definition 3.8 ([24])**.** The representation of the expected value is given by:

$$E[\chi] = \int_0^1 \varphi^{-1}(\gamma) \, \mathrm{d}\gamma \tag{11}$$

where φ^{-1} represents the inverse uncertainty distribution of the uncertain variable χ.

Theorem 3.9 ([26])**.** *Let χ and η be independent uncertain variables with finite expected values. Then, for any real numbers c and d, we have:*

$$E[c\chi + d\varrho] = cE[\chi] + dE[\varrho]. \tag{12}$$

Definition 3.10 ([24])**.** Consider an uncertain variable χ with a confidence level parameter $\beta \in (0, 1]$. The β-optimistic and β-pessimistic values of χ, denoted as $\chi_{\sup}(\beta)$ and $\chi_{\inf}(\beta)$ respectively, are defined as follows:

$$\chi_{\sup}(\beta) = \sup\{t \mid M\{\chi \geq t\} \geq \beta\} \tag{13}$$

$$\chi_{\inf}(\beta) = \inf\{t \mid M\{\chi \leq t\} \geq \beta\}. \tag{14}$$

4. Problem description

This study focuses on the development of a sustainable supply chain designed for a multi-stage, multi-objective, multi-product solid transportation challenge, incorporating budgetary and safety constraints. It examines economic, environmental, and social factors as objective functions with the aim to identify the quantities of each a product to be transported from factories through distribution centers and retailers to customers, using u modes of transport.

The described scenario involves a system comprising H factories, DC distribution centers, RT retailers, and B customers, each with specific requirements. Within this framework, each H factory has the ability to transport different quantities of product A to any DC distribution center using U modes of transport. In these distribution centers, in turn, this product is transported to RT retailers using U modes of transport. Ultimately, the RT retailers receive the product from the DC centers and transport it to the B customers using U modes of transport.

Assumptions

The assumptions of the mathematical model are as follows:

- The supply chain has three main levels, namely factories (h), distribution centers (dc), retailers (rt), and customers (b), each being characterized by a demand requirement.
- Factories (h) can deliver multiple heterogeneous products to distribution centers (dc), which, in turn, can ship products to retailers (rt). Retailers receive products and deliver them to customers (b) using various conveyances.
- Buyers can purchase various products at prices with limited budgets for each destination.
- The initiation of transportation imposes a fixed charge, constituting a consistent expense unaffected by variables such as usage, output, or sales fluctuations.
- Carbon emission charges are included to ensure transport durability and minimize damage.
- Different modes of transport are taken into account at each stage of the supply chain.
- Safety measures are implemented at every stage for reducing risks and guaranteeing the safe passage of goods.
- The model optimizes multiple conflicting objectives, including profit maximization, carbon emission reduction, and time minimization, under the same constraints.
- All parameters are considered as uncertain interval.

Notations

- h: Index related to the factories.
- dc: Index related to the distribution centers.
- u: Index related to the transportation modes (conveyances).
- a: Index related to the products.
- rt: Index related to the retailers.
- b: Index related to the customers.
- $[\xi_{A^a_{L_h}}, \xi_{A^a_{R_h}}]$: An uncertain interval for the amount of the available product at the hth factory for the ath product.
- $[\xi_{b^a_{L_b}}, \xi_{b^a_{R_b}}]$: An uncertain interval for the demand of the bth customer for the ath product.
- $[\xi_{e^1_{L_u}}, \xi_{e^1_{R_u}}]$: An uncertain interval for capacity of uth conveyance to move the product in stage 1.
- $[\xi_{e^2_{L_u}}, \xi_{e^2_{R_u}}]$: An uncertain interval for capacity of uth conveyance to move the product in stage 2.
- $[\xi_{e^3_{L_u}}, \xi_{e^3_{R_u}}]$: An uncertain interval for capacity of uth conveyance to move the product in stage 3.
- $[\xi_{C^a_{L_{hdcu}}}, \xi_{C^a_{R_{hdcu}}}]$: An uncertain interval cost for transporting the ath product from the hth factory to the dcth distribution center using the uth conveyance.
- $[\xi_{C^a_{L_{dcrtu}}}, \xi_{C^a_{R_{dcrtu}}}]$: An uncertain interval cost for transporting the ath product from the dcth distribution center to the rtth retailer using the uth mode of transport.
- $[\xi_{C^a_{L_{rtbu}}}, \xi_{C^a_{R_{rtbu}}}]$: An uncertain interval cost for transporting the ath product from the rtth retailer to the bth customer using the uth conveyance.
- $[\xi_{F^a_{L_{hdcu}}}, \xi_{F^a_{R_{hdcu}}}]$: An uncertain interval fixed charge for transporting the ath product from the hth factory to the dcth distribution center using the uth conveyance.
- $[\xi_{F^a_{L_{dcrtu}}}, \xi_{F^a_{R_{dcrtu}}}]$: An uncertain interval fixed charge for transporting the ath product from the dcth distribution center to the rtth retailer using the uth conveyance.

- $[\xi_{F^a_{L_{rtbu}}}, \xi_{F^a_{R_{rtbu}}}]$: An uncertain interval fixed charge for transporting the ath product from the rtth retailer to the bth customer using the uth conveyance.
- $[\xi_{T^a_{L_{hdcu}}}, \xi_{T^a_{R_{hdcu}}}]$: An uncertain interval transportation time from the hth factory to the dcth distribution center using the uth conveyance for the ath product.
- $[\xi_{T^a_{L_{dcrtu}}}, \xi_{T^a_{R_{dcrtu}}}]$: An uncertain interval transportation time from the dcth distribution center to the rtth retailer using the uth conveyance for the ath product.
- $[\xi_{T^a_{L_{rtbu}}}, \xi_{T^a_{R_{rtbu}}}]$: An uncertain interval transportation time from the rtth retailer to the bth customer using the uth conveyance for the ath product.
- $[\xi_{n^a_{L_{hdcu}}}, \xi_{n^a_{R_{hdcu}}}]$: An uncertain interval carbon emission charge per unit of transportation from the hth factory to the dcth distribution center using the uth conveyance for the ath product.
- $[\xi_{n^a_{L_{dcrtu}}}, \xi_{n^a_{R_{dcrtu}}}]$: An uncertain interval carbon emission charge per unit of transportation from the dcth distribution center to the rtth retailer using the uth conveyance for the ath product.
- $[\xi_{n^a_{L_{rtbu}}}, \xi_{n^a_{R_{rtbu}}}]$: An uncertain interval carbon emission charge per unit of transportation from the rtth retailer to the bth customer using the uth conveyance for the ath product.
- α: Carbon tax per unit of carbon emission ($\alpha \geq 0$).
- $[\xi_{S^a_{L_{dc}}}, \xi_{S^a_{R_{dc}}}]$: An uncertain interval selling price per unit for the ath product at the dcth distribution center.
- $[\xi_{S^a_{L_{rt}}}, \xi_{S^a_{R_{rt}}}]$: An uncertain interval selling price per unit for the ath product at the rtth retailer.
- $[\xi_{S^a_{L_b}}, \xi_{S^a_{R_b}}]$: An uncertain interval selling price per unit for the ath product at the bth customer.
- $[\xi_{V^a_{L_h}}, \xi_{V^a_{R_h}}]$: An uncertain interval purchasing cost per unit for the ath product at the hth factory.
- $[\xi_{V_{L^a_{dc}}}, \xi_{V^a_{R_{dc}}}]$: An uncertain interval purchasing cost for the ath product at the dcth distribution center.
- $[\xi_{V^a_{L_{rt}}}, \xi_{V^a_{R_{rt}}}]$: An uncertain interval purchasing cost for the ath product at the rtth retailer.
- $[\xi_{Bg_{L_{dc}}}, \xi_{Bg_{R_{dc}}}]$: An uncertain budget at the dcth distribution center.
- $[\xi_{Bg_{L_{rt}}}, \xi_{Bg_{R_{rt}}}]$: An uncertain budget at the rtth retailer.
- $[\xi_{Bg_{L_b}}, \xi_{Bg_{R_b}}]$: An uncertain budget at the bth customer.
- x^a_{hdcu}: Unit amount of ath product to be transported from the hth factory to the dcth distribution center using the uth conveyance (decision variable).
- y^a_{dcrtu}: Unit amount of ath product to be transported from the dcth distribution center to the rtth retailer using the uth conveyance (decision variable).
- z^a_{rtbu}: Unit amount of ath product to be transported from the rtth retailer to the bth customer using the uth conveyance (decision variable).
- $\theta^1(x^a_{hdcu})$: Binary variable in stage 1, with a value of 1 indicating the utilization of factory h and 0 otherwise.
- $\theta^2(y^a_{dcrtu})$: Binary variable in stage 2, with a value of 1 indicating the utilization of distribution center dc and 0 otherwise.
- $\theta^3(z^a_{rtbu})$: Binary variable in stage 3, with a value of 1 indicating the utilization of retailer rt and 0 otherwise.
- $[\xi_{Ms_{L^a_{hdcu}}}, \xi_{Ms_{R^a_{hdcu}}}]$: An uncertain interval of desired safety measure for transporting ath product from the hth factory to the dcth distribution center using the uth conveyance.
- $[\xi_{Ms_{L^a_{dcrtu}}}, \xi_{Ms_{R^a_{dcrtu}}}]$: An uncertain interval of desired safety measure for transporting ath product from the dcth distribution center to the rtth retailer using the uth conveyance (decision variable).
- $[\xi_{Ms_{L^a_{rtbu}}}, \xi_{Ms_{R^a_{rtbu}}}]$: An uncertain interval of desired safety measure for transporting ath product from the rtth retailer to the bth customer using the uth conveyance (decision variable).
- For all h and $\forall\, h$: denote h ranging from 1 to H.
- For all dc and $\forall\, dc$: denote dc ranging from 1 to DC.
- For all u and $\forall\, u$: denote u ranging from 1 to U.
- For all rt and $\forall\, rt$: denote rt ranging from 1 to RT.
- For all b and $\forall\, b$: denote b ranging from 1 to B.
- For all a and $\forall\, a$: denote a ranging from 1 to A.

The formulation of the proposed model in mathematical programming is presented as follows:

$$
(P_1)\begin{cases}
\max Z^1 = \sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{DC}\sum\limits_{u=1}^{U}\Big\{\Big(\Big(\Big[\xi_{S^a_{L_{dc}}},\xi_{S^a_{R_{dc}}}\Big]-\Big[\xi_{V^a_{L_h}},\xi_{V^a_{R_h}}\Big]-\Big[\xi_{C^a_{L_{hdcu}}},\xi_{C^a_{R_{hdcu}}}\Big]\Big)x^a_{hdcu} \\
\quad -\Big[\xi_{F^a_{L_{hdcu}}},\xi_{F^a_{R_{hdcu}}}\Big]\theta^1\big(x^a_{hdcu}\big)\Big\}+\sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{DC}\sum\limits_{rt=1}^{RT}\sum\limits_{u=1}^{U}\Big\{\Big(\Big(\Big[\xi_{S^a_{L_{rt}}},\xi_{S^a_{R_{rt}}}\Big]-\Big[\xi_{V^a_{L_{dc}}},\xi_{V^a_{R_{dc}}}\Big] & (1.1)\\
\quad -\Big[\xi_{C^a_{L_{dcrtu}}},\xi_{C^a_{R_{dcrtu}}}\Big]\Big)y^a_{dcrtu}-\Big[\xi_{F^a_{L_{dcrtu}}},\xi_{F^a_{R_{dcrtu}}}\Big]\theta^2\big(y^a_{dcrtu}\big)\Big\}+\sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{RT}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\Big\{\Big(\Big(\Big[\xi_{S^a_{L_b}},\xi_{S^a_{R_b}}\Big] \\
\quad -\Big[\xi_{V^a_{L_{rt}}},\xi_{V^a_{R_{rt}}}\Big]-\Big[\xi_{C^a_{L_{rtbu}}},\xi_{C^a_{R_{rtbu}}}\Big]\Big)z^a_{rtbu}-\Big[\xi_{F^a_{L_{rtbu}}},\xi_{F^a_{R_{rtbu}}}\Big]\theta^3\big(z^a_{rtbu}\big)\Big\} \\
\min Z^2 = \alpha\Big\{\sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{DC}\sum\limits_{u=1}^{U}\Big[\xi_{\eta^a_{L_{hdcu}}},\xi_{\eta^a_{R_{hdcu}}}\Big]x^a_{hdcu}+\sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{DC}\sum\limits_{rt=1}^{RT}\sum\limits_{u=1}^{U}\Big[\xi_{\eta^a_{L_{dcrtu}}},\xi_{\eta^a_{R_{dcrtu}}}\Big]y^a_{dcrtu} & (1.2)\\
\quad +\sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{RT}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\Big[\xi_{\eta^a_{L_{rtbu}}},\xi_{\eta^a_{R_{rtbu}}}\Big]z^a_{rtbu}\Big\} \\
\min Z^3 = \sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{DC}\sum\limits_{u=1}^{U}\Big[\xi_{T^a_{L_{hdcu}}},\xi_{T^a_{R_{hdcu}}}\Big]\theta^1\big(x^a_{hdcu}\big)+\sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{DC}\sum\limits_{rt=1}^{RT}\sum\limits_{u=1}^{U}\Big[\xi_{T^a_{L_{dcrtu}}},\xi_{T^a_{R_{dcrtu}}}\Big]\theta^2\big(y^a_{dcrtu}\big) & (1.3)\\
\quad +\sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{RT}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\Big[\xi_{T^a_{L_{rtbu}}},\xi_{T^a_{R_{rtbu}}}\Big]\theta^3\big(z^a_{rtbu}\big)\Big\} \\
\sum\limits_{dc=1}^{DC}\sum\limits_{u=1}^{U}x^a_{hdcu}=\Big[\xi_{a^a_{L_h}},\xi_{a^a_{R_h}}\Big] \qquad \forall h, a & (1.4)\\
\sum\limits_{rt=1}^{RT}\sum\limits_{u=1}^{U}z^a_{rtbu}=\Big[\xi_{b^a_{L_b}},\xi_{b^a_{R_b}}\Big] \qquad \forall b, a & (1.5)\\
\sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{DC}x^a_{hdcu}=\Big[\xi_{e^1_{L_u}},\xi_{e^1_{R_u}}\Big] \qquad \forall u & (1.6)\\
\sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{DC}\sum\limits_{rt=1}^{RT}y^a_{dcrtu}=\Big[\xi_{e^2_{L_u}},\xi_{e^2_{R_u}}\Big] \qquad \forall u & (1.7)\\
\sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{RT}\sum\limits_{b=1}^{B}z^a_{rtbu}=\Big[\xi_{e^3_{L_u}},\xi_{e^3_{R_u}}\Big] \qquad \forall u & (1.8)\\
\sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{u=1}^{U}\Big\{\Big(\Big(\Big[\xi_{V^a_{L_h}},\xi_{V^a_{R_h}}\Big]+\Big[\xi_{C_{L^a_{hdcu}}},\xi_{C_{R^a_{hdcu}}}\Big]\Big)x^a_{hdcu}+\Big[\xi_{F^a_{L_{hdcu}}},\xi_{F^a_{R_{hdcu}}}\Big]\theta^1\big(x^a_{hdcu}\big)\Big\} \\
\quad =\Big[\xi_{Bg_{L_{dc}}},\xi_{Bg_{R_{dc}}}\Big] \qquad \forall dc & (1.9)\\
\sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{DC}\sum\limits_{u=1}^{U}\Big\{\Big(\Big(\Big[\xi_{V^a_{L_{dc}}},\xi_{V^a_{R_{dc}}}\Big]+\Big[\xi_{C_{L^a_{dcrtu}}},\xi_{C_{R^a_{dcrtu}}}\Big]\Big)y^a_{dcrtu}+\Big[\xi_{F^a_{L_{dcrtu}}},\xi_{F^a_{R_{dcrtu}}}\Big]\theta^2\big(y^a_{dcrtu}\big)\Big\} \\
\quad =\Big[\xi_{Bg_{L_{rt}}},\xi_{Bg_{R_{rt}}}\Big] \qquad \forall rt & (1.10)\\
\sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{RT}\sum\limits_{u=1}^{U}\Big\{\Big(\Big(\Big[\xi_{V^a_{L_{rt}}},\xi_{V^a_{R_{rt}}}\Big]+\Big[\xi_{C_{L^a_{rtbu}}},\xi_{C_{R^a_{rtbu}}}\Big]\Big)z^a_{rtbu}+\Big[\xi_{F^a_{L_{rtbu}}},\xi_{F^a_{R_{rtbu}}}\Big]\theta^3\big(z^a_{rtbu}\big)\Big\} \\
\quad =\Big[\xi_{Bg_{L_b}},\xi_{Bg_{R_b}}\Big] \qquad \forall b & (1.11)\\
\sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{DC}\sum\limits_{u=1}^{U}x^a_{hdcu}=\Big[\xi_{Ms_{L^a_{hdcu}}},\xi_{Ms_{R^a_{hdcu}}}\Big] \qquad \forall a, h, dc, u & (1.12)\\
\sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{DC}\sum\limits_{rt=1}^{RT}\sum\limits_{u=1}^{U}y^a_{dcrtu}=\Big[\xi_{Ms_{L^a_{dcrtu}}},\xi_{Ms_{R^a_{dcrtu}}}\Big] \qquad \forall a, dc, rt, u & (1.13)\\
\sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{RT}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}z^a_{rtbu}=\Big[\xi_{Ms_{L^a_{rtbu}}},\xi_{Ms_{R^a_{rtbu}}}\Big] \qquad \forall a, rt, b, u & (1.14)\\
\sum\limits_{h=1}^{H}\sum\limits_{u=1}^{U}x^a_{hdcu}=\sum\limits_{rt=1}^{RT}\sum\limits_{u=1}^{U}y^a_{dcrtu} \qquad \forall dc & (1.15)\\
\sum\limits_{dc=1}^{DC}\sum\limits_{u=1}^{U}y^a_{dcrtu}=\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}z^a_{rtbu} \qquad \forall rt & (1.16)\\
\theta^1\big(x^a_{hdcu}\big)=\begin{cases}1 \text{ if } x^a_{hdcu}>0\\ 0 \text{ otherwise}\end{cases} \qquad \forall a, h, dc, u & (1.17)\\
\theta^2\big(y^a_{dcrtu}\big)=\begin{cases}1 \text{ if } y^a_{dcrtu}>0\\ 0 \text{ otherwise}\end{cases} \qquad \forall a, dc, rt, u & (1.18)\\
\theta^3\big(z^a_{rtbu}\big)=\begin{cases}1 \text{ if } z^a_{rtbu}>0\\ 0 \text{ otherwise}\end{cases} \qquad \forall a, rt, b, u & (1.19)\\
x^a_{hdcu}\geq 0,\quad y^a_{dcrtu}\geq 0,\quad z^a_{rtbu}\geq 0 \qquad \forall h, dc, u, rt. & (1.20)
\end{cases}
$$

A feasible solution within the framework of model (P_1) is considered under the following conditions:

$$\sum_{h=1}^{H} \xi_{a^a_{L_h}} \geq \sum_{b=1}^{B} \xi_{b^a_{L_b}} \qquad \forall a,$$
$$\sum_{h=1}^{H} \xi_{a^a_{R_h}} \geq \sum_{b=1}^{B} \xi_{b^a_{R_b}} \qquad \forall a,$$
$$\sum_{u=1}^{U} \xi_{e^1_{L_u}} = \sum_{u=1}^{U} \xi_{e^2_{L_u}} = \sum_{u=1}^{U} \xi_{e^3_{L_u}} \geq \sum_{b=1}^{B} \xi_{b^a_{L_b}} \qquad \forall a,$$
$$\sum_{u=1}^{U} \xi_{e^1_{R_u}} = \sum_{u=1}^{U} \xi_{e^2_{R_u}} = \sum_{u=1}^{U} \xi_{e^3_{R_u}} \geq \sum_{b=1}^{B} \xi_{b^a_{R_b}} \qquad \forall a.$$

In our model, we address three objectives characterized by uncertain intervals, with each parameter falling within an interval defined by upper and lower limits. Our primary objective is to optimize the total profit, while the secondary objective focuses on minimizing carbon emissions, the third objective is geared towards minimizing the overall transportation time necessary for delivering items from factories to customers. All parameters within the constraints are confined by uncertain upper and lower limits.

Constraint (1.4) signifies the quantity of products "a" that needs to be transported from factory "h", bounded by lower and upper limits. Constraint (1.5) concerns the overall demand for products "a" from customers, constrained by both a lower and an upper limit. Constraints (1.6)–(1.8) address the transportation capacity considerations at the initial stage, second stage, and final stage of various transportation modes within the SCN system. Constraints (1.9)–(1.11) emphasize the importance of aligning the total cost and purchase price of items with the budget allocated to each recipient. Constraints (1.12)–(1.14) ensure the safety facture at each stage. Constraints (1.15) and (1.16) are associated with the flow of conversation within the system. Constraints (1.17)–(1.19) ensure the imposition of fixed charge when transporting products through stage 1, stage 2, and stage 3, respectively. Constraint (1.20) guarantees the non-negativity of the decision variables.

5. Formulation of the uncertain programming model

In this section, we introduce the uncertain programming model for the proposed framework, applying the principles delineated by Alefeld and Herzberger [2] and Moore [34]. These principles are employed to describe the equivalents of the upper bounds Z_R^1, Z_R^2, Z_R^3, the lower bounds Z_L^1, Z_L^2, Z_L^3, and the central values Z_C^1, Z_C^2, Z_C^3 of the objective functions in the original problem P_1.

$$
\left\{
\begin{aligned}
Z_L^1 &= \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left(\xi_{S^a_{L_{dc}}} - \xi_{V_{R^a_h}} - \xi_{C^a_{R_{hdcu}}}\right)x^a_{hdcu} - \xi_{F^a_{R_{hdcu}}}\,\theta^1\left(x^a_{hdcu}\right)\\
&\quad + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left(\xi_{S_{L^a_{rt}}} - \xi_{V^a_{R_{dc}}} - \xi_{C^a_{R_{dcrtu}}}\right)y^a_{dcrtu} - \xi_{F^a_{R_{dcrtu}}}\,\theta^2\left(y^a_{dcrtu}\right)\\
&\quad + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\left(\xi_{S_{L^a_b}} - \xi_{V^a_{R_{rt}}} - \xi_{C^a_{R_{rtbu}}}\right)z^a_{rtbu} - \xi_{F^a_{R_{rtbu}}}\,\theta^3\left(z^a_{rtbu}\right)\\
Z_R^1 &= \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left(\xi_{S^a_{R_{dc}}} - \xi_{V^a_{L_h}} - \xi_{C^a_{L_{hdcu}}}\right)x^a_{hdcu} - \xi_{F^a_{L_{hdcu}}}\,\theta^1\left(x^a_{hdcu}\right)\\
&\quad + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left(\xi_{S_{R^a_{rt}}} - \xi_{V^a_{L_{dc}}} - \xi_{C^a_{L_{dcrtu}}}\right)y^a_{dcrtu} - \xi_{F^a_{L_{dcrtu}}}\,\theta^2\left(y^a_{dcrtu}\right)\\
&\quad + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\left(\xi_{S_{R^a_b}} - \xi_{V^a_{L_{rt}}} - \xi_{C^a_{L_{rtbu}}}\right)z^a_{rtbu} - \xi_{F^a_{L_{rtbu}}}\,\theta^3\left(z^a_{rtbu}\right)\\
Z_C^1 &= \frac{Z_L^1 + Z_R^1}{2}\\
Z_L^2 &= \alpha\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{\eta^a_{L_{hdcu}}}\,x^a_{hdcu} + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{\eta^a_{L_{dcrtu}}}\,y^a_{dcrtu} + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{\eta^a_{L_{rtbu}}}\,z^a_{rtbu}\right\}\\
Z_R^2 &= \alpha\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{\eta^a_{R_{hdcu}}}\,x^a_{hdcu} + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{\eta^a_{R_{dcrtu}}}\,y^a_{dcrtu} + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{\eta^a_{R_{rtbu}}}\,z^a_{rtbu}\right\}\\
Z_C^2 &= \alpha\left\{\frac{Z_L^2 + Z_R^2}{2}\right\}\\
Z_R^3 &= \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{T^a_{R_{hdcu}}}\,\theta^1\left(x^a_{hdcu}\right) + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{T^a_{R_{dcrtu}}}\,\theta^2\left(y^a_{dcrtu}\right) + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{T^a_{R_{rtbu}}}\,\theta^3\left(z^a_{rtbu}\right)\\
Z_C^3 &= \frac{Z_L^3 + Z_R^3}{2}\\
Z_L^3 &= \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{T^a_{L_{hdcu}}}\,\theta^1\left(x^a_{hdcu}\right) + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{T^a_{L_{dcrtu}}}\,\theta^2\left(y^a_{dcrtu}\right) + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{T^a_{L_{rtbu}}}\,\theta^3\left(z^a_{rtbu}\right).
\end{aligned}
\right.
$$

Using Hu and Wang's method [22], we derive the equivalent constraint representation:

$$
\begin{cases}
\xi_{a^a_{L_h}} \le \sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} x^a_{hdcu} \le \xi_{a^a_{R_h}} & \forall h, a \\
\xi_{b^a_{L_b}} \le \sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} z^a_{rtbu} \le \xi_{b^a_{R_b}} & \forall b, a \\
\xi_{e^1_{L_u}} \le \sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu} \le \xi_{e^1_{R_u}} & \forall u \\
\xi_{e^2_{L_u}} \le \sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu} \le \xi_{e^2_{R_u}} & \forall u \\
\xi_{e^3_{L_u}} \le \sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{b=1}^{B} z^a_{rtbu} \le \xi_{e^3_{R_u}} & \forall u \\
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{u=1}^{U} \left\{ \frac{\xi_{V^a_{L_h}} + \xi_{V^a_{R_h}} + \xi_{C_{L^a_{hdcu}}} + \xi_{C_{R^a_{hdcu}}}}{2} \right\} x^a_{hdcu} + \left\{ \frac{\xi_{F^a_{L_{hdcu}}} + \xi_{F^a_{R_{hdcu}}}}{2} \right\} \theta^1\left(x^a_{hdcu}\right) & \\
\quad \le \frac{\xi_{Bg_{L_{dc}}} + \xi_{Bg_{R_{dc}}}}{2} & \forall dc \\
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{k=1}^{K} \left\{ \frac{\xi_{V^a_{L_{dc}}} + \xi_{V^a_{R_{dc}}} + \xi_{C_{L^a_{dcrtu}}} + \xi_{C_{R^a_{dcrtu}}}}{2} \right\} y^a_{dcrtu} + \left\{ \frac{\xi_{F^a_{L_{dcrtu}}} + \xi_{F^a_{R_{dcrtu}}}}{2} \right\} \theta^2\left(y^a_{dcrtu}\right) & \\
\quad \le \frac{\xi_{Bg_{L_{rt}}} + \xi_{Bg_{R_{rt}}}}{2} & \forall rt \\
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} \left\{ \frac{\xi^a_{V_{L_{rt}}} + \xi_{V^a_{R_{rt}}} + \xi_{C_{L^a_{rtbu}}} + \xi_{C_{R^a_{rtbu}}}}{2} \right\} z^a_{rtbu} + \left\{ \frac{\xi_{F^a_{L_{rtbu}}} + \xi_{F^a_{R_{rtbu}}}}{2} \right\} \theta^3\left(z^a_{rtbu}\right) & \\
\quad \le \frac{\xi_{Bg_{L_b}} + \xi_{Bg_{R_b}}}{2} & \forall b \\
\xi_{Ms_{L^a_{hdcu}}} \le \sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} x^a_{hdcu} \le \xi_{Ms_{R^a_{hdcu}}} & \forall a, h, dc, u \\
\xi_{Ms_{L^a_{dcrtu}}} \le \sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} y^a_{dcrtu} \le \xi_{Ms_{R^a_{dcrtu}}} & \forall a, dc, rt, u \\
\xi_{Ms_{L^a_{rtbu}}} \le \sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{b=1}^{B} e \sum_{u=1}^{U} z^a_{rtbu} \le \xi_{Ms_{R^a_{rtbu}}} & \forall a, rt, b, u \\
\qquad (1.15)-(1.20). &
\end{cases}
$$

The uncertain programming model may be given as follows:

$$(P_2)\begin{cases}
\max Z_R^1 = \sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{u=1}^{U}\Big\{\Big(\xi_{S^a_{R_{dc}}} - \xi_{V^a_{L_h}} - \xi_{C^a_{L_{hdcu}}}\Big)x^a_{hdcu} - \xi_{F^a_{L_{hdcu}}}\,\theta^1\big(x^a_{hdcu}\big)\Big\} \\
\quad + \sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{u=1}^{U}\Big\{\Big(\xi_{S^a_{R_{rt}}} - \xi_{V^a_{L_{dc}}} - \xi_{C^a_{L_{dcrtu}}}\Big)y^a_{dcrtu} - \xi_{F^a_{L_{dcrtu}}}\,\theta^2\big(y^a_{dcrtu}\big)\Big\} \qquad (2.1)\\
\quad + \sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\Big\{\Big(\xi_{S^a_{R_b}} - \xi_{V^a_{L_{rt}}} - \xi_{C^a_{L_{rtbu}}}\Big)z^a_{rtbu} - \xi_{F^a_{L_{rtbu}}}\,\theta^3\big(z^a_{rtbu}\big)\Big\} \\
\max Z_C^1 = \sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{u=1}^{U}\Big\{\Big(\xi_{S^a_{C_{dc}}} - \xi_{V^a_{C_h}} - \xi_{C^a_{C_{hdcu}}}\Big)x^a_{hdcu} - \xi_{F^a_{C_{hdcu}}}\,\theta^1\big(x^a_{hdcu}\big)\Big\} \\
\quad + \sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{u=1}^{U}\Big\{\Big(\xi_{S^a_{C_{rt}}} - \xi_{V^a_{C_{dc}}} - \xi_{C^a_{C_{dcrtu}}}\Big)y^a_{dcrtu} - \xi_{F^a_{C_{dcrtu}}}\,\theta^2\big(y^a_{dcrtu}\big)\Big\} \qquad (2.2)\\
\quad + \sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\Big\{\Big(\xi_{S^a_{C_b}} - \xi_{V^a_{C_{rt}}} - \xi_{C^a_{C_{rtbu}}}\Big)z^a_{rtbu} - \xi_{F^a_{C_{rtbu}}}\,\theta^3\big(z^a_{rtbu}\big)\Big\} \\
\min Z_R^2 = \alpha\Big\{\sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{u=1}^{U}\xi_{\eta^a_{R_{hdcu}}}\,x^a_{hdcu} + \sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{u=1}^{U}\xi_{\eta^a_{R_{dcrtu}}}\,y^a_{dcrtu} \\
\quad + \sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\xi_{\eta^a_{R_{rtbu}}}\,z^a_{rtbu}\Big\} \qquad (2.3)\\
\min Z_C^2 = \alpha\Big\{\sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{u=1}^{U}\xi_{\eta^a_{C_{hdcu}}}\,x^a_{hdcu} + \sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{u=1}^{U}\xi_{\eta^a_{C_{dcrtu}}}\,y^a_{dcrtu} \\
\quad + \sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\xi_{\eta^a_{C_{rtbu}}}\,z^a_{rtbu}\Big\} \qquad (2.4)\\
\min Z_R^3 = \sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{u=1}^{U}\xi_{T^a_{R_{hdcu}}}\,\theta^1\big(x^a_{hdcu}\big) + \sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{u=1}^{U}\xi_{T^a_{R_{dcrtu}}}\,\theta^2\big(y^a_{dcrtu}\big) \\
\quad + \sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\xi_{T^a_{R_{rtbu}}}\,\theta^3\big(Z^a_{rtbu}\big) \qquad (2.5)\\
\min Z_C^3 = \sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{u=1}^{U}\xi_{T^a_{C_{hdcu}}}\,\theta^1\big(x^a_{hdcu}\big) + \sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{u=1}^{U}\xi_{T^a_{C_{dcrtu}}}\,\theta^2\big(y^a_{dcrtu}\big) \\
\quad + \sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{b=1}^{B}\sum\limits_{u=1}^{U}\xi_{T^a_{C_{rtbu}}}\,\theta^3\big(Z^a_{rtbu}\big) \qquad (2.6)\\
\hdashline
\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{u=1}^{U}x^a_{hdcu} - \xi_{a^a_{L_h}} \ge 0 \qquad \forall h, a \qquad (2.7)\\
\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{u=1}^{U}x^a_{hdcu} - \xi_{a^a_{R_h}} \le 0 \qquad \forall h, a \qquad (2.8)\\
\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{u=1}^{U}z^a_{rtbu} - \xi_{b^a_{L_b}} \ge 0 \qquad \forall b, a \qquad (2.9)\\
\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{u=1}^{U}z^a_{rtbu} - \xi_{b^a_{R_b}} \le 0 \qquad \forall b, a \qquad (2.10)\\
\sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{\mathrm{DC}}x^a_{hdcu} - \xi_{e_{L^1_u}} \ge 0 \qquad \forall u \qquad (2.11)\\
\sum\limits_{a=1}^{A}\sum\limits_{h=1}^{H}\sum\limits_{dc=1}^{\mathrm{DC}}x^a_{hdcu} - \xi_{e^1_{R_u}} \le 0 \qquad \forall u \qquad (2.12)\\
\sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{rt=1}^{\mathrm{RT}}y^a_{dcrtu} - \xi_{e^2_{L_u}} \ge 0 \qquad \forall u \qquad (2.13)\\
\sum\limits_{a=1}^{A}\sum\limits_{dc=1}^{\mathrm{DC}}\sum\limits_{rt=1}^{\mathrm{RT}}y^a_{dcrtu} - \xi_{e^2_{R_u}} \le 0 \qquad \forall u \qquad (2.14)\\
\sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{b=1}^{B}z^a_{rtbu} - \xi_{e^3_{L_u}} \ge 0 \qquad \forall u \qquad (2.15)\\
\sum\limits_{a=1}^{A}\sum\limits_{rt=1}^{\mathrm{RT}}\sum\limits_{b=1}^{B}z^a_{rtbu} - \xi_{e^3_{R_u}} \le 0 \qquad \forall u \qquad (2.16)
\end{cases}$$

$$
(P_2)\begin{cases}
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^{a}_{hdcu} - \xi_{Ms_{L^{a}_{hdcu}}} \geq 0 & \forall a,h,dc,b \quad (2.17)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^{a}_{hdcu} - \xi_{Ms_{R^{a}_{hdcu}}} \leq 0 & \forall a,h,dc,u \quad (2.18)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y^{a}_{dcrtu} - \xi_{Ms_{L^{a}_{dcrtu}}} \geq 0 & \forall a,dc,rt,u \quad (2.19)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y^{a}_{dcrtu} - \xi_{Ms_{R^{a}_{dcrtu}}} \leq 0 & \forall a,dc,rt,u \quad (2.20)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z^{a}_{rtbu} - \xi_{Ms_{L^{a}_{rtbu}}} \geq 0 & \forall a,rt,b,u \quad (2.21)\\
\sum_{a=1}^{A} e \sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z^{a}_{rtbu} - \xi_{Ms_{R^{a}_{rtbu}}} \leq 0 & \forall a,rt,b,u \quad (2.22)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\left\{\left(\frac{\xi_{V^{a}_{L_h}}+\xi_{V^{a}_{R_h}}+\xi_{C_{L^{a}_{hdcu}}}+\xi_{C_{R^{a}_{hdcu}}}}{2}\right)x^{a}_{hdcu}+\left(\frac{\xi_{F^{a}_{L_{hdcu}}}+\xi_{F^{a}_{R_{hdcu}}}}{2}\right)\theta^{1}\left(x^{a}_{hdcu}\right)\right\} & \\
\qquad -\frac{\xi_{Bg_{L_{dc}}}+\xi_{Bg_{R_{dc}}}}{2}\Bigg\} \leq 0 & \forall dc \quad (2.23)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left\{\left(\frac{\xi_{V^{a}_{L_{dc}}}+\xi_{V^{a}_{R_{dc}}}+\xi_{C_{L^{a}_{dcrtu}}}+\xi_{C_{R^{a}_{dcrtu}}}}{2}\right)y^{a}_{dcrtu}+\left(\frac{\xi_{F^{a}_{L_{dcrtu}}}+\xi_{F^{a}_{R_{dcrtu}}}}{2}\right)\theta^{2}\left(y^{a}_{dcrtu}\right)\right\} & \\
\qquad -\frac{\xi_{Bg_{L_{rt}}}+\xi_{Bg_{R_{rt}}}}{2}\Bigg\} \leq 0 & \forall rt \quad (2.24)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left\{\left(\frac{\xi_{V^{a}_{L_{rt}}}+\xi_{V^{a}_{R_{rt}}}+\xi_{C_{L^{a}_{rtbu}}}+\xi_{C_{R^{a}_{rtbu}}}}{2} z^{a}_{rtbu}\right)+\left(\frac{\xi_{F^{a}_{L_{rtbu}}}+\xi_{F^{a}_{R_{rtbu}}}}{2}\right)\theta^{3}\left(z^{a}_{rtbu}\right)\right. & \\
\qquad -\frac{\xi_{B_{L_b}}+\xi_{B_{R_b}}}{2}\Bigg\} \leq 0 & \forall b \quad (2.25)\\
(1.15)-(1.20).
\end{cases}
$$

The Expected Value Model (EVM) and the Chance-Constrained Model (CCM) are important frameworks for addressing uncertainty in classification tasks. These models offer distinct methodologies tailored to handle a wide range of preferences and constraints when dealing with uncertainty.

5.1. The Expected Values Model

Liu [25] introduced the expected value model of uncertain programming, optimizing specific objective expected functions subject to expected constraints. In this context, we express our problem formulation within the framework of the EVM.

$$
(P_3)\left\{
\begin{aligned}
\max E\left[Z_R^1\right] &= E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left(\xi_{S^a_{R_{dc}}}-\xi_{V^a_{L_h}}-\xi_{C^a_{L_{hdcu}}}\right)x^a_{hdcu}-\xi_{F^a_{L_{hdcu}}}\,\theta^1\left(x^a_{hdcu}\right)\right]\\
&\quad+E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left(\xi_{S_{R^a_{rt}}}-\xi_{V^a_{L_{dc}}}-\xi_{C_{L^a_{dcrtu}}}\right)y^a_{dcrtu}-\xi_{F_{L^a_{dcrtu}}}\,\theta^2\left(y^a_{dcrtu}\right)\right] && (3.1)\\
&\quad+E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\left(\xi_{S_{R^a_b}}-\xi_{V_{L^a_{rt}}}-\xi_{C^a_{L_{rtbu}}}\right)z^a_{rtbu}-\xi_{F^a_{L_{rtbu}}}\,\theta^3\left(z^a_{rtbu}\right)\right]\\
\max E\left[Z_C^1\right] &= E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left(\xi_{S^a_{C_{dc}}}-\xi_{V^a_{C_h}}-\xi_{C_{C^a_{L_{hdcu}}}}\right)x^a_{hdcu}-\xi_{F_{C^a_{L_{hdcu}}}}\,\theta^1\left(x^a_{hdcu}\right)\right]\\
&\quad+E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left(\xi_{S_{C^a_{rt}}}-\xi_{V^a_{C_{dc}}}-\xi_{C_{C^a_{dcrtu}}}\right)y^a_{dcrtu}-\xi_{F_{C^a_{dcrtu}}}\,\theta^2\left(y^a_{dcrtu}\right)\right] && (3.2)\\
&\quad+E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\left(\xi_{S_{C^a_b}}-\xi_{V_{C^a_{rt}}}-\xi_{C^a_{C_{rtbu}}}\right)z^a_{rtbu}-\xi_{F^a_{C_{rtbu}}}\,\theta^3\left(z^a_{rtbu}\right)\right]\\
\min E\left[Z_R^2\right] &= E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{\eta^a_{R_{hdcu}}}\,x^a_{hdcu}\right]+E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{\eta^a_{R_{dcrtu}}}\,y^a_{dcrtu}\right]\\
&\quad+E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{\eta^a_{R_{rtbu}}}\,z^a_{rtbu}\right] && (3.3)\\
\min E\left[Z_C^2\right] &= E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{\eta^a_{C_{hdcu}}}\,x^a_{hdcu}\right]+E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{\eta^a_{C_{dcrtu}}}\,y^a_{dcrtu}\right]\\
&\quad+E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{\eta^a_{C_{rtbu}}}\,z^a_{rtbu}\right] && (3.4)\\
\min E\left[Z_R^3\right] &= E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{T^a_{R_{hdcu}}}\,\theta^1\left(x^a_{hdcu}\right)\right]+E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{T^a_{R_{dcrtu}}}\,\theta^2\left(y^a_{dcrtu}\right)\right]\\
&\quad+E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{T^a_{R_{rtbu}}}\,\theta^3\left(z^a_{rtbu}\right)\right] && (3.5)\\
\min E\left[Z_C^3\right] &= E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{T^a_{C_{hdcu}}}\,\theta^1\left(x^a_{hdcu}\right)\right]+E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{T^a_{C_{dcrtu}}}\,\theta^2\left(y^a_{dcrtu}\right)\right]\\
&\quad+E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{T^a_{C_{rtbu}}}\,\theta^3\left(z^a_{rtbu}\right)\right] && (3.6)
\end{aligned}
\right.
$$

Subject to

$$E\left[\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} - \xi_{a_{L_h}^{a}}\right] \geq 0 \qquad h,\, a \tag{3.7}$$

$$E\left[\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} - \xi_{a_{R_h}^{a}}\right] \leq 0 \qquad \forall h,\, a \tag{3.8}$$

$$E\left[\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z_{rtbu}^{a} - \xi_{b_{L_b}^{a}}\right] \geq 0 \qquad \forall b,\, a \tag{3.9}$$

$$E\left[\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z_{rtbu}^{a} - \xi_{b_{R_b}^{a}}\right] \leq 0 \qquad \forall b,\, a \tag{3.10}$$

$$E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x_{hdcu}^{a} - \xi_{e_{L_u}^{1}}\right] \geq 0 \qquad \forall u \tag{3.11}$$

$$E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x_{hdcu}^{a} - \xi_{e_{R_u}^{1}}\right] \leq 0 \qquad \forall u \tag{3.12}$$

$$E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y_{dcrtu}^{a} - \xi_{e_{L_u}^{2}}\right] \geq 0 \qquad \forall u \tag{3.13}$$

$$E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y_{dcrtu}^{a} - \xi_{e_{R_u}^{2}}\right] \leq 0 \qquad \forall u \tag{3.14}$$

$$E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z_{rtbu}^{a} - \xi_{e_{L_u}^{3}}\right] \geq 0 \qquad \forall u \tag{3.15}$$

$$E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z_{rtbu}^{a} - \xi_{e_{R_u}^{3}}\right] \leq 0 \qquad \forall u \tag{3.16}$$

$$E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\left\{\left(\frac{\xi_{V_{L_h}^{a}} + \xi_{V_{R_h}^{a}} + \xi_{C_{L_{hdcu}}^{a}} + \xi_{C_{R_{hdcu}}^{a}}}{2}\right)x_{hdcu}^{a} + \left(\frac{\xi_{F_{L_{hdcu}}^{a}} + \xi_{F_{R_{hdcu}}^{a}}}{2}\right)\theta^{1}(x_{hdcu}^{a})\right\} - \frac{\xi_{Bg_{L_{dc}}} + \xi_{Bg_{R_{dc}}}}{2}\right] \leq 0 \qquad \forall dc \tag{3.17}$$

$$E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left\{\left(\frac{\xi_{V_{L_{dc}}^{a}} + \xi_{V_{R_{dc}}^{a}} + \xi_{C_{L_{dcrtu}}^{a}} + \xi_{C_{R_{dcrtu}}^{a}}}{2}\right)y_{dcrtu}^{a} + \left(\frac{\xi_{F_{L_{dcrtu}}^{a}} + \xi_{F_{R_{dcrtu}}^{a}}}{2}\right)\theta^{2}\left(y_{dcrtu}^{a}\right)\right\} - \frac{\xi_{Bg_{L_{rt}}} + \xi_{Bg_{R_{rt}}}}{2}\right] \leq 0 \qquad \forall rt \tag{3.18}$$

$$E\left[\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\left\{\left(\frac{\xi_{V_{L_{rt}}^{a}} + \xi_{V_{R_{rt}}^{a}} + \xi_{C_{L_{rtbu}}^{a}} + \xi_{C_{R_{rtbu}}^{a}}}{2}\right)z_{rtbu}^{a} + \left(\frac{\xi_{F_{L_{rtbu}}^{a}} + \xi_{F_{R_{rtbu}}^{a}}}{2}\right)\theta^{3}\left(z_{rtbu}^{a}\right)\right\} - \frac{\xi_{Bg_{L_b}} + \xi_{Bg_{R_b}}}{2}\right] \leq 0 \qquad \forall b \tag{3.19}$$

$$E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} - \xi_{Ms_{L_{hdcu}}^{a}}\right] \geq 0 \qquad \forall a, h, dc, u \tag{3.20}$$

$$E\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} - \xi_{Ms_{R_{hdcu}}^{a}}\right] \leq 0 \qquad \forall a, h, dc, u \tag{3.21}$$

$$E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y_{dcrtu}^{a} - \xi_{Ms_{L_{dcrtu}}^{a}}\right] \geq 0 \qquad \forall a, dc, rt, u \tag{3.22}$$

$$E\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y_{dcrtu}^{a} - \xi_{Ms_{R_{dcrtu}}^{a}}\right] \leq 0 \qquad \forall a, dc, rt, u \tag{3.23}$$

$$E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z_{rtbu}^{a} - \xi_{Ms_{L_{rtbu}}^{a}}\right] \geq 0 \qquad \forall a, rt, b, u \tag{3.24}$$

$$E\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z_{rtbu}^{a} - \xi_{Ms_{L_{rtbu}}^{a}}\right] \leq 0 \qquad \forall a, rt, b, u \tag{3.25}$$

(1.15)−(1.20).

5.2. Chance Constrained Model

The chance constrained model, initially introduced by Charnes and Cooper [6] and subsequently expanded by Liu [25] for uncertain programming, offers a robust approach to model uncertain decision systems. This model posits that uncertain constraints will be satisfied with a confidence level denoted as α, providing a safety margin determined by the decision maker.

We formulate the chance constrained model for our specific problem as follows:

(P_4)

$$\max \overline{Z}^{1U}, \quad \min \overline{Z}^{2L}, \quad \min \overline{Z}^{3L} \tag{4.1}$$

$$M\left\{\left[\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left(\left[\xi_{S^a_{dc}} - \xi_{V^a_h} - \xi_{C^a_{hdcu}}\right]x^a_{hdcu} - \xi_{F^a_{hdcu}}\theta^1\left(x^a_{hdcu}\right)\right)\right] \ge \overline{Z}^{1U}\right\} \ge \alpha^1 \tag{4.2}$$

$$M\left\{\left[\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left(\left[\xi_{S^a_{rt}} - \xi_{V^a_{dc}} - \xi_{C^a_{dcrtu}}\right]y^a_{dcrtu} - \xi_{F^a_{dcrtu}}\theta^2\left(y^a_{dcrtu}\right)\right)\right] \ge \overline{Z}^{1U}\right\} \ge \alpha^1 \tag{4.3}$$

$$M\left\{\left[\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\left(\left[\xi_{S^a_{b}} - \xi_{V^a_{rt}} - \xi_{C^a_{rtbu}}\right]z^a_{rtbu} - \xi_{F^a_{rtbu}}\theta^3\left(z^a_{rtbu}\right)\right)\right] \ge \overline{Z}^{1U}\right\} \ge \alpha^1 \tag{4.4}$$

$$\begin{aligned} M\Bigg\{\Bigg[&\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{\eta^a_{hdcu}}x^a_{hdcu} + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{\eta^a_{dcrtu}}y^a_{dcrtu} \\ &+ \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{\eta^a_{rtbu}}z^a_{rtbu}\Bigg] \le \overline{Z}^{2L}\Bigg\} \ge \alpha^2 \end{aligned} \tag{4.5}$$

$$\begin{aligned} M\Bigg\{\Bigg(&\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\xi_{T^a_{R_{hdcu}}}\theta^1\left(x^a_{hdcu}\right) + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\xi_{T^a_{R_{dcrtu}}}\theta^2\left(y^a_{dcrtu}\right) \\ &+ \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\xi_{T^a_{R_{rtbu}}}\theta^3\left(z^a_{rtbu}\right)\Bigg] \le \overline{Z}^{3L}\Bigg\} \ge \alpha^3 \end{aligned} \tag{4.6}$$

$$M\left\{\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}x^a_{hdcu} - \xi_{a^a_{L_h}} \ge 0\right\} \ge \beta_{a^a_{L_h}} \qquad \forall h, a \tag{4.7}$$

$$M\left\{\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}x^a_{hdcu} - \xi_{a^a_{R_h}} \le 0\right\} \ge \beta_{a^a_{R_h}} \qquad \forall h, a \tag{4.8}$$

$$M\left\{\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}z^a_{rtbu} - \xi_{b^a_{L_b}} \ge 0\right\} \ge \beta_{b^a_{L_b}} \qquad \forall b, a \tag{4.9}$$

$$M\left\{\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}z^a_{rtbu} - \xi_{b^a_{R_b}} \le 0\right\} \ge \beta_{b^a_{R_b}} \qquad \forall b, a \tag{4.10}$$

$$M\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}x^a_{hdcu} - \xi_{e^1_{L_u}} \ge 0\right\} \ge \beta_{e^1_{L_u}} \qquad \forall u \tag{4.11}$$

$$M\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}x^a_{hdcu} - \xi_{e^1_{R_u}} \le 0\right\} \ge \beta_{e^1_{R_u}} \qquad \forall u \tag{4.12}$$

$$M\left\{\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}y^a_{dcrtu} - \xi_{e^2_{L_u}} \ge 0\right\} \ge \beta_{e^2_{L_u}} \qquad \forall u \tag{4.13}$$

$$M\left\{\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}y^a_{dcrtu} - \xi_{e^2_{R_u}} \le 0\right\} \ge \beta_{e^2_{R_u}} \qquad \forall u \tag{4.14}$$

$$M\left\{\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}z^a_{rtbu} - \xi_{e^3_{L_u}} \ge 0\right\} \ge \beta_{e^3_{L_u}} \qquad \forall u \tag{4.15}$$

$$M\left\{\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}z^a_{rtbu} - \xi_{e^3_{R_u}} \le 0\right\} \ge \beta_{e^3_{R_u}} \qquad \forall u \tag{4.16}$$

$$M\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\left[\left(\frac{\xi_{V^a_{L_h}}+\xi_{V^a_{R_h}}+\xi_{C_{L^a_{hdcu}}}+\xi_{C_{R^a_{hdcu}}}}{2}\right)x^a_{hdcu}+\left(\frac{\xi_{F^a_{L_{hdcu}}}+\xi_{F^a_{R_{hdcu}}}}{2}\right)\theta^1\left(x^a_{hdcu}\right)\right] - \frac{\xi_{Bg_{L_{dc}}}\xi_{B_{R_{dc}}}}{2}\leq 0\right\}\geq \beta_{Bg_{dc}} \quad \forall dc \tag{4.17}$$

$$M\left\{\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left[\left(\frac{\xi_{V^a_{L_{dc}}}+\xi_{V^a_{R_{dc}}}+\xi_{C_{L^a_{dcrtu}}}+\xi_{C_{R^a_{dcrtu}}}}{2}\right)y^a_{dcrtu}+\left(\frac{\xi_{F^a_{L_{dcrtu}}}+\xi_{F^a_{R_{dcrtu}}}}{2}\right)\theta^2\left(y^a_{dcrtu}\right)\right] - \frac{\xi_{Bg_{L_{rt}}}+\xi_{Bg_{R_{rt}}}}{2}\leq 0\right\}\geq \beta_{Bg_{rt}} \quad \forall rt \tag{4.18}$$

$$M\left\{\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left[\left(\frac{\xi^a_{V_{L_{rt}}}+\xi_{V^a_{R_{rt}}}+\xi_{C_{L^a_{rtbu}}}+\xi_{C_{R^a_{rtbu}}}}{2}\right)z^a_{rtbu}+\left(\frac{\xi_{F^a_{L_{rtbu}}}+\xi_{F_{R^a_{rtbu}}}}{2}\right)\theta^3\left(z^a_{rtbu}\right)\right] - \frac{\xi_{B_{L_b}}+\xi_{B_{R_b}}}{2}\leq 0\right\}\geq \beta_{Bg_b} \quad \forall b \tag{4.19}$$

$$M\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}x^a_{hdcu}-\xi_{Ms_{L^a_{hdcu}}}\geq 0\right\}\geq \beta_{Ms_{L^a_{hdcu}}} \quad \forall a,h,dc,u \tag{4.20}$$

$$M\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}x^a_{hdcu}-\xi_{Ms_{R^a_{hdcu}}}\leq 0\right\}\geq \beta_{Ms_{R^a_{hdcu}}} \quad \forall a,h,dc,u \tag{4.21}$$

$$M\left\{\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}y^a_{dcrtu}-\xi_{Ms_{L^a_{dcrtu}}}\geq 0\right\}\geq \beta_{Ms_{L^a_{dcrtu}}} \quad \forall a,dc,rt,u \tag{4.22}$$

$$M\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}y^a_{dcrtu}-\xi_{Ms_{R^a_{dcrtu}}}\leq 0\right\}\geq \beta_{Ms_{R^a_{dcrtu}}} \quad \forall a,dc,rt,u \tag{4.23}$$

$$M\left\{\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}z^a_{rtbu}-\xi_{Ms_{L^a_{rtbu}}}\geq 0\right\}\geq \beta_{Ms_{L^a_{rtbu}}} \quad \forall a,rt,b,u \tag{4.24}$$

$$M\left\{\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}z^a_{rtbu}-\xi_{Ms_{R^a_{rtbu}}}\leq 0\right\}\geq \beta_{Ms_{R^a_{rtbu}}} \quad \forall a,rt,b,u \tag{4.25}$$

(1.15)–(1.20).

In CCM,

$$\alpha_1,\ \alpha_2,\ \alpha_3,\ \beta_{a^a_{L_h}},\ \beta_{a^a_{R_h}},\ \beta_{b^a_{L_b}},\ \beta_{b^a_{R_b}},\ \beta_{e^1_{L_u}},\ \beta_{e^1_{R_u}},\ \beta_{e^2_{L_u}},\ \beta_{e^2_{R_u}},\ \beta_{e^3_{L_u}},\ \beta_{e^3_{R_u}},\ \beta_{Bg_{dc}},\ \beta_{Bg_{rt}},\ \beta_{Bg_b},\ \beta_{Ms_{L^a_{hdcu}}},$$
$$\beta_{Ms_{R^a_{hdcu}}},\ \beta_{Ms_{L^a_{dcrtu}}},\ \beta_{Ms_{R^a_{dcrtu}}},\ \beta_{Ms_{R^a_{rtbu}}},\ \beta_{Ms_{L^a_{rtbu}}}$$

respectively, are predetermined confidence levels. The objectives $\overline{Z^1}^U$, $\overline{Z^2}^L$, $\overline{Z^3}^L$ determine the critical values corresponding to the first, second, and third constraints, respectively. The first constraint establishes the α_1-optimistic value of the overall profit for the α_1-transportation plan, the second constraint determines the α_2-pessimistic value of atmospheric pollution in relation to the α_2-transportation plan, and the third constraint establishes the α_3-pessimistic value of shipping/transportation time for the α_3 transportation plan. The remaining constraints will also hold at their corresponding confidence levels:

$$\beta_{a^a_{L_h}},\ \beta_{a^a_{R_h}},\ \beta_{b^a_{L_b}},\ \beta_{b^a_{R_b}},\ \beta_{e^1_{L_u}},\ \beta_{e^1_{R_u}},\ \beta_{e^2_{L_u}},\ \beta_{e^2_{R_u}},\ \beta_{e^3_{L_u}},\ \beta_{e^3_{R_u}},\ \beta_{Bg_{dc}},\ \beta_{Bg_{rt}},\ \text{and}$$
$$\beta_{Bg_b}\beta_{Ms_{L^a_{hdcu}}},\ \beta_{Ms_{R^a_{hdcu}}},\ \beta_{Ms_{L^a_{dcrtu}}},\ \beta_{Ms_{R^a_{dcrtu}}},\ \beta_{Ms_{R^a_{rtbu}}},\ \beta_{Ms_{L^a_{rtbu}}}$$

respectively.

6. Deterministic equivalents of the model

We employ the theorem outlined by Majumder *et al.* [28] to deduce the equivalent of the proposed model, as follows:

Theorem 6.1 ([28]). *Let*

$$\xi_{S^a_{L_{dc}}},\ \xi_{S^a_{R_{dc}}},\ \xi_{V^a_{L_h}},\ \xi_{V^p_{R_h}},\ \xi_{C^a_{L_{hdcu}}},\ \xi_{C^a_{R_{hdcu}}},\ \xi_{F^a_{L_{hdcu}}},\ \xi_{F^a_{R_{hdcu}}},\ \xi_{S^a_{L_{rt}}},\ \xi_{S^a_{R_{rt}}},\ \xi_{V^a_{L_{dc}}},\ \xi_{V^a_{R_{dc}}},\ \xi_{C^a_{L_{dcrtu}}},\ \xi_{C^a_{R_{dcrtu}}},$$
$$\xi_{F^a_{L_{dcrtu}}},\ \xi_{F^a_{R_{dcrtu}}},\ \xi_{S^a_{L_b}},\ \xi_{S^a_{R_b}},\ \xi_{V^a_{L_{rt}}},\ \xi_{V^a_{R_{rt}}},\ \xi_{C^a_{L_{rtbu}}},\ \xi_{C^a_{R_{rtbu}}},\ \xi_{F^a_{L_{rtbu}}},\ \xi_{F^a_{R_{rtbu}}},\ \xi_{\eta^a_{L_{hdcu}}},\ \xi_{\eta^a_{R_{hdcu}}},\ \xi_{\eta^a_{L_{dcrtu}}},$$
$$\xi_{\eta^a_{R_{dcrtu}}},\ \xi_{\eta^a_{L_{rtbu}}},\ \xi_{\eta^a_{R_{rtbu}}},\ \xi_{T^a_{L_{hdcu}}},\ \xi_{T^a_{R_{hdcu}}},\ \xi_{T^a_{L_{dcrtu}}},\ \xi_{T^a_{R_{dcrtu}}},\ \xi_{T^a_{L_{rtbu}}},\ \xi_{T^a_{R_{rtbu}}},\ \xi_{a^a_{L_h}},\ \xi_{a^a_{R_h}},\ \xi_{b^a_{L_b}},\ \xi_{b^a_{R_b}},\ \xi_{e^1_{L_u}},$$
$$\xi_{e^1_{R_u}},\ \xi_{e^2_{L_u}},\ \xi_{e^2_{R_u}},\ \xi_{e^3_{L_u}},\ \xi_{e^3_{R_u}},\ \xi_{Bg_{L_{dc}}},\ \xi_{Bg_{R_{dc}}},\ \xi_{B_{L_{rt}}},\ \xi_{B_{R_{rt}}},\ \xi_{B_{L_b}},\ \xi_{B_{R_b}},\ \xi_{\beta_{Ms_{L^a_{hdcu}}}},\ \xi_{\beta_{Ms_{R^a_{hdcu}}}},\ \xi_{\beta_{Ms_{L^a_{dcrtu}}}},$$
$$\xi_{\beta_{Ms_{R^a_{dcrtu}}}},\ \xi_{\beta_{Ms_{R^a_{rtbu}}}},\ \xi_{\beta_{Ms_{L^a_{rtbu}}}}$$

be independent uncertain variables associated with the regular uncertainty distributions

$$\phi_{\xi_{S^a_{L_{dc}}}},\ \phi_{\xi_{S^a_{R_{dc}}}},\ \phi_{\xi_{V^a_{L_h}}},\ \phi_{\xi_{V^a_{R_h}}},\ \phi_{\xi_{C^a_{L_{hdcu}}}},\ \phi_{\xi_{C^a_{R_{hdcu}}}},\ \phi_{\xi_{F^a_{L_{hdcu}}}},\ \phi_{\xi_{F^a_{R_{hdcu}}}},\ \phi_{\xi_{S^a_{L_{rt}}}},\ \phi_{\xi_{S^a_{R_h}}},\ \phi_{\xi_{V^a_{L_{dc}}}},\ \phi_{\xi_{V^a_{R_{dc}}}},$$
$$\phi_{\xi_{C^a_{L_{dcrtu}}}},\ \phi_{\xi_{C^a_{R_{dcrtu}}}},\ \phi_{\xi_{F^a_{L_{dcrtu}}}},\ \phi_{\xi_{F^a_{R_{dcrtu}}}},\ \phi_{\xi_{S^a_{L_b}}},\ \phi_{\xi_{S^a_{R_b}}},\ \phi_{\xi_{V^a_{L_{rt}}}},\ \phi_{\xi_{V^a_{R_{rt}}}},\ \phi_{\xi_{C^a_{L_{rtbu}}}},\ \phi_{\xi_{C^a_{R_{rtbu}}}},\ \phi_{\xi_{F^a_{L_{rtbu}}}},$$
$$\phi_{\xi_{F^a_{R_{rtbu}}}},\ \phi_{\xi_{\eta^a_{L_{hdcu}}}},\ \phi_{\xi_{\eta^a_{R_{hdcu}}}},\ \phi_{\xi_{\eta^a_{L_{dcrtu}}}},\ \phi_{\xi_{\eta^a_{R_{dcrtu}}}},\ \phi_{\xi_{\eta^a_{L_{rtbu}}}},\ \phi_{\xi_{\eta^a_{R_{rtbu}}}},\ \phi_{\xi_{T^a_{L_{hdcu}}}},\ \phi_{\xi_{T^a_{R_{hdcu}}}},\ \phi_{\xi_{T^a_{L_{dcrtu}}}},\ \phi_{\xi_{T^a_{R_{dcrtu}}}},$$
$$\phi_{\xi_{T^a_{L_{rtbu}}}},\ \phi_{\xi_{T^a_{R_{rtbu}}}},\ \phi_{\xi_{a^a_{L_h}}},\ \phi_{\xi_{a^a_{R_h}}},\ \phi_{\xi_{b^a_{L_b}}},\ \phi_{\xi_{b^a_{R_b}}},\ \phi_{\xi_{e^1_{L_u}}},\ \phi_{\xi_{e^1_{R_u}}},\ \phi\xi_{e^2_{L_u}},\ \phi_{\xi_{e^2_{R_u}}},\ \phi_{\xi_{e^3_{L_u}}},\ \phi_{\xi_{e^3_{R_u}}},\ \phi_{\xi_{Bg_{L_{dc}}}},\ \phi_{\xi_{Bg_{R_{dc}}}},$$
$$\phi_{\xi_{B_{L_{rt}}}},\ \phi_{\xi_{B_{R_{rt}}}},\ \phi_{\xi_{B_{L_b}}},\ \phi_{\xi_{B_{R_b}}},\ \phi_{\beta_{Ms_{L^a_{hdcu}}}},\ \phi_{\beta_{Ms_{R^a_{hdcu}}}},\ \phi_{\beta_{Ms_{L^a_{dcrtu}}}},\ \phi_{\beta_{Ms_{R^a_{dcrtu}}}},\ \phi_{\beta_{Ms_{R^a_{rtbu}}}},\ \phi_{\beta_{Ms_{L^a_{rtbu}}}}$$

respectively.

Then the deterministic equivalents of the EVM and the CCM are presented by the models (P_5) and (P_6) presented below.

6.1. Expected Value Model

Model (P_3) is equivalent to the subsequent formulation.

$$
(P_5)\begin{cases}
\max E\left[Z_R^1\right] = \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left[\left(\int_0^1 \phi_{\xi_{S_{R_{dc}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{V_{L_h}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{C_{L_{hdcu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\right)x_{hdcu}^a \right. \\
\left. \quad - \int_0^1 \phi_{\xi_{F_{L_{hdcu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\theta^1\left(x_{hdcu}^a\right)\right] \\
\quad + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left[\left(\int_0^1 \phi_{\xi_{S_{R_{rt}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{V_{L_{dc}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{C_{L_{dcrtu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\right)y_{dcrtu}^a \right. \\
\left. \quad - \int_0^1 \phi_{\xi_{F_{L_{dcrtu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\theta^2\left(y_{dcrtu}^a\right)\right] \qquad (5.1) \\
\quad + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\left[\left(\int_0^1 \phi_{\xi_{S_{R_b}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{V_{L_{rt}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{C_{L_{rtbu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\right)z_{rtbu}^a \right. \\
\left. \quad - \int_0^1 \phi_{\xi_{F_{L_{rtbu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\theta^3\left(z_{rtbu}^a\right)\right] \\
\max E\left[Z_C^1\right] = \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left[\left(\int_0^1 \phi_{\xi_{S_{C_{dc}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{V_{C_h}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{C_{C_{hdcu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\right)x_{hdcu}^a \right. \\
\left. \quad - \int_0^1 \phi_{\xi_{F_{C_{hdcu}}}^a}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^1\left(x_{hdcu}^a\right)\right] \\
\quad + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left[\left(\int_0^1 \phi_{\xi_{S_{C_{rt}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{V_{C_{dc}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{C_{C_{dcrtu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\right)y_{dcrtu}^a \right. \\
\left. \quad - \int_0^1 \phi_{\xi_{F_{C_{dcrtu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^2\left(y_{dcrtu}^a\right)\right] \qquad (5.2) \\
\quad + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\left[\left(\int_0^1 \phi_{\xi_{S_{C_b}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{V_{C_{rt}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta - \int_0^1 \phi_{\xi_{C_{C_{rtbu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\right)z_{rtbu}^a \right. \\
\left. \quad - \int_0^1 \phi_{\xi_{F_{C_{rtbu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^3\left(z_{rtbu}^a\right)\right] \\
\min E\left[Z_R^2\right] = \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{\eta_{R_{hdcu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\, x_{hdcu}^a + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{\eta_{R_{dcrtu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\, y_{dcrtu}^a \\
\quad + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{\eta_{R_{rtbu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\, z_{rtbu}^a \qquad (5.3) \\
\min E\left[Z_C^2\right] = \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{\eta_{C_{hdcu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\, x_{hdcu}^a + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{\eta_{C_{dcrtu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\, y_{dcrtu}^a \\
\quad + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{\eta_{C_{rtbu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\, z_{rtbu}^a \qquad (5.4) \\
\min E\left[Z_R^3\right] = \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{T_{R_{hdcu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^1\left(x_{hdcu}^a\right) + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{T_{R_{dcrtu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^2\left(y_{dcrtu}^a\right) \\
\quad + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{T_{R_{rtbu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^3\left(Z_{rtbu}^a\right) \qquad (5.5) \\
\min E\left[Z_C^3\right] = \sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{T_{C_{hdcu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^1\left(x_{hdcu}^a\right) + \sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{T_{C_{dcrtu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^2\left(y_{dcrtu}^a\right) \\
\quad + \sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}\int_0^1 \phi_{\xi_{T_{C_{rtbu}}^a}}^{-1}(\Delta)\,\mathrm{d}\Delta\,\theta^3\left(Z_{rtbu}^a\right). \qquad (5.6)
\end{cases}
$$

Subject to:

(P_5)

$$\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^a_{hdcu} \geq \int_0^1 \phi^{-1}_{\xi_{a^a_{L_h}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall h,\, a \tag{5.7}$$

$$\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^a_{hdcu} \leq \int_0^1 \phi^{-1}_{\xi_{a^a_{R_h}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall h,\, a \tag{5.8}$$

$$\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z^a_{rtbu} \geq \int_0^1 \phi^{-1}_{\xi_{b^a_{L_b}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall b,\, a \tag{5.9}$$

$$\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z^a_{rtbu} \leq \int_0^1 \phi^{-1}_{\xi_{b^a_{R_b}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall b,\, a \tag{5.10}$$

$$\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu} \geq \int_0^1 \phi^{-1}_{\xi_{e^1_{L_u}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall u \tag{5.11}$$

$$\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu} \leq \int_0^1 \phi^{-1}_{\xi_{e^1_{R_u}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall u \tag{5.12}$$

$$\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu} \geq \int_0^1 \phi^{-1}_{\xi_{e^2_{L_u}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall u \tag{5.13}$$

$$\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu} \leq \int_0^1 \phi^{-1}_{\xi_{e^2_{R_u}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall u \tag{5.14}$$

$$\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z^a_{rtbu} \geq \int_0^1 \phi^{-1}_{\xi_{e^3_{L_u}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall u \tag{5.15}$$

$$\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z^a_{rtbu} \leq \int_0^1 \phi^{-1}_{\xi_{e^3_{R_u}}}(\Delta)\,\mathrm{d}\Delta, \qquad \forall u \tag{5.16}$$

$$\begin{aligned}\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\Bigg\{&\left(\frac{\int_0^1 \phi^{-1}_{\xi_{V^a_{L_h}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{V^a_{R_h}}}(\Delta)\,\mathrm{d}\Delta}{2}+\frac{\int_0^1 \phi^{-1}_{\xi_{C_{L^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{R^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)x^a_{hdcu}\\ &+\left(\frac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{F^a_{R_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^1\left(x^a_{hdcu}\right)\Bigg\}\leq\frac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_{dc}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{Bg_{R_{dc}}}}(\Delta)\,\mathrm{d}\Delta}{2}\qquad \forall dc\end{aligned} \tag{5.17}$$

$$\begin{aligned}\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\Bigg\{&\left(\frac{1}{2}\int_0^1 \phi^{-1}_{\xi_{V^a_{L_{dc}}}}(\Delta)\,\mathrm{d}\Delta+\frac{1}{2}\int_0^1 \phi^{-1}_{\xi_{V^a_{R_{dc}}}}(\Delta)\,\mathrm{d}\Delta+\frac{1}{2}\int_0^1 \phi^{-1}_{\xi_{C_{L^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta+\frac{1}{2}\int_0^1 \phi^{-1}_{\xi_{C_{R^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta\right)y^a_{dcrtu}\\ &+\left(\frac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{F^a_{R_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^2\left(y^a_{dcrtu}\right)\Bigg\}\leq\frac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_{rt}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{Bg_{R_{rt}}}}(\Delta)\,\mathrm{d}\Delta}{2}\qquad \forall rt\end{aligned} \tag{5.18}$$

$$\begin{aligned}\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\Bigg\{&\left(\frac{\int_0^1 \phi^{-1}_{\xi_{V^a_{L_{rt}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{V^a_{R_{rt}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{L^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{R^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)z^a_{rtbu}\\ &+\left(\frac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{F^a_{R_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^3\left(z^a_{rtbu}\right)\Bigg\}\leq\frac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_b}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{Bg_{R_b}}}(\Delta)\,\mathrm{d}\Delta}{2}\qquad \forall b\end{aligned} \tag{5.19}$$

$$\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^a_{hdcu} \geq \int_0^1 \phi^{-1}_{\xi_{Ms_{L^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta \qquad \forall a,\, h,\, dc,\, u \tag{5.20}$$

$$\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^a_{hdcu} \leq \int_0^1 \phi^{-1}_{\xi_{Ms_{R^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta \qquad \forall a,\, h,\, dc,\, u \tag{5.21}$$

$$\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y^a_{dcrtu} \geq \int_0^1 \phi^{-1}_{\xi_{Ms_{L^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta \qquad \forall a,\, dc,\, rt,\, u \tag{5.22}$$

$$\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y^a_{dcrtu} \leq \int_0^1 \phi^{-1}_{\xi_{Ms_{R^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta \qquad \forall a,\, dc,\, rt,\, u \tag{5.23}$$

$$\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z^a_{rtbu} \geq \int_0^1 \phi^{-1}_{\xi_{Ms_{L^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta \qquad \forall a,\, rt,\, b,\, u \tag{5.24}$$

$$\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z^a_{rtbu} \leq \int_0^1 \phi^{-1}_{\xi_{Ms_{L^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta \qquad \forall a,\, rt,\, b,\, u \tag{5.25}$$

(1.15)–(1.20).

6.2. Chance Constrained Model

The model (P_4) is equivalent to the following model (P_6).

$$
(P_6)\left\{
\begin{array}{lll}
\max \overline{Z^1}^U, \quad \min \overline{Z^2}^L, \quad \min \overline{Z^3}^L & & (6.1)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U}\left(\phi^{-1}_{\xi_{S^a_{dc}}}\left(\alpha^1\right)-\phi^{-1}_{\xi_{V^a_h}}\left(\alpha^1\right)-\phi^{-1}_{\xi_{C^a_{hdcu}}}\left(\alpha^1\right)\right)x^a_{hdcu}-\phi^{-1}_{\xi_{F^a_{hdcu}}}\left(\alpha^1\right)\theta^1\left(x^a_{hdcu}\right) & & \\
\quad +\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U}\left(\phi^{-1}_{\xi_{S^a_{rt}}}\left(\alpha^1\right)-\phi^{-1}_{\xi_{V^a_{dc}}}\left(\alpha^1\right)-\phi^{-1}_{\xi_{C^a_{dcrtu}}}\left(\alpha^1\right)\right)y^a_{dcrtu}-\phi^{-1}_{\xi_{F^a_{dcrtu}}}\left(\alpha^1\right)\theta^2\left(y^a_{dcrtu}\right) & & (6.2)\\
\quad +\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U}\left(\phi^{-1}_{\xi_{S^a_b}}\left(\alpha^1\right)-\phi^{-1}_{\xi_{V^a_{rt}}}\left(\alpha^1\right)-\phi^{-1}_{\xi_{C^a_{rtbu}}}\left(\alpha^1\right)\right)z^a_{rtbu}-\phi^{-1}_{\xi_{F^a_{rtbu}}}\left(\alpha^1\right)\theta^3\left(z^a_{rtbu}\right)\geq \overline{Z^1}^U & & \\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U}\phi^{-1}_{\xi_{\eta^a_{hdcu}}}\left(\alpha^2\right)x^a_{hdcu}+\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U}\phi^{-1}_{\xi_{\eta^a_{dcrtu}}}\left(\alpha^2\right)y^a_{dcrtu} & & \\
\quad +\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U}\phi^{-1}_{\xi_{\eta^a_{rtbu}}}\left(\alpha^2\right)z^a_{rtbu}\leq \overline{Z^2}^L & & (6.3)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U}\phi^{-1}_{\xi_{T^a_{hdcu}}}\left(\alpha^3\right)\theta^1\left(x^a_{hdcu}\right)+\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U}\phi^{-1}_{\xi_{T^a_{dcrtu}}}\left(\alpha^3\right)\theta^2\left(y^a_{dcrtu}\right) & & \\
\quad +\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U}\phi^{-1}_{\xi_{T^a_{rtbu}}}\left(\alpha^3\right)\theta^3\left(z^a_{rtbu}\right)\leq \overline{Z^3}^L & & (6.4)\\
\sum_{dc=1}^{DC}\sum_{u=1}^{U}x^a_{hdcu}-\phi^{-1}_{\xi_{a^a_{L_h}}}\left(\beta_{a^a_{L_h}}\right)\geq 0 & \forall h,a & (6.5)\\
\sum_{dc=1}^{DC}\sum_{u=1}^{U}x^a_{hdcu}-\phi^{-1}_{\xi_{a^a_{R_h}}}\left(1-\beta_{a^a_{R_h}}\right)\leq 0 & \forall h,a & (6.6)\\
\sum_{rt=1}^{RT}\sum_{u=1}^{U}z^a_{rtbu}-\phi^{-1}_{\xi_{b^a_{L_b}}}\left(\beta_{b^a_{L_b}}\right)\geq 0 & \forall b,a & (6.7)\\
\sum_{rt=1}^{RT}\sum_{u=1}^{U}z^a_{rtbu}-\phi^{-1}_{\xi_{b^a_{R_b}}}\left(1-\beta_{b^a_{R_b}}\right)\leq 0 & \forall b,a & (6.8)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}x^a_{hdcu}-\phi^{-1}_{\xi_{e^1_{L_u}}}\left(\beta_{e^1_{L_u}}\right)\geq 0 & \forall u & (6.9)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}x^a_{hdcu}-\phi^{-1}_{\xi_{e^1_{R_u}}}\left(1-\beta_{e^1_{R_u}}\right)\leq 0 & \forall u & (6.10)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}y^a_{dcrtu}-\phi^{-1}_{\xi_{e^2_{L_u}}}\left(\beta_{e^2_{L_u}}\right)\geq 0 & \forall u & (6.11)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}y^a_{dcrtu}-\phi^{-1}_{\xi_{e^2_{R_u}}}\left(1-\beta_{e^2_{R_u}}\right)\leq 0 & \forall u & (6.12)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{b=1}^{B}z^a_{rtbu}-\phi^{-1}_{\xi_{e^3_{L_u}}}\left(\beta_{e^3_{L_u}}\right)\geq 0 & \forall u & (6.13)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}z^a_{rtbu}-\phi^{-1}_{\xi_{e^3_{R_u}}}\left(1-\beta_{e^3_{R_u}}\right)\leq 0 & \forall u & (6.14)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\left\{\left(\frac{\phi^{-1}_{\xi_{V^a_{L_h}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{V^a_{R_h}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{C_{L^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{C_{R^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)}{2}\right)x^a_{hdcu}\right. & & \\
\left.+\left(\frac{\phi^{-1}_{\xi_{F_{L^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{F_{R^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)}{2}\right)\theta^1\left(x^a_{hdcu}\right)\right\}-\frac{\phi^{-1}_{\xi_{B_{L_{dc}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{Bg_{R_{dc}}}}\left(\beta_{Bg_{dc}}\right)}{2}\leq 0 & \forall dc & (6.15)
\end{array}
\right.
$$

$$
(P_6)\begin{cases}
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left\{\left(\dfrac{\phi^{-1}_{\xi_{V^a_{L_{dc}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{V^a_{R_{dc}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{C_{L^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{C_{R^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)}{2}\right)y^a_{dcrtu}\right. \\
\left.+\left(\dfrac{\phi^{-1}_{\xi_{F_{L^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{F_{R^a_{dcrtu}}}}\left(\beta_{B_{rt}}\right)}{2}\right)\theta^2\left(y^a_{dcrtu}\right)\right\}-\dfrac{\phi^{-1}_{\xi_{Bg_{L_{rt}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{Bg_{R_{rt}}}}\left(\beta_{Bg_{rt}}\right)}{2}\leq 0 \quad \forall rt \quad (6.16)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left\{\left(\dfrac{\phi^{-1}_{\xi_{V^a_{L_{rt}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{V^a_{R_{rt}}}}\left(\beta_{B_b}\right)+\phi^{-1}_{\xi_{C_{L^a_{rtbu}}}}\left(\beta_{B_b}\right)+\phi^{-1}_{\xi_{C_{R^a_{rtbu}}}}\left(\beta_{Bg_b}\right)}{2}\right)z^a_{rtbu}\right. \\
\left.+\left(\dfrac{\phi^{-1}_{\xi_{F_{L^a_{rtbu}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{F_{R^a_{rtbu}}}}\left(\beta_{Bg_b}\right)}{2}\right)\theta^3\left(z^a_{rtbu}\right)\right\}-\dfrac{\phi^{-1}_{\xi_{Bg_{L_b}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{Bg_{R_b}}}\left(\beta_{Bg_b}\right)}{2}\leq 0 \quad \forall b \quad (6.17)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}x^a_{hdcu}-\phi^{-1}_{\xi_{\beta_{Ms_{L^a_{hdcu}}}}}\left(\beta_{Ms_{L^a_{hdcu}}}\right)\geq 0 \quad \forall a,h,dc,u \quad (6.18)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}x^a_{hdcu}-\phi^{-1}_{\xi_{\beta_{Ms_{R^a_{hdcu}}}}}\left(1-\beta_{Ms_{R^a_{hdcu}}}\right)\leq 0 \quad \forall a,h,dc,u \quad (6.19)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}y^a_{dcrtu}-\phi^{-1}_{\xi_{\beta_{Ms_{L^a_{dcrtu}}}}}\left(\beta_{Ms_{L^a_{dcrtu}}}\right)\geq 0 \quad \forall a,dc,u \quad (6.20)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}y^a_{dcrtu}-\phi^{-1}_{\xi_{\beta_{Ms_{R^a_{dcrtu}}}}}\left(1-\beta_{Ms_{R^a_{dcrtu}}}\right)\leq 0 \quad \forall a,dc,rt,u \quad (6.21)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}z^a_{rtbu}-\phi^{-1}_{\xi_{\beta_{Ms_{L^a_{rtbu}}}}}\left(\beta_{Ms_{L^a_{rtbu}}}\right)\geq 0 \quad \forall a,rt,b,u \quad (6.22)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U}z^a_{rtbu}-\phi^{-1}_{\xi_{\beta_{Ms_{R^a_{rtbu}}}}}\left(1-\beta_{Ms_{R^a_{rtbu}}}\right)\leq 0 \quad \forall a,rt,b,u \quad (6.23)\\
(1.15)-(1.20).
\end{cases}
$$

7. Methodologies for deterministic equivalence

7.1. Linear Weighted Method

Linear Weighted method commonly solves Interval multi-objective optimization problems, by transforming them to Single Objective optimization problems. Weights signify objective importance, assessed by the decision-maker.

For the EVM, the Linear Weighted Method can be described in the following manner:

$$
(P_7)\left\{
\begin{array}{lll}
\min -\lambda^1_R E\left[Z^1_R\right] - \lambda^1_C E\left[Z^1_C\right] + \lambda^2_R E\left[Z^2_R\right] + \lambda^2_C E\left[Z^2_C\right] + \lambda^3_R E\left[Z^3_R\right] + \lambda^3_C E\left[Z^3_C\right] & & (7.1)\\
\sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} x^a_{hdcu} \geq \int_0^1 \phi^{-1}_{\xi_{a^a_{L_h}}}(\Delta)\,\mathrm{d}\Delta & \forall h,\, a & (7.2)\\
\sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} x^a_{hdcu} \leq \int_0^1 \phi^{-1}_{\xi_{a^a_{R_h}}}(\Delta)\,\mathrm{d}\Delta & \forall h,\, a & (7.3)\\
\sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} z^a_{rtbu} \geq \int_0^1 \phi^{-1}_{\xi_{b^a_{L_b}}}(\Delta)\,\mathrm{d}\Delta & \forall b,\, a & (7.4)\\
\sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} z^a_{rtbu} \leq \int_0^1 \phi^{-1}_{\xi_{b^a_{R_b}}}(\Delta)\,\mathrm{d}\Delta & \forall b,\, a & (7.5)\\
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu} \geq \int_0^1 \phi^{-1}_{\xi_{e^1_{L_u}}}(\Delta)\,\mathrm{d}\Delta & \forall u & (7.6)\\
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu} \leq \int_0^1 \phi^{-1}_{\xi_{e^1_{R_u}}}(\Delta)\,\mathrm{d}\Delta & \forall u & (7.7)\\
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu} \geq \int_0^1 \phi^{-1}_{\xi_{e^2_{L_u}}}(\Delta)\,\mathrm{d}\Delta & \forall u & (7.8)\\
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu} \leq \int_0^1 \phi^{-1}_{\xi_{e^2_{R_u}}}(\Delta)\,\mathrm{d}\Delta 0 & \forall u & (7.9)\\
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{b=1}^{B} z^a_{rtbu} \geq \int_0^1 \phi^{-1}_{\xi_{e^3_{L_u}}}(\Delta)\,\mathrm{d}\Delta & \forall u & (7.10)\\
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{b=1}^{B} z^a_{rtbu} \leq \int_0^1 \phi^{-1}_{\xi_{e^3_{R_u}}}(\Delta)\,\mathrm{d}\Delta & \forall u & (7.11)\\
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{u=1}^{U} \left\{ \left(\frac{\int_0^1 \phi^{-1}_{\xi_{V^a_{L_h}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{V^a_{R_h}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{C_{L^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{C_{R^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta}{2} \right) x^a_{hdcu} \right. & & \\
\quad \left. + \left(\frac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{F^a_{R_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta}{2} \right) \theta^1\left(x^a_{hdcu}\right) \right\} \leq \frac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_{dc}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{Bg_{R_{dc}}}}(\Delta)\,\mathrm{d}\Delta}{2}; & \forall dc & (7.12)\\
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} \left\{ \left(\frac{\int_0^1 \phi^{-1}_{\xi_{V^a_{L_{dc}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{V^a_{R_{dc}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1} 5\xi_{C_{L^a_{dcrtu}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{C_{R^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta}{2} \right) y^a_{dcrtu} \right. & & \\
\quad \left. + \left(\frac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{F^a_{R_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta}{2} \right) \theta^2(y^a_{dcrtu}) \right\} \leq \frac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_{rt}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{Bg_{R_{rt}}}}(\Delta)\,\mathrm{d}\Delta}{2}; & \forall rt & (7.13)\\
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} \left\{ \left(\frac{\int_0^1 \phi^{-1}_{\xi_{V^a_{L_{rt}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{V^a_{R_{rt}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{C_{L^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{C_{R^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta}{2} \right) z^a_{rtbu} \right. & & \\
\quad \left. + \left(\frac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{F^a_{R_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta}{2} \right) \theta^3(z^a_{rtbu}) \right\} \leq \frac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_b}}}(\Delta)\,\mathrm{d}\Delta + \int_0^1 \phi^{-1}_{\xi_{Bg_{R_b}}}(\Delta)\,\mathrm{d}\Delta}{2}; & \forall b & (7.14)\\
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} x^a_{hdcu} \geq \int_0^1 \phi^{-1}_{\xi_{Ms_{L^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta & \forall a, h, dc, u & (7.15)\\
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} x^a_{hdcu} \leq \int_0^1 \phi^{-1}_{\xi_{Ms_{R^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta & d\forall a, h, dc, u & (7.16)\\
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} y^a_{dcrtu} \geq \int_0^1 \phi^{-1}_{\xi_{Ms_{L^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta & \forall a, dc, rt, u & (7.17)\\
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} y^a_{dcrtu} \leq \int_0^1 \phi^{-1}_{\xi_{Ms_{R^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta & \forall a, dc, rt, u & (7.18)\\
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{b=1}^{B} \sum_{u=1}^{U} z^a_{rtbu} \geq \int_0^1 \phi^{-1}_{\xi_{Ms_{L^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta & \forall a, rt, b, u & (7.19)\\
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{b=1}^{B} \sum_{u=1}^{U} z^a_{rtbu} \leq \int_0^1 \phi^{-1}_{\xi_{Ms_{L^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta & \forall a, rt, b, u & (7.20)\\
\qquad (1.15)-(1.20). & &
\end{array}
\right.
$$

For the chance constrained model, the Linear Weighted Method can be described in the following manner:

$$
(P_8)\left\{
\begin{array}{lll}
\min\left(-\lambda^1\overline{Z^1}+\lambda^2\overline{Z^2}+\lambda^3\overline{Z^3}\right) & & (8.1)\\
\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^a_{hdcu}-\phi^{-1}_{\xi_{a^a_{L_h}}}\left(\beta_{a^a_{L_h}}\right)\geq 0 & \forall h,\, a & (8.2)\\
\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^a_{hdcu}-\phi^{-1}_{\xi_{a^a_{R_h}}}\left(1-\beta_{a^a_{R_h}}\right)\leq 0 & \forall h,\, a & (8.3)\\
\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{u} z^a_{rtbu}-\phi^{-1}_{\xi_{b^a_{L_b}}}\left(\beta_{b^a_{L_b}}\right)\geq 0 & \forall b,\, a & (8.4)\\
\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z^a_{rtbu}-\phi^{-1}_{\xi_{b^a_{R_b}}}\left(1-\beta_{b^a_{R_b}}\right)\leq 0 & \forall b,\, a & (8.5)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu}-\phi^{-1}_{\xi_{e^1_{L_u}}}\left(\beta_{e^1_{L_u}}\right)\geq 0 & \forall u & (8.6)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu}-\phi^{-1}_{\xi_{e^1_{R_u}}}\left(1-\beta_{e^1_{R_u}}\right)\leq 0 & \forall u & (8.7)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu}-\phi^{-1}_{\xi_{e^2_{L_u}}}\left(\beta_{e^2_{L_u}}\right)\geq 0 & \forall u & (8.8)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu}-\phi^{-1}_{\xi_{e^2_{R_u}}}\left(1-\beta_{e^2_{R_u}}\right)\leq 0 & \forall u & (8.9)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z^a_{rtbu}-\phi^{-1}_{\xi_{e^3_{L_u}}}\left(\beta_{e^3_{L_u}}\right)\geq 0 & \forall u & (8.10)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z^a_{rtbu}-\phi^{-1}_{\xi_{e^3_{R_u}}}\left(1-\beta_{e^3_{R_u}}\right)\leq 0 & \forall u & (8.11)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\left\{\left(\frac{\phi^{-1}_{\xi_{V^a_{L_h}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{V^a_{R_h}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{C_{L^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{C_{R^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)}{2}\right)x^a_{hdcu}\right. & & \\
\quad\left.+\left(\frac{\phi^{-1}_{\xi_{F_{L^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{F_{R^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)}{2}\right)\theta^1\left(x^a_{hdcu}\right)\right\}-\frac{\phi^{-1}_{\xi_{Bg_{L_{dc}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{Bg_{R_{dc}}}}\left(\beta_{B_{dc}}\right)}{2}\leq 0 & \forall dc & (8.12)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left\{\left(\frac{\phi^{-1}_{\xi_{V^a_{L_{dc}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{V^a_{R_{dc}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{C_{L^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{C_{R^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)}{2}\right)y^a_{dcrtu}\right. & & \\
\quad\left.+\left(\frac{\phi^{-1}_{\xi_{F_{L^a_{dcrtu}}}}\left(\beta_{B_p}\right)+\phi^{-1}_{\xi_{F_{R^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)}{2}\right)\theta^2\left(y^a_{dcrtu}\right)\right\}-\frac{\phi^{-1}_{\xi_{Bg_{L_{rt}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{Bg_{R_{rt}}}}\left(\beta_{Bg_{rt}}\right)}{2}\leq 0 & \forall rt & (8.13)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left\{\left(\frac{\phi^{-1}_{\xi_{V^a_{L_{rt}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{V^a_{R_{rt}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{C_{L^a_{rtbu}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{C_{R^a_{rtbu}}}}\left(\beta_{Bg_b}\right)}{2}\right)z^a_{rtbu}\right. & & \\
\quad\left.+\left(\frac{\phi^{-1}_{\xi_{F_{L^a_{rtbu}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{F_{R^a_{rtbu}}}}\left(\beta_{Bg_b}\right)}{2}\right)\theta^3\left(z^a_{rtbu}\right)\right\}-\frac{\phi^{-1}_{\xi_{Bg_{L_b}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{Bg_{R_b}}}\left(\beta_{Bg_b}\right)}{2}\leq 0 & \forall b & (8.14)
\end{array}
\right.
$$

$$
(P_8)\begin{cases}
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U} x^a_{hdcu} - \phi^{-1}_{\xi_{\beta_{Ms_{L^a_{hdcu}}}}}\left(\beta_{Ms_{L^a_{hdcu}}}\right) \geq 0 & \forall a,h,dc,u \quad (8.15)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U} x^a_{hdcu} - \phi^{-1}_{\xi_{\beta_{Ms_{R^a_{hdcu}}}}}\left(1-\beta_{Ms_{R^a_{hdcu}}}\right) \leq 0 & \forall a,h,dc,u \quad (8.16)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U} y^a_{dcrtu} - \phi^{-1}_{\xi_{\beta_{Ms_{L^a_{dcrtu}}}}}\left(\beta_{Ms_{L^a_{dcrtu}}}\right) \geq 0 & \forall a,dc,rt,u \quad (8.17)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U} y^a_{dcrtu} - \phi^{-1}_{\xi_{\beta_{Ms_{R^a_{dcrtu}}}}}\left(1-\beta_{Ms_{R^a_{dcrtu}}}\right) \leq 0 & \forall a,dc,rt,u \quad (8.18)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U} z^a_{rtbu} - \phi^{-1}_{\xi_{\beta_{Ms_{L^a_{rtbu}}}}}\left(\beta_{Ms_{L^a_{rtbu}}}\right) \geq 0 & \forall a,rt,b,u \quad (8.19)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U} z^a_{rtbu} - \phi^{-1}_{\xi_{\beta_{Ms_{R^a_{rtbu}}}}}\left(1-\beta_{Ms_{R^a_{rtbu}}}\right) \leq 0 & \forall a,rt,b,u \quad (8.20)\\
(1.15)-(1.20) & \\
\lambda^1+\lambda^2+\lambda^3=1 & \\
\lambda^1,\lambda^2,\lambda^3\in[0,1]. &
\end{cases}
$$

Theorem 7.1 ([36]). *A feasible solution of the EVM as presented in model* (P_5) *possesses the following characteristics:*

- *is an optimal solution for the compromise model* (P_7) *if and only if it is Pareto optimal for the multi objective model* (P_5).
- *It stands as a Pareto optimal solution for the multi objective model* (P_5) *if and only if is an optimal solution for the compromise Model* (P_7).
- *A similar theorem can be readily established for the multi-objective model* (P_6) *and the compromise model* (P_8).

7.2. Fuzzy programming method

In 1965, Zadeh [41] introduced the concept of fuzzy set theory, and subsequently, in 1978, Zimmermann developed fuzzy programming techniques for addressing multi-objective linear programs. Fuzzy set theory has since become a vital tool for handling and analyzing optimization problems, serving as a robust mathematical framework for managing incomplete and imprecise information.

For the EVM, the fuzzy programming method can be described in the following manner:

$$
(P_9)\begin{cases}
\max \lambda \\
\dfrac{E\left[Z^1\right]-E\left[Z^1\right]^L}{E\left[Z^1\right]^U-E\left[Z^1\right]^L}\geq \lambda & (9.1)\\
\dfrac{E\left[Z^2\right]^U-E\left[Z^2\right]}{E\left[Z^2\right]^U-E\left[Z^2\right]^L}\geq \lambda & (9.2)\\
\dfrac{E\left[Z^3\right]^U-E\left[Z^3\right]}{E\left[Z^3\right]^U-E\left[Z^3\right]^L}\geq \lambda & (9.3)\\
\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^a_{hdcu}\geq \int_0^1 \phi^{-1}_{\xi_{a^a_{L_h}}}(\Delta)\,\mathrm{d}\Delta \quad \forall h,a & (9.4)\\
\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x^a_{hdcu}\leq \int_0^1 \phi^{-1}_{\xi_{a^a_{R_h}}}(\Delta)\,\mathrm{d}\Delta \quad \forall h,a & (9.5)\\
\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z^a_{rtbu}\geq \int_0^1 \phi^{-1}_{\xi_{b^a_{L_b}}}(\Delta)\,\mathrm{d}\Delta \quad \forall\ b,a & (9.6)\\
\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z^a_{rtbu}\leq \int_0^1 \phi^{-1}_{\xi_{b^a_{R_b}}}(\Delta)\,\mathrm{d}\Delta \quad \forall b,a & (9.7)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu}\geq \int_0^1 \phi^{-1}_{\xi_{e^1_{L_u}}}(\Delta)\,\mathrm{d}\Delta \quad \forall u & (9.8)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu}\leq \int_0^1 \phi^{-1}_{\xi_{e^1_{R_u}}}(\Delta)\,\mathrm{d}\Delta \quad \forall u & (9.9)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu}\geq \int_0^1 \phi^{-1}_{\xi_{e^2_{L_u}}}(\Delta)\,\mathrm{d}\Delta \quad \forall u & (9.10)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu}\leq \int_0^1 \phi^{-1}_{\xi_{e^2_{R_u}}}(\Delta)\,\mathrm{d}\Delta \quad \forall u & (9.11)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z^a_{rtbu}\geq \int_0^1 \phi^{-1}_{\xi_{e^3_{L_u}}}(\Delta)\,\mathrm{d}\Delta \quad \forall u & (9.12)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z^a_{rtbu}\leq \int_0^1 \phi^{-1}_{\xi_{e^3_{R_u}}}(\Delta)\,\mathrm{d}\Delta \quad \forall u & (9.13)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\left\{\left(\dfrac{\int_0^1 \phi^{-1}_{\xi_{V^a_{L_h}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{V^a_{R_h}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{L^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{R^a_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)x^a_{hdcu}\right.\\
\quad\left.+\left(\dfrac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{hdck}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{F^a_{R_{hdcu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^1(x^a_{hdcu})\right\}\leq \dfrac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_{dc}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{Bg_{R_{dc}}}}(\Delta)\,\mathrm{d}\Delta}{2} \quad \forall dc & (9.14)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\left\{\left(\dfrac{\int_0^1 \phi^{-1}_{\xi_{V^a_{L_{dc}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{V^a_{R_{dc}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{L^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{R^a_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)y^a_{dcrtu}\right.\\
\quad\left.+\left(\dfrac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{F^a_{R_{dcrtu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^2(y^a_{dcrtu})\right\}\leq \dfrac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_{rt}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{Bg_{R_{rt}}}}(\Delta)\,\mathrm{d}\Delta}{2} \quad \forall rt & (9.15)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\left\{\left(\dfrac{\int_0^1 \phi^{-1}_{\xi_{V^a_{L_{rt}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{V^a_{R_{rt}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{L^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{C_{R^a_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)z^a_{rtbu}\right.\\
\quad\left.+\left(\dfrac{\int_0^1 \phi^{-1}_{\xi_{F^a_{L_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{F^a_{R_{rtbu}}}}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^3(z^a_{rtbu})\right\}\leq \dfrac{\int_0^1 \phi^{-1}_{\xi_{Bg_{L_b}}}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi^{-1}_{\xi_{Bg_{R_b}}}(\Delta)\,\mathrm{d}\Delta}{2} \quad \forall b & (9.16)
\end{cases}
$$

$$
(P_9)\begin{cases}
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} \geq \int_0^1 \phi_{\xi_{Ms_{L_{hdcu}^{a}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a, h, dc, u \quad (9.17)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} \leq \int_0^1 \phi_{\xi_{Ms_{R_{hdcu}^{a}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a, h, dc, u \quad (9.18)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y_{dcrtu}^{a} \geq \int_0^1 \phi_{\xi_{Ms_{L_{dcrtu}^{a}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a, dc, rt, u \quad (9.19)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y_{dcrtu}^{a} \leq \int_0^1 \phi_{\xi_{Ms_{R_{dcrtu}^{a}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a, dc, rt, u \quad (9.20)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z_{rtbu}^{a} \geq \int_0^1 \phi_{\xi_{Ms_{L_{rtbu}^{a}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a, rt, b, u \quad (9.21)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z_{rtbu}^{a} \leq \int_0^1 \phi_{\xi_{Ms_{L_{rtbu}^{a}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a, rt, b, u \quad (9.22)\\
(1.15)-(1.20).
\end{cases}
$$

For the CCM, the fuzzy method can be described in the following manner:

$$
(P_{10})\left\{
\begin{array}{llr}
\max \lambda & & (10.1)\\[4pt]
\dfrac{E\left[Z^1\right] - E\left[Z^1\right]^L}{E[Z^1]^U - E\left[Z^1\right]^L} \geq \lambda & & (10.2)\\[8pt]
\dfrac{E\left[Z^2\right]^U - E\left[Z^2\right]}{E\left[Z^2\right]^U - E\left[Z^2\right]^L} \geq \lambda & & (10.3)\\[8pt]
\dfrac{E\left[Z^3\right]^U - E\left[Z^3\right]}{E\left[Z^3\right]^U - E\left[Z^3\right]^L} \geq \lambda & & (10.4)\\[8pt]
\sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} x^a_{hdcu} - \phi^{-1}_{\xi_{a^a_{L_h}}} \left(\beta_{a^a_{L_h}}\right) \geq 0 & \forall h,\, a & (10.5)\\[6pt]
\sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} x^a_{hdcu} - \phi^{-1}_{\xi_{a^a_{R_h}}} \left(1 - \beta_{a^a_{R_h}}\right) \leq 0 & \forall h,\, a & (10.6)\\[6pt]
\sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} z^a_{rtbu} - \phi^{-1}_{\xi_{b^a_{L_b}}} \left(\beta_{b^a_{L_b}}\right) \geq 0 & \forall b,\, a & (10.7)\\[6pt]
\sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} z^a_{rtbu} - \phi^{-1}_{\xi_{b^a_{R_b}}} \left(1 - \beta_{b^a_{R_b}}\right) \leq 0 & \forall b,\, a & (10.8)\\[6pt]
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu} - \phi^{-1}_{\xi_{e^1_{L_u}}} \left(\beta_{e^1_{L_u}}\right) \geq 0 & \forall u & (10.10)\\[6pt]
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{dc=1}^{\mathrm{DC}} x^a_{hdcu} - \phi^{-1}_{\xi_{e^1_{R_u}}} \left(1 - \beta_{e^1_{R_u}}\right) \leq 0 & \forall u & (10.11)\\[6pt]
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu} - \phi^{-1}_{\xi_{e^2_{L_u}}} \left(\beta_{e^2_{L_u}}\right) \geq 0 & \forall u & (10.12)\\[6pt]
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{rt=1}^{\mathrm{RT}} y^a_{dcrtu} - \phi^{-1}_{\xi_{e^2_{R_u}}} \left(1 - \beta_{e^2_{R_u}}\right) \leq 0 & \forall u & (10.13)\\[6pt]
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{b=1}^{B} z^a_{rtbu} - \phi^{-1}_{\xi_{e^3_{L_u}}} \left(\beta_{e^3_{L_u}}\right) \geq 0 & \forall u & (10.14)\\[6pt]
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{b=1}^{B} z^a_{rtbu} - \phi^{-1}_{\xi_{e^3_{R_u}}} \left(1 - \beta_{e^3_{R_u}}\right) \leq 0 & \forall u & (10.15)\\[6pt]
\sum_{a=1}^{A} \sum_{h=1}^{H} \sum_{u=1}^{U} \left\{ \left(\dfrac{\phi^{-1}_{\xi_{V^a_{L_h}}}\left(\beta_{Bg_{\mathrm{DC}}}\right) + \phi^{-1}_{\xi_{V^a_{R_h}}}\left(\beta_{Bg_{\mathrm{DC}}}\right) + \phi^{-1}_{\xi_{C_{L^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right) + \phi^{-1}_{\xi_{C_{R^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)}{2} \right) x^a_{hdcu} \right. & & \\[6pt]
\quad \left. + \left(\dfrac{\phi^{-1}_{\xi_{F_{L^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right) + \phi^{-1}_{\xi_{F_{R^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)}{2} \right) \theta^1\left(x^a_{hdcu}\right) \right\} - \dfrac{\phi^{-1}_{\xi_{Bg_{L_{dc}}}}\left(\beta_{Bg_{dc}}\right) + \phi^{-1}_{\xi_{Bg_{R_{dc}}}}\left(\beta_{Bg_{dc}}\right)}{2} \leq 0 & \forall dc & (10.16)\\[6pt]
\sum_{a=1}^{A} \sum_{dc=1}^{\mathrm{DC}} \sum_{u=1}^{U} \left\{ \left(\dfrac{\phi^{-1}_{\xi_{V^a_{L_{dc}}}}\left(\beta_{Bg_{rt}}\right) + \phi^{-1}_{\xi_{V^a_{R_{dc}}}}\left(\beta_{Bg_{rt}}\right) + \phi^{-1}_{\xi_{C_{L^a_{dcrtu}}}}\left(\beta_{B_{rt}}\right) + \phi^{-1}_{\xi_{C_{R^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)}{2} \right) y^a_{dcrtu} \right. & & \\[6pt]
\quad \left. + \left(\dfrac{\phi^{-1}_{\xi_{F_{L^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right) + \phi^{-1}_{\xi_{F_{R^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)}{2} \right) \theta^2(y^a_{dcrtu}) \right\} - \dfrac{\phi^{-1}_{\xi_{B_{L_{rt}}}}\left(\beta_{Bg_{rt}}\right) + \phi^{-1}_{\xi_{Bg_{R_{rt}}}}\left(\beta_{Bg_{rt}}\right)\left(\beta_{Bg_{rt}}\right)}{2} \leq 0 & \forall rt & (10.17)\\[6pt]
\sum_{a=1}^{A} \sum_{rt=1}^{\mathrm{RT}} \sum_{u=1}^{U} \left\{ \left(\dfrac{\phi^{-1}_{\xi_{V^a_{L_{rt}}}}\left(\beta_{Bg_b}\right) + \phi^{-1}_{\xi_{V^a_{R_{rt}}}}(\beta_{Bg_b}) + \phi^{-1}_{\xi_{C_{L^a_{rtbu}}}}\left(\beta_{Bg_b}\right) + \phi^{-1}_{\xi_{C_{R^a_{rtbu}}}}\left(\beta_{Bg_b}\right)}{2} \right) z^a_{rtbu} \right. & & \\[6pt]
\quad \left. + \left(\dfrac{\phi^{-1}_{\xi_{F_{L^a_{rtbu}}}}\left(\beta_{Bg_b}\right) + \phi^{-1}_{\xi_{F_{R^a_{rtbu}}}}\left(\beta_{Bg_b}\right)}{2} \right) \theta^3\left(z^a_{rtbu}\right) \right\} - \dfrac{\phi^{-1}_{\xi_{Bg_{L_b}}}\left(\beta_{Bg_b}\right) + \phi^{-1}_{\xi_{Bg_{R_b}}}\left(\beta_{Bg_b}\right)}{2} \leq 0 & \forall b & (10.18)
\end{array}
\right.
$$

$$(P_{10})\begin{cases}
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U} x_{hdcu}^{a} - \phi^{-1}_{\xi_{\beta_{Ms_{L^a_{hdcu}}}}}\left(\beta_{Ms_{L^a_{hdcu}}}\right) \geq 0 & \forall a,h,dc,u \quad (10.19)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U} x_{hdcu}^{a} - \phi^{-1}_{\xi_{\beta_{Ms_{R^a_{hdcu}}}}}\left(1-\beta_{Ms_{R^a_{hdcu}}}\right) \leq 0 & \forall a,h,dc,u \quad (10.20)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U} y_{dcrtu}^{a} - \phi^{-1}_{\xi_{\beta_{Ms_{L^a_{dcrtu}}}}}\left(\beta_{Ms_{L^a_{dcrtu}}}\right) \geq 0 & \forall a,dc,rt,u \quad (10.21)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U} y_{dcrtu}^{a} - \phi^{-1}_{\xi_{\beta_{Ms_{R^a_{dcrtu}}}}}\left(1-\beta_{Ms_{R^a_{dcrtu}}}\right) \leq 0 & \forall a,dc,rt,u \quad (10.22)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U} z_{rtbu}^{a} - \phi^{-1}_{\xi_{\beta_{Ms_{L^a_{rtbu}}}}}\left(\beta_{Ms_{L^a_{rtbu}}}\right) \geq 0 & \forall a,rt,b,u \quad (10.23)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U} z_{rtbu}^{a} - \phi^{-1}_{\xi_{\beta_{Ms_{R^a_{rtbu}}}}}\left(1-\beta_{Ms_{R^a_{rtbu}}}\right) \leq 0 & \forall a,rt,b,u \quad (10.24)\\
(1.15)-(1.20)
\end{cases}$$

where ${Z^1}^L, {Z^2}^L, {Z^3}^L$ denote the lower boundaries, and ${Z^1}^U, {Z^2}^U, {Z^3}^U$ signify the upper limits for the objectives Z^1, Z^2, Z^3.

Theorem 7.2 ([36])**.** *A feasible solution of the EVM as presented in model* (P_5) *possesses the following characteristics:*

- *is an optimal solution for the compromise model* (P_9) *if and only if it is Pareto optimal for the multi-objective model* (P_5)*.*
- *It stands as a Pareto optimal solution for the multi-objective model* (P_5) *if and only if is an optimal solution for the compromise model* (P_9)*.*
- *A similar theorem can be readily established for the multi-objective model* (P_6) *and the compromise model* (P_9)*.*

7.3. Goal programming method

The goal programming technique, initially formulated by Charnes and Cooper in 1961 [6], centers on defining a series of goals for each objective function, delineating the benchmarks that a Decision Maker (DM) aims to achieve. This method prioritizes minimizing the deviation between the current solution and its predetermined objectives. A fundamental element of this technique involves embedding a reference point within the objective function, introducing a distance variable to steer the exploration.

For the EVM, the goal programming method can be described in the following manner:

$$
(P_{11})\left\{
\begin{array}{lll}
\min d_{01}+d_{11}+d_{02}+d_{12}+d_{03}+d_{13} & & (11.1)\\
-E\left[Z^{1}\right]-d01+d11=-E\left[Z^{1}\right]^{U} & & (11.2)\\
E\left[Z^{2}\right]+d02-d12=E\left[Z^{2}\right]^{L} & & (11.3)\\
E\left[Z^{3}\right]+d03-d13=E\left[Z^{3}\right]^{L} & & (11.4)\\
\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} \geq \int_0^1 \phi_{\xi_{a^a_{L_h}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall h,a & (11.5)\\
\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} \leq \int_0^1 \phi_{\xi_{a^a_{R_h}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall h,a & (11.6)\\
\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z_{rtbu}^{a} \geq \int_0^1 \phi_{\xi_{b^a_{L_b}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall b,a & (11.7)\\
\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} z_{rtbu}^{a} \leq \int_0^1 \phi_{\xi_{b^a_{R_b}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall b,a & (11.8)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}} x_{hdcu}^{a} \geq \int_0^1 \phi_{\xi_{e^1_{L_u}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall u & (11.9)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{j=dc}^{\mathrm{DC}} x_{hdcu}^{a} \leq \int_0^1 \phi_{\xi_{e^1_{R_u}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall u & (11.10)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y_{dcrtu}^{a} \geq \int_0^1 \phi_{\xi_{e^2_{L_u}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall u & (11.11)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}} y_{dcrtu}^{a} \leq \int_0^1 \phi_{\xi_{e^2_{R_u}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall u & (11.12)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z_{rtbu}^{a} \geq \int_0^1 \phi_{\xi_{e^3_{L_u}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall u & (11.13)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B} z_{rtbu}^{a} \leq \int_0^1 \phi_{\xi_{e^3_{R_u}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall u & (11.14)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\Bigg\{\left(\frac{\int_0^1 \phi_{\xi_{V^a_{L_h}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{V^a_{R_h}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{C_{L^a_{hdcu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{C_{R^a_{hdcu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2}\right)x_{hdcu}^{a} & & \\
\quad+\left(\frac{\int_0^1 \phi_{\xi_{F^a_{L_{hdcu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{F^a_{R_{hdcu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^{1}(x_{hdcu}^{a})\Bigg\} \leq \frac{\int_0^1 \phi_{\xi_{Bg_{L_{dc}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{Bg_{R_{dc}}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2} & \forall dc & (11.15)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U}\Bigg\{\left(\frac{\int_0^1 \phi_{\xi_{V^a_{L_{dc}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{V^a_{R_{dc}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{C_{L^a_{dcrtu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{C_{R^a_{dcrtu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2}\right)y_{dcrtu}^{a} & & \\
\quad+\left(\frac{\int_0^1 \phi_{\xi_{F^a_{L_{dcrtu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{F^a_{R_{dcrtu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^{2}\left(y_{dcrtu}^{a}\right)\Bigg\} \leq \frac{\int_0^1 \phi_{\xi_{Bg_{L_{rt}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{Bg_{R_{rt}}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2} & \forall rt & (11.16)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U}\Bigg\{\left(\frac{\int_0^1 \phi_{\xi_{V^a_{L_{rt}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{V^a_{R_{rt}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{C_{L^a_{rtbu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{C_{R^a_{rtbu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2}\right)z_{rtbu}^{a} & & \\
\quad+\left(\frac{\int_0^1 \phi_{\xi_{F^a_{L_{rtbu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{F^a_{R_{rtbu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2}\right)\theta^{3}\left(z_{rtbu}^{a}\right)\Bigg\} \leq \frac{\int_0^1 \phi_{\xi_{Bg_{L_b}}}^{-1}(\Delta)\,\mathrm{d}\Delta+\int_0^1 \phi_{\xi_{Bg_{R_b}}}^{-1}(\Delta)\,\mathrm{d}\Delta}{2} & \forall b & (11.17)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} \geq \int_0^1 \phi_{\xi_{Ms_{L^a_{hdcu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a,h,dc,u & (11.18)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{\mathrm{DC}}\sum_{u=1}^{U} x_{hdcu}^{a} \leq \int_0^1 \phi_{\xi_{Ms_{R^a_{hdcu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a,h,dc,u & (11.19)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y_{dcrtu}^{a} \geq \int_0^1 \phi_{\xi_{Ms_{L^a_{dcrtu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a,dc,rt,u & (11.20)\\
\sum_{a=1}^{A}\sum_{dc=1}^{\mathrm{DC}}\sum_{rt=1}^{\mathrm{RT}}\sum_{u=1}^{U} y_{dcrtu}^{a} \leq \int_0^1 \phi_{\xi_{Ms_{R^a_{dcrtu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a,dc,rt,u & (11.21)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z_{rtbu}^{a} \geq \int_0^1 \phi_{\xi_{Ms_{L^a_{rtbu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a,rt,b,u & (11.22)\\
\sum_{a=1}^{A}\sum_{rt=1}^{\mathrm{RT}}\sum_{b=1}^{B}\sum_{u=1}^{U} z_{rtbu}^{a} \leq \int_0^1 \phi_{\xi_{Ms_{L^a_{rtbu}}}}^{-1}(\Delta)\,\mathrm{d}\Delta & \forall a,rt,b,u & (11.23)\\
\quad\quad (1.15)-(1.20) & &
\end{array}\right.
$$

where $-E[Z^1]^U$, $E[Z^2]^L$, $E[Z^3]^L$ represent the lower bounds of the objectives $-E[Z^1]$, $E[Z^2]$, $E[Z^3]$, respectively.

For CCM, the goal programming method can be described in the following manner:

$$
(P12)\begin{cases}
\min d_{01}+d_{11}+d_{02}+d_{12}+d_{03}+d_{13} & (12.1)\\
-\overline{Z^1}-d_{01}+d_{11}=-\overline{Z^1}^U & (12.2)\\
\overline{Z^2}-d_{02}+d_{12}=\overline{Z^2}^L & (12.3)\\
\overline{Z^3}^U-d_{03}+d_{13}=\overline{Z^3}^L & (12.4)\\
\sum_{dc=1}^{DC}\sum_{u=1}^{U}x^a_{hdcu}-\phi^{-1}_{\xi_{a^a_{L_h}}}\left(\beta_{a^a_{L_h}}\right)\geq 0 \quad \forall h,a & (12.5)\\
\sum_{dc=1}^{DC}\sum_{u=1}^{U}x^a_{hdcu}-\phi^{-1}_{\xi_{a^a_{R_h}}}\left(1-\beta_{a^a_{R_h}}\right)\leq 0 \quad \forall h,a & (12.6)\\
\sum_{rt=1}^{RT}\sum_{u=1}^{U}z^a_{rtbu}-\phi^{-1}_{\xi_{b^a_{L_b}}}\left(\beta_{b^a_{L_b}}\right)\geq 0 \quad \forall b,a & (12.7)\\
\sum_{rt=1}^{RT}\sum_{u=1}^{U}z^a_{rtbu}-\phi^{-1}_{\xi_{b^a_{R_b}}}\left(1-\beta_{b^a_{R_b}}\right)\leq 0 \quad \forall b,a & (12.8)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}x^a_{hdcu}-\phi^{-1}_{\xi_{e^1_{L_u}}}\left(\beta_{e^1_{L_u}}\right)\geq 0 \quad \forall u & (12.9)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}x^a_{hdcu}-\phi^{-1}_{\xi_{e^1_{R_u}}}\left(1-\beta_{e^1_{R_u}}\right)\leq 0 \quad \forall u & (12.10)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}y^a_{dcrtu}-\phi^{-1}_{\xi_{e^2_{L_u}}}\left(\beta_{e^2_{L_u}}\right)\geq 0 \quad \forall u & (12.11)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}y^a_{dcrtu}-\phi^{-1}_{\xi_{e^2_{R_u}}}\left(1-\beta_{e^2_{R_u}}\right)\leq 0 \quad \forall u & (12.12)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}z^a_{rtbu}-\phi^{-1}_{\xi_{e^3_{L_u}}}\left(\beta_{e^3_{L_u}}\right)\geq 0 \quad \forall u & (12.13)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{b}z^a_{rtbu}-\phi^{-1}_{\xi_{e^3_{R_u}}}\left(1-\beta_{e^3_{R_u}}\right)\leq 0 \quad \forall u & (12.14)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{u=1}^{U}\left\{\left(\frac{\phi^{-1}_{\xi_{V^a_{L_h}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{V^a_{R_H}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{C_{L^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{C_{R^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)}{2}\right)x^a_{hdcu}\right\} & \\
+\left(\frac{\phi^{-1}_{\xi_{F_{L^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{F_{R^a_{hdcu}}}}\left(\beta_{Bg_{dc}}\right)}{2}\right)\theta^1(x^a_{hdcu})-\frac{\phi^{-1}_{\xi_{Bg_{L_{dc}}}}\left(\beta_{Bg_{dc}}\right)+\phi^{-1}_{\xi_{Bg_{R_{dc}}}}\left(\beta_{B_{dc}}\right)}{2}\leq 0 \quad \forall dc & (12.15)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{u=1}^{U}\left\{\left(\frac{\phi^{-1}_{\xi_{V^a_{L_{dc}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{V^a_{R_{dc}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{C_{L^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{C_{R^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)}{2}\right)y^a_{dcrtu}\right\} & \\
+\left(\frac{\phi^{-1}_{\xi_{F_{L^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{F_{R^a_{dcrtu}}}}\left(\beta_{Bg_{rt}}\right)}{2}\right)\theta^2(y^a_{dcrtu})-\frac{\phi^{-1}_{\xi_{B_{L_{rt}}}}\left(\beta_{Bg_{rt}}\right)+\phi^{-1}_{\xi_{Bg_{R_{rt}}}}\left(\beta_{Bg_{rt}}\right)}{2}\leq 0 \quad \forall rt & (12.16)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{u=1}^{U}\left\{\left(\frac{\phi^{-1}_{\xi_{V^a_{L_{rt}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{V^a_{R_{rt}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{C_{L^a_{rtbu}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{C_{R^a_{rtbu}}}}\left(\beta_{Bg_b}\right)}{2}\right)z^a_{rtbu}\right\} & \\
+\left(\frac{\phi^{-1}_{\xi_{F_{L^a_{rtbu}}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{F_{R^a_{rtbu}}}}\left(\beta_{Bg_b}\right)}{2}\right)\theta^3(z^a_{rtbu})-\frac{\phi^{-1}_{\xi_{Bg_{L_b}}}\left(\beta_{Bg_b}\right)+\phi^{-1}_{\xi_{Bg_{R_b}}}\left(\beta_{Bg_b}\right)}{2}\leq 0 \quad \forall b & (12.17)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U}x^a_{hdcu}-\phi^{-1}_{\xi_{\beta_{Ms_{L^a_{hdcu}}}}}\left(\beta_{Ms_{L^a_{hdcu}}}\right)\geq 0 \quad \forall h,dc,u & (12.18)\\
\sum_{a=1}^{A}\sum_{h=1}^{H}\sum_{dc=1}^{DC}\sum_{u=1}^{U}x^a_{hdcu}-\phi^{-1}_{\xi_{\beta_{Ms_{R^a_{hdcu}}}}}\left(1-\beta_{Ms_{R^a_{hdcu}}}\right)\leq 0 \quad \forall a,h,dc,u & (12.19)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U}y^a_{dcrtu}-\phi^{-1}_{\xi_{\beta_{Ms_{L^a_{dcrtu}}}}}\left(\beta_{Ms_{L^a_{dcrtu}}}\right)\geq 0 \quad \forall a,dc,rt,u & (12.20)\\
\sum_{a=1}^{A}\sum_{dc=1}^{DC}\sum_{rt=1}^{RT}\sum_{u=1}^{U}y^a_{dcrtu}-\phi^{-1}_{\xi_{\beta_{Ms_{R^a_{dcrtu}}}}}\left(1-\beta_{Ms_{R^a_{dcrtu}}}\right)\leq 0 \quad \forall a,dc,rt,u & (12.21)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U}z^a_{rtbu}-\phi^{-1}_{\xi_{\beta_{Ms_{L^a_{rtbu}}}}}\left(\beta_{Ms_{L^a_{rtbu}}}\right)\geq 0 \quad \forall a,rt,b,u & (12.22)\\
\sum_{a=1}^{A}\sum_{rt=1}^{RT}\sum_{b=1}^{B}\sum_{u=1}^{U}z^a_{rtbu}-\phi^{-1}_{\xi_{\beta_{Ms_{R^a_{rtbu}}}}}\left(1-\beta_{Ms_{R^a_{rtbu}}}\right)\leq 0 \quad \forall a,rt,b,u & (12.23)\\
(1.15)-(1.20). &
\end{cases}
$$

Theorem 7.3 ([36]). *A feasible solution of the EVM as presented in model* (P_5) *possesses the following characteristics:*

- *is an optimal solution for the compromise model* (P_{11}) *if and only if it is Pareto optimal for the multi objective model* (P_5).
- *It stands as a Pareto optimal solution for the multi objective model* (P_5) *if and only if is an optimal solution for the compromise model* (P_{11}).
- *A similar theorem can be readily established for the multi-objective model* (P_6) *and the compromise model* (P_{12}).

8. Numerical examples

An eminent fertilizer manufacturing enterprise in Algeria specializes in producing two categories of fertilizers: natural and mineral. The company manages two production facilities ($H = 2$) located at three distribution centers (DC = 3). Additionally, two retailers (RT = 2) strategically serve three different regions, while three customers ($B = 3$) are situated in distinct cities within the nation. The logistics network entails the transportation of fertilizers from the production facilities to customers through distribution centers and retailers. This transportation is facilitated by two types of conveyances ($U = 2$): medium and small trucks. Initiating a transport operation from production facilities h to customers b, routed through distribution centers and retailers, necessitates reserving a specific vehicle u, incurring a predetermined charge. This fixed charge is combined with the direct transportation costs $\theta^1(x^a_{hdcu})$, $\theta^2(y^a_{dcrtu})$, and $\theta^3(z^a_{rtbu})$.

$$\theta^1(x^a_{hdcu}) = \begin{cases} 1 & \text{if } x^a_{hdcu} > 0, \\ 0 & \text{otherwise} \end{cases}$$

$$\theta^2(y^a_{dcrtu}) = \begin{cases} 1 & \text{if } y^a_{dcrtu} > 0, \\ 0 & \text{otherwise} \end{cases}$$

$$\theta^3(z^a_{rtbu}) = \begin{cases} 1 & \text{if } z^a_{rtbu} > 0, \\ 0 & \text{otherwise} \end{cases}$$

$$x^a_{hdcu} \geq 0, \quad y^a_{dcrtu} \geq 0, \quad z^a_{rtbu} \geq 0.$$

The primary aim of the director of the production company is to optimize the overall profit while concurrently minimizing both the required time and the total CO_2 emissions. Parameters like Unit transportation costs, fixed charges, transportation times, supplies at factories, demands at each destination's in three stages, conveyance capacities, budget constraints at destinations, selling prices, CO_2 emissions, purchasing costs, the safety factor, and the desired safety measure are in the context of interval zigzag variables. We consider the profit in euro per ton, fixed-charge are defined in euros for open road, time is measured in hours, CO_2 emissions are quantified in kilograms, and penalty expenses for CO_2 emissions are expressed in euros. The model includes penalty charges, with the company incurring a penalty of $\alpha = 0.2$ euros per kilogram for exceeding 150 quintals (1 quintal = 100 kg) of CO_2 emissions, payable to the government. And we consider the desired safety measure at each stage as follows:

$$[\mathcal{Z}|200, 220, 300|; \mathcal{Z}|250, 255, 300|]$$
$$[\mathcal{Z}|220, 250, 280|; \mathcal{Z}|200, 225, 290|]$$
$$[\mathcal{Z}|260, 270, 310|; \mathcal{Z}|210, 225, 390|].$$

For the formulation and resolution of the models, we utilize two separate soft-computing tools, namely MATLAB and LINGO-17.0. The specified data used for this example are reported in Tables 1–36.

TABLE 1. The amount of the available product at the hth factory for the ath products $[\xi_{a^1_{L_h}}; \xi_{a^1_{R_h}}]$.

h	1	2
$\left[\xi_{A^1_{L_h}}; \xi_{A^1_{R_h}}\right]$	$[\mathcal{Z}\|38, 40, 42\|; \mathcal{Z}\|72, 85, 100\|]$	$[\mathcal{Z}\|29, 30, 31\|; \mathcal{Z}\|50, 90, 110\|]$
$\left[\xi_{A^2_{L_h}}; \xi_{A^2_{R_h}}\right]$	$[\mathcal{Z}\|4, 30, 40\|; \mathcal{Z}\|72, 85, 110\|]$	$[\mathcal{Z}\|38, 40, 42\|; \mathcal{Z}\|68, 70, 72\|]$

TABLE 2. The demand of the bth customer for the ath product $[\xi_{b^1_{L_b}}; \xi_{b^1_{R_b}}]$.

b	1	2	3
$\left[\xi_{b^1_{L_b}}; \xi_{b^1_{R_b}}\right]$	$[\mathcal{Z}\|18, 20, 23\|; \mathcal{Z}\|25, 27, 30\|]$	$[\mathcal{Z}\|17, 18, 19\|; \mathcal{Z}\|25, 35, 65\|]$	$[\mathcal{Z}\|25, 55, 85\|; \mathcal{Z}\|45, 65, 85\|]$
$\left[\xi_{b^2_{L_b}}; \xi_{b^2_{R_b}}\right]$	$[\mathcal{Z}\|16, 40, 45\|; \mathcal{Z}\|25, 50, 65\|]$	$[\mathcal{Z}\|15, 20, 65\|; \mathcal{Z}(40, 50, 75)]$	$[\mathcal{Z}\|15, 20, 65\|; \mathcal{Z}\|25, 45, 85\|]$

TABLE 3. Capacity of uth conveyance to move the product $[\xi_{e_{L_u}}, \xi_{e_{R_u}}]$.

u	1	2
$\left[\xi_{e_{L_u}}; \xi_{e_{R_u}}\right]$	$[\mathcal{Z}\|60, 63\|, 67\|; \mathcal{Z}\|93, 95, 100\|]$	$[\mathcal{Z}\|90, 100, 110\|; \mathcal{Z}\|140, 150, 160\|]$

TABLE 4. The cost for transporting the ath product from the hth factory to the dcth distribution center using the uth conveyance.

$a = 1$	$dc = 1$	$dc = 2$	$dc = 3$
$h = 1$	$[\mathcal{Z}\|8, 9, 16\|;\ \mathcal{Z}\|10, 20, 25\|]$	$[\mathcal{Z}\|2, 12, 13\|;\ \mathcal{Z}\|20, 22, 25\|]$	$[\mathcal{Z}\|12, 14, 26\|;\ \mathcal{Z}\|20, 24, 28\|]$
$h = 2$	$[\mathcal{Z}\|1, 13, 18\|;\ \mathcal{Z}\|10, 13, 23\|]$	$[\mathcal{Z}\|18, 19, 20\|;\ \mathcal{Z}\|19, 20, 21\|]$	$[\mathcal{Z}\|10, 15, 18\|;\ \mathcal{Z}\|13, 15, 28\|]$
$u = 1$			
$a = 2$	$dc = 1$	$dc = 2$	$dc = 3$
$h = 1$	$[\mathcal{Z}\|8, 12, 21\|;\ \mathcal{Z}\|10, 12, 22\|]$	$[\mathcal{Z}\|8, 25, 27\|;\ \mathcal{Z}\|(8, 25, 27\|]$	$[\mathcal{Z}\|10, 15, 17\|;\ \mathcal{Z}\|11, 12, 23\|]$
$h = 2$	$[\mathcal{Z}\|10, 11, 21\|;\ \mathcal{Z}\|13, 14, 27\|]$	$[\mathcal{Z}\|5, 25, 28\|;\ \mathcal{Z}\|9, 25, 30\|]$	$[\mathcal{Z}\|2, 17, 18\|;\ \mathcal{Z}\|14, 16, 30\|]$
$u = 1$			

Table 5. The cost for transporting the ath product from the hth factory to the dcth distribution center using the uth conveyance.

$a=1$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|10,11,14\|;\ \mathcal{Z}\|12,22,27\|]$	$[\mathcal{Z}\|4,14,15\|;\ \mathcal{Z}\|22,24,27\|]$	$[\mathcal{Z}\|14,16,28\|;\ \mathcal{Z}\|23,26,30\|]$
$h=2$	$[\mathcal{Z}\|2,17,20\|;\ \mathcal{Z}\|6,23,25\|]$	$[\mathcal{Z}\|19,20,23\|;\ \mathcal{Z}\|22,25,33\|]$	$[\mathcal{Z}\|12,17,19\|;\ \mathcal{Z}\|23,25,38\|]$
$u=2$			
$a=2$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|18,22,31\|;\ \mathcal{Z}\|20,22,32\|]$	$[\mathcal{Z}\|10,35,37\|;\ \mathcal{Z}\|28,55,57\|]$	$[\mathcal{Z}\|13,17,19\|;\ \mathcal{Z}\|18,22,23\|]$
$h=2$	$[\mathcal{Z}\|6,9,18\|;\ \mathcal{Z}\|3,10,22\|]$	$[\mathcal{Z}\|1,35,38\|;\ \mathcal{Z}\|19,35,40\|]$	$[\mathcal{Z}\|22,27,28\|;\ \mathcal{Z}\|34,36,40\|]$
$u=2$			

Table 6. The cost for transporting the ath product from the dcth distribution center to the rtth retailer using the uth mode of transport.

$a=1$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|5,10,12\|;\ \mathcal{Z}\|15,20,22\|]$	$[\mathcal{Z}\|4,14,16\|;\ \mathcal{Z}\|23,24,27\|]$
$dc=2$	$[\mathcal{Z}\|4,11,14\|;\ \mathcal{Z}\|14,16,20\|]$	$[\mathcal{Z}\|15,19,21\|;\ \mathcal{Z}\|17,19,20\|]$
$dc=3$	$[\mathcal{Z}\|10,15,22\|;\ \mathcal{Z}\|13,27,32\|]$	$[\mathcal{Z}\|10,22,23\|;\ \mathcal{Z}\|20,25,33\|]$
$u=1$		
$a=2$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|5,10,16\|;\ \mathcal{Z}\|12,14,19\|]$	$[\mathcal{Z}\|7,20,22\|;\ \mathcal{Z}\|6,12,17\|]$
$dc=2$	$[\mathcal{Z}\|12,14,17\|;\ \mathcal{Z}\|18,19,22\|]$	$[\mathcal{Z}\|4,19,25\|;\ \mathcal{Z}\|10,17,25\|]$
$dc=3$	$[\mathcal{Z}\|6,8,10\|;\ \mathcal{Z}\|11,14,16\|]$	$[\mathcal{Z}\|13,19,20\|;\ \mathcal{Z}\|16,17,23\|]$
$u=1$		

Table 7. The cost for transporting the ath product from the dcth distribution center to the rtth retailer using the uth mode of transport.

$a=1$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|8,10,13\|;\ \mathcal{Z}\|14,20,25\|]$	$[\mathcal{Z}\|8,12,15\|;\ \mathcal{Z}\|22,24,27\|]$
$dc=2$	$[\mathcal{Z}\|2,37,40\|;\ \mathcal{Z}\|6,33,35\|]$	$[\mathcal{Z}\|29,30,33\|;\ \mathcal{Z}\|42,45,43\|]$
$dc=3$	$[\mathcal{Z}\|4,20,26\|;\ \mathcal{Z}\|4,10,12\|]$	$[\mathcal{Z}\|14,15,20\|;\ \mathcal{Z}\|4,7,10\|]$
$u=2$		
$a=2$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|18,22,31\|;\ \mathcal{Z}\|20,22,32\|]$	$[\mathcal{Z}\|10,35,37\|;\ \mathcal{Z}\|28,55,57\|]$
$dc=2$	$[\mathcal{Z}\|6,9,18\|;\ \mathcal{Z}\|3,10,22\|]$	$[\mathcal{Z}\|1,35,38\|;\ \mathcal{Z}\|19,35,40\|]$
$dc=3$	$[\mathcal{Z}\|6,10,16\|;\ \mathcal{Z}\|2,6,10\|]$	$[\mathcal{Z}\|4,7,9\|;\ \mathcal{Z}\|9,10,12\|]$
$u=2$		

TABLE 8. The cost for transporting the ath product from the rtth retailer to the bth customer using the uth conveyance.

$a=1$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|5,10,12\|,\mathcal{Z}\|15,20,22\|]$	$[\mathcal{Z}\|4,14,16\|,\mathcal{Z}\|23,24,27\|]$	$[\mathcal{Z}\|15,16,19\|,\mathcal{Z}\|19,20,24\|]$
$rt=2$	$[\mathcal{Z}\|4,11,14\|,\mathcal{Z}\|14,16,20\|]$	$[\mathcal{Z}\|15,19,21\|,\mathcal{Z}\|17,19,20\|]$	$[\mathcal{Z}\|12,13,15\|,\mathcal{Z}\|16,17,20\|]$
$u=1$			
$a=2$	$b=1$	$b=2$	$b=3$
$rt=1$	$\mathcal{Z}\|5,10,16\|,\mathcal{Z}\|12,14,19\|$	$\mathcal{Z}\|7,20,22\|,\mathcal{Z}\|6,12,17\|$	$\mathcal{Z}\|12,17,19\|,\mathcal{Z}\|15,19,22\|$
$rt=2$	$\mathcal{Z}\|12,14,17\|,\mathcal{Z}\|18,19,22\|$	$\mathcal{Z}\|4,19,25\|,\mathcal{Z}\|10,17,25\|$	$\mathcal{Z}\|4,12,14\|,\mathcal{Z}\|16,17,20\|$
$u=1$			

TABLE 9. The cost for transporting the ath product from the rtth retailer to the bth customer using the uth conveyance.

$a=1$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|8,10,13\|,\mathcal{Z}\|14,20,25\|]$	$[\mathcal{Z}\|8,12,15\|,\mathcal{Z}\|22,24,27\|]$	$[\mathcal{Z}\|14,16,28\|,\mathcal{Z}\|23,26,30\|]$
$rt=2$	$[\mathcal{Z}\|2,37,40\|,\mathcal{Z}\|6,33,35\|]$	$[\mathcal{Z}\|29,30,33\|,\mathcal{Z}\|42,45,43\|]$	$[\mathcal{Z}\|42,47,49\|,\mathcal{Z}\|43,45,48\|]$
$u=2$			
$a=2$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|18,22,31\|,\mathcal{Z}\|20,22,32\|]$	$[\mathcal{Z}\|10,35,37\|,\mathcal{Z}\|28,55,57\|]$	$[\mathcal{Z}\|13,17,19\|,\mathcal{Z}\|18,22,23\|]$
$rt=2$	$[\mathcal{Z}\|6,9,18\|,\mathcal{Z}\|3,10,22\|]$	$[\mathcal{Z}\|1,35,38\|,\mathcal{Z}\|19,35,40\|]$	$[\mathcal{Z}\|22,27,28\|,\mathcal{Z}\|34,36,40\|]$
$u=2$			

TABLE 10. Fixed charge for transporting the ath product from the hth factory to the dcth distribution center using the uth conveyance.

$a=1$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|2,7,11\|,\mathcal{Z}\|6,9,20\|]$	$[\mathcal{Z}\|5,11,13\|,\mathcal{Z}\|2,14,17\|]$	$[\mathcal{Z}\|11,12,18\|,\mathcal{Z}\|11,29,32\|]$
$h=2$	$[\mathcal{Z}\|1,17,20\|,\mathcal{Z}\|12,19,28\|]$	$[\mathcal{Z}\|14,24,26\|,\mathcal{Z}\|26,27,30\|]$	$[\mathcal{Z}\|11,12,14\|,\mathcal{Z}\|19,20,30\|]$
$u=1$			
$a=2$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|20,28,33\|,\mathcal{Z}\|24,28,36\|]$	$[\mathcal{Z}\|20,39,40\|,\mathcal{Z}\|38,45,47\|]$	$[\mathcal{Z}\|11,12,16\|,\mathcal{Z}\|18,20,29\|]$
$h=2$	$[\mathcal{Z}\|14,16,19\|,\mathcal{Z}\|13,20,33\|]$	$[\mathcal{Z}\|5,9,25\|,\mathcal{Z}\|29,35,60\|]$	$[\mathcal{Z}\|20,26,30\|,\mathcal{Z}\|44,46,60\|]$
$u=1$			

Table 11. Fixed charge for transporting the ath product from the hth factory to the dcth distribution center using the uth conveyance.

$a=1$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|4,6,9\|,\mathcal{Z}\|10,11,12\|]$	$[\mathcal{Z}\|1,2,5\|,\mathcal{Z}\|9,10,15\|]$	$[\mathcal{Z}\|11,12,13\|,\mathcal{Z}\|15,19,20\|]$
$h=2$	$[\mathcal{Z}\|2,4,6\|,\mathcal{Z}\|9,10,11\|]$	$[\mathcal{Z}\|9,10,13\|,\mathcal{Z}\|14,15,19\|]$	$[\mathcal{Z}\|11,12,16\|,\mathcal{Z}\|19,20,24\|]$
$u=2$			
$a=2$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|3,5,7\|,\mathcal{Z}\|9,10,12\|]$	$[\mathcal{Z}\|4,5,7\|,\mathcal{Z}\|8,10,15\|]$	$[\mathcal{Z}\|3,6,8\|,\mathcal{Z}\|9,11,19\|]$
$h=2$	$[\mathcal{Z}\|4,5,8\|,\mathcal{Z}\|9,11,12\|]$	$[\mathcal{Z}\|2,3,7\|,\mathcal{Z}\|8,9,10\|]$	$[\mathcal{Z}\|12,13,15\|,\mathcal{Z}\|17,19,20\|]$
$u=2$			

Table 12. Fixed charge for transporting the ath product from the dcth distribution center to the rtth retailer using the uth conveyance.

$a=1$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|2,4,7\|,\mathcal{Z}\|8,10,12\|]$	$[\mathcal{Z}\|4,14,16\|,\mathcal{Z}\|18,20,22\|]$
$dc=2$	$[\mathcal{Z}\|5,9,11\|,\mathcal{Z}\|16,19,23\|]$	$[\mathcal{Z}\|11,12,14\|,\mathcal{Z}\|16,19,22\|]$
$dc=3$	$[\mathcal{Z}\|6,12,16\|,\mathcal{Z}\|19,22,25\|]$	$[\mathcal{Z}\|10,16,19\|,\mathcal{Z}\|22,25,29\|]$
$u=1$		
$a=2$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|3,4,5\|,\mathcal{Z}\|9,10,12\|]$	$[\mathcal{Z}\|5,6,7\|,\mathcal{Z}\|9,10,11\|]$
$dc=2$	$[\mathcal{Z}\|2,4,7\|,\mathcal{Z}\|8,9,10\|]$	$[\mathcal{Z}\|4,6,9\|,\mathcal{Z}\|10,11,15\|]$
$dc=3$	$[\mathcal{Z}\|2,3,4\|,\mathcal{Z}\|5,6,7\|]$	$[\mathcal{Z}\|2,4,5\|,\mathcal{Z}\|8,9,10\|]$
$u=1$		

Table 13. Fixed charge for transporting the ath product from the dcth distribution center to the rtth retailer using the uth conveyance.

$a=1$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|8,13,18\|,\mathcal{Z}\|7,9,19\|]$	$[\mathcal{Z}\|3,10,17\|,\mathcal{Z}\|10,12,26\|]$
$dc=2$	$[\mathcal{Z}\|6,8,9\|,\mathcal{Z}\|8,20,26\|]$	$[\mathcal{Z}\|1,8,11\|,\mathcal{Z}\|7,12,28\|]$
$dc=3$	$[\mathcal{Z}\|9,17,19\|,\mathcal{Z}\|1,9,17\|]$	$[\mathcal{Z}\|6,10,13\|,\mathcal{Z}\|5,8,9\|]$
$u=2$		
$a=2$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|23,44,52\|,\mathcal{Z}\|29,60,72\|]$	$[\mathcal{Z}\|15,16,17\|,\mathcal{Z}\|10,22,31\|]$
$dc=2$	$[\mathcal{Z}\|4,10,27\|,\mathcal{Z}\|8,19,19\|]$	$[\mathcal{Z}\|5,8,29\|,\mathcal{Z}\|10,11,15\|]$
$dc=3$	$[\mathcal{Z}\|8,10,12\|,\mathcal{Z}\|15,26,30\|]$	$[\mathcal{Z}\|2,4,5\|,\mathcal{Z}\|6,10,20\|]$
$u=2$		

TABLE 14. Fixed charge for transporting the ath product from the rtth retailer to the bth customer using the uth conveyance.

$a=1$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|2,3,4\|,\mathcal{Z}\|5,6,7\|]$	$[\mathcal{Z}\|5,7,8\|,\mathcal{Z}\|9,10,12\|]$	$[\mathcal{Z}\|4,5,7\|,\mathcal{Z}\|9,10,11\|]$
$rt=2$	$[\mathcal{Z}\|5,6,9\|,\mathcal{Z}\|6,7,15\|]$	$[\mathcal{Z}\|2,3,33\|,\mathcal{Z}\|4,5,9\|]$	$[\mathcal{Z}\|2,7,9\|,\mathcal{Z}\|9,12,14\|]$
$u=1$			
$a=2$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|1,2,3\|,\mathcal{Z}\|6,7,9\|]$	$[\mathcal{Z}\|1,5,7\|,\mathcal{Z}\|8,9,17\|]$	$[\mathcal{Z}\|3,7,9\|,\mathcal{Z}\|10,12,13\|]$
$rt=2$	$[\mathcal{Z}\|4,5,8\|,\mathcal{Z}\|10,12,17\|]$	$[\mathcal{Z}\|1,5,8\|,\mathcal{Z}\|9,10,14\|]$	$[\mathcal{Z}\|2,7,8\|,\mathcal{Z}\|10,11,14\|]$
$u=1$			

TABLE 15. Fixed charge for transporting the ath product from the rtth retailer to the bth customer using the uth conveyance.

$a=1$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|15,20,32\|,\mathcal{Z}\|25,60,72\|]$	$[\mathcal{Z}\|14,24,36\|,\mathcal{Z}\|33,44,57\|]$	$[\mathcal{Z}\|25,26,29\|,\mathcal{Z}\|39,50,64\|]$
$rt=2$	$[\mathcal{Z}\|3,9,10\|,\mathcal{Z}\|11,15,19\|]$	$[\mathcal{Z}\|3,11,15\|,\mathcal{Z}\|8,10,15\|]$	$[\mathcal{Z}\|9,11,21\|,\mathcal{Z}\|19,24,60\|]$
$u=2$			
$a=2$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|8,12,20\|,\mathcal{Z}\|11,20,30\|]$	$[\mathcal{Z}\|5,11,30\|,\mathcal{Z}\|4,9,13\|]$	$[\mathcal{Z}\|2,9,10\|,\mathcal{Z}\|12,14,19\|]$
$rt=2$	$[\mathcal{Z}\|8,9,11\|,\mathcal{Z}\|11,13,19\|]$	$[\mathcal{Z}\|3,8,10\|,\mathcal{Z}\|12,14,22\|]$	$[\mathcal{Z}\|3,11,12\|,\mathcal{Z}\|13,15,19\|]$
$u=2$			

TABLE 16. Transportation time from the hth factory to the dcth distribution center using the uth conveyance for the ath product.

$a=1$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|1,2,5\|,\mathcal{Z}\|6,7,10\|]$	$[\mathcal{Z}\|4,5,9\|,\mathcal{Z}\|5,6,10\|]$	$[\mathcal{Z}\|1,2,3\|,\mathcal{Z}\|5,6,9\|]$
$h=2$	$[\mathcal{Z}\|4,9,20\|,\mathcal{Z}\|21,22,24\|]$	$[\mathcal{Z}\|10,12,16\|,\mathcal{Z}\|20,22,25\|]$	$[\mathcal{Z}\|11,12,14\|,\mathcal{Z}\|20,25,30\|]$
$u=1$			
$a=2$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|22,38,33\|,\mathcal{Z}\|54,68,76\|]$	$[\mathcal{Z}\|10,19,20\|,\mathcal{Z}\|18,25,37\|]$	$[\mathcal{Z}\|1,2,6\|,\mathcal{Z}\|8,30,39\|]$
$h=2$	$[\mathcal{Z}\|4,6,9\|,\mathcal{Z}\|33,40,53\|]$	$[\mathcal{Z}\|15,19,22\|,\mathcal{Z}\|9,55,70\|]$	$[\mathcal{Z}\|10,17,34\|,\mathcal{Z}\|55,77,71\|]$
$u=1$			

TABLE 17. Transportation time from the hth factory to the dcth distribution center using the uth conveyance for the ath product.

$a=1$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|12,14,17\|, \mathcal{Z}\|20,21,22\|]$	$[\mathcal{Z}\|11,12,15\|, \mathcal{Z}\|19,30,35\|]$	$[\mathcal{Z}\|1,2,3\|, \mathcal{Z}\|5,9,20\|]$
$h=2$	$[\mathcal{Z}\|2,4,6\|, \mathcal{Z}\|19,40,51\|]$	$[\mathcal{Z}\|19,50,73\|, \mathcal{Z}\|77,95,100\|]$	$[\mathcal{Z}\|1,12,16\|, \mathcal{Z}\|6,60,67\|]$
$u=2$			
$a=2$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|3,5,7\|, \mathcal{Z}\|9,10,12\|]$	$[\mathcal{Z}\|4,5,9\|, \mathcal{Z}\|9,10,15\|]$	$[\mathcal{Z}\|3,6,8\|, \mathcal{Z}\|8,21,29\|]$
$h=2$	$[\mathcal{Z}\|4,5,8\|, \mathcal{Z}\|9,11,12\|]$	$[\mathcal{Z}\|2,3,7\|, \mathcal{Z}\|8,9,10\|]$	$[\mathcal{Z}\|12,13,15\|, \mathcal{Z}\|27,29,30\|]$
$u=2$			

TABLE 18. Transportation time from the dcth distribution center to the rtth retailer using the uth conveyance for the ath product.

$a=1$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|8,9,16\|, \mathcal{Z}\|10,20,25\|]$	$[\mathcal{Z}\|2,12,13\|, \mathcal{Z}\|20,22,25\|]$
$dc=2$	$[\mathcal{Z}\|6,7,11\|, \mathcal{Z}\|15,19,23\|]$	$[\mathcal{Z}\|6,8,9\|, \mathcal{Z}\|15,19,24\|]$
$dc=3$	$[\mathcal{Z}\|12,14,26\|, \mathcal{Z}\|20,24,28\|]$	$[\mathcal{Z}\|10,11,18\|, \mathcal{Z}\|19,25,38\|]$
$u=1$		
$a=2$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|5,8,14\|, \mathcal{Z}\|11,13,24\|]$	$[\mathcal{Z}\|8,20,28\|, \mathcal{Z}\|8,20,28\|]$
$dc=2$	$[\mathcal{Z}\|1,13,18\|, \mathcal{Z}\|10,13,23\|]$	$[\mathcal{Z}\|18,19,20\|, \mathcal{Z}\|19,20,21\|]$
$dc=3$	$[\mathcal{Z}\|10,15,18\|, \mathcal{Z}\|13,15,28\|]$	$[\mathcal{Z}\|3,15,16\|, \mathcal{Z}\|9,12,21\|]$
$u=1$		

TABLE 19. Transportation time from the dcth distribution center to the rtth retailer using the uth conveyance for the ath product.

$a=1$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|8,10,15\|, \mathcal{Z}\|11,13,25\|]$	$[\mathcal{Z}\|8,10,12\|, \mathcal{Z}\|8,10,18\|]$
$dc=2$	$[\mathcal{Z}\|5,7,8\|, \mathcal{Z}\|9,10,11\|]$	$[\mathcal{Z}\|6,7,9\|, \mathcal{Z}\|11,14,19\|]$
$dc=3$	$[\mathcal{Z}\|8,15,20\|, \mathcal{Z}\|16,18,34\|]$	$[\mathcal{Z}\|9,10,11\|, \mathcal{Z}\|12,13,17\|]$
$u=2$		
$a=2$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|8,12,21\|, \mathcal{Z}\|10,12,22\|]$	$[\mathcal{Z}\|8,25,27\|, \mathcal{Z}\|8,25,27\|]$
$dc=2$	$[\mathcal{Z}\|10,11,21\|, \mathcal{Z}\|13,14,26\|]$	$[\mathcal{Z}\|24,26,28\|, \mathcal{Z}\|27,29,30\|]$
$dc=3$	$[\mathcal{Z}\|10,15,17\|, \mathcal{Z}\|11,12,23\|]$	$[\mathcal{Z}\|8,20,22\|, \mathcal{Z}\|10,20,25\|]$
$u=2$		

TABLE 20. Transportation time from the rtth retailer to the bth customer using the uth conveyance for the ath product.

$a=1$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|10,11,21\|,\mathcal{Z}\|13,14,26\|]$	$[\mathcal{Z}\|24,26,28\|,\mathcal{Z}\|27,29,30\|]$	$[\mathcal{Z}\|8,20,22\|,\mathcal{Z}\|10,20,25\|]$
$rt=2$	$[\mathcal{Z}\|10,11,21\|,\mathcal{Z}\|13,14,27\|]$	$[\mathcal{Z}\|5,25,28\|,\mathcal{Z}\|9,25,30\|]$	$[\mathcal{Z}\|2,17,18\|,\mathcal{Z}\|14,16,30\|]$
$u=1$			
$a=2$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|4,14,21\|,\mathcal{Z}\|16,18,34\|]$	$[\mathcal{Z}\|10,11,21\|,\mathcal{Z}\|8,16,20\|]$	$[\mathcal{Z}\|1,17,18\|,\mathcal{Z}\|14,15,29\|]$
$rt=2$	$[\mathcal{Z}\|5,6,10\|,\mathcal{Z}\|5,7,12\|]$	$[\mathcal{Z}\|4,5,10\|,\mathcal{Z}\|5,6,11\|]$	$[\mathcal{Z}\|6,7,10\|,\mathcal{Z}\|9,10,19\|]$
$u=1$			

TABLE 21. Transportation time from the rtth retailer to the bth customer using the uth conveyance for the ath product.

$a=1$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|2,7,11\|,\mathcal{Z}\|6,9,20\|]$	$[\mathcal{Z}\|5,11,13\|,\mathcal{Z}\|2,14,17\|]$	$[\mathcal{Z}\|11,12,18\|,\mathcal{Z}\|11,29,32\|]$
$h=2$	$[\mathcal{Z}\|1,17,20\|,\mathcal{Z}\|12,19,28\|]$	$[\mathcal{Z}\|14,24,26\|,\mathcal{Z}\|26,27,30\|]$	$[\mathcal{Z}\|11,12,14\|,\mathcal{Z}\|19,20,30\|]$
$u=2$			
$a=2$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|4,8,14\|,\mathcal{Z}\|8,9,17\|]$	$[\mathcal{Z}\|4,5,10\|,\mathcal{Z}\|6,7,13\|]$	$[\mathcal{Z}\|6,8,10\|,\mathcal{Z}\|7,9,16\|]$
$h=2$	$[\mathcal{Z}\|4,7,8\|,\mathcal{Z}\|9,10,11\|]$	$[\mathcal{Z}\|4,5,12\|,\mathcal{Z}\|6,7,13\|]$	$[\mathcal{Z}\|9,11,15\|,\mathcal{Z}\|11,12,22\|]$
$u=2$			

TABLE 22. Carbon emission charge per unit of transportation from the hth factory to the dcth distribution center using the uth conveyance for the ath product.

$a=1$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|11,13,20\|]$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|8,10,17\|]$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|10,11,19\|]$
$h=2$	$[\mathcal{Z}\|5,10,12\|,\mathcal{Z}\|7,17,20\|]$	$[\mathcal{Z}\|7,9,10\|,\mathcal{Z}\|9,10,20\|]$	$[\mathcal{Z}\|2,10,12\|,\mathcal{Z}\|2,19,20\|]$
$u=1$			
$a=2$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|6,10,12\|,\mathcal{Z}\|6,14,16\|]$	$[\mathcal{Z}\|7,8,12\|,\mathcal{Z}\|9,10,14\|]$	$[\mathcal{Z}\|10,12,18\|,\mathcal{Z}\|12,14,20\|]$
$h=2$	$[\mathcal{Z}\|6,10,20\|,\mathcal{Z}\|10,11,23\|]$	$[\mathcal{Z}\|5,6,10\|,\mathcal{Z}\|5,10,13\|]$	$[\mathcal{Z}\|6,10,15\|,\mathcal{Z}\|6,10,19\|]$
$u=1$			

TABLE 23. Carbon emission charge per unit of transportation from the hth factory to the dcth distribution center using the uth conveyance for the ath product.

$a=1$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|10,12,15\|,\mathcal{Z}\|15,19,23\|]$	$[\mathcal{Z}\|12,15,20\|,\mathcal{Z}\|18,20,27\|]$	$[\mathcal{Z}\|17,19,40\|,\mathcal{Z}\|19,21,22\|]$
$h=2$	$[\mathcal{Z}\|5,10,12\|,\mathcal{Z}\|7,17,20\|]$	$[\mathcal{Z}\|16,18,20\|,\mathcal{Z}\|33,39,40\|]$	$[\mathcal{Z}\|32,50,52\|,\mathcal{Z}\|32,39,-0\|]$
$u=2$			
$a=2$	$dc=1$	$dc=2$	$dc=3$
$h=1$	$[\mathcal{Z}\|10,10,22\|,\mathcal{Z}\|18,19,23\|]$	$[\mathcal{Z}\|17,20,32\|,\mathcal{Z}\|29,60,64\|]$	$[\mathcal{Z}\|33,32,38\|,\mathcal{Z}\|32,34,60\|]$
$h=2$	$[\mathcal{Z}\|9,30,50\|,\mathcal{Z}\|50,61,63\|]$	$[\mathcal{Z}\|24,26,40\|,\mathcal{Z}\|35,50,53\|]$	$[\mathcal{Z}\|23,26,45\|,\mathcal{Z}\|33,50,79\|]$
$u=2$			

TABLE 24. Carbon emission charge per unit of transportation from the dcth distribution center to the rtth retailer using the uth conveyance for the ath product.

$a=1$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|4,6,16\|,\mathcal{Z}\|8,9,17\|]$	$[\mathcal{Z}\|4,6,10\|,\mathcal{Z}\|5,7,12\|]$
$dc=2$	$[\mathcal{Z}\|7,10,16\|,\mathcal{Z}\|11,18,19\|]$	$[\mathcal{Z}\|2,7,14\|,\mathcal{Z}\|6,8,16\|]$
$dc=3$	$[\mathcal{Z}\|8,10,15\|,\mathcal{Z}\|10,11,20\|]$	$[\mathcal{Z}\|6,10,13\|,\mathcal{Z}\|9,11,19\|]$
$u=1$		
$a=2$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|6,8,14\|,\mathcal{Z}\|8,10,18\|]$	$[\mathcal{Z}\|5,8,14\|,\mathcal{Z}\|7,9,16\|]$
$dc=2$	$[\mathcal{Z}\|11,13,14\|,\mathcal{Z}\|22,25,28\|]$	$[\mathcal{Z}\|11,13,14\|,\mathcal{Z}\|13,14,16\|]$
$dc=3$	$[\mathcal{Z}\|10,11,20\|,\mathcal{Z}\|10,12,32\|]$	$[\mathcal{Z}\|12,13,16\|,\mathcal{Z}\|22,26,31\|]$
$u=1$		

TABLE 25. Carbon emission charge per unit of transportation from the dcth distribution center to the rtth retailer using the uth conveyance for the ath product.

$a=1$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|10,13,17\|,\mathcal{Z}\|13,18,47\|]$	$[\mathcal{Z}\|22,26,40\|,\mathcal{Z}\|14,18,20\|]$
$dc=2$	$[\mathcal{Z}\|6,9,10\|,\mathcal{Z}\|9,10,11\|]$	$[\mathcal{Z}\|12,19,20\|,\mathcal{Z}\|22,23,27\|]$
$dc=3$	$[\mathcal{Z}\|13,19,22\|,\mathcal{Z}\|9,18,19\|]$	$[\mathcal{Z}\|11,12,14\|,\mathcal{Z}\|6,7,10\|]$
$u=2$		
$a=2$	$rt=1$	$rt=2$
$dc=1$	$[\mathcal{Z}\|5,9,10\|,\mathcal{Z}\|5,9,10\|]$	$[\mathcal{Z}\|11,12,18\|,\mathcal{Z}\|11,18,22\|]$
$dc=2$	$[\mathcal{Z}\|23,25,29\|,\mathcal{Z}\|24,26,27\|]$	$[\mathcal{Z}\|10,12,19\|,\mathcal{Z}\|11,17,20\|]$
$dc=3$	$[\mathcal{Z}\|12,19,20\|,\mathcal{Z}\|30,32,33\|]$	$[\mathcal{Z}\|18,19,23\|,\mathcal{Z}\|10,22,31\|]$
$u=2$		

TABLE 26. Carbon emission charge per unit of transportation from the rtth retailer to the bth customer using the uth conveyance for the ath product.

$a=1$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|11,13,14\|,\mathcal{Z}\|15,17,18\|]$	$[\mathcal{Z}\|8,10,14\|,\mathcal{Z}\|18,21,23\|]$	$[\mathcal{Z}\|10,11,12\|,\mathcal{Z}\|11,13,14\|]$
$rt=2$	$[\mathcal{Z}\|11,13,14\|,\mathcal{Z}\|18,22,24\|]$	$[\mathcal{Z}\|11,13,14\|\mathcal{Z}\|15,18,19\|]$	$[\mathcal{Z}\|11,13,14\|,\mathcal{Z}\|20,22,25\|]$
$u=1$			
$a=2$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|1,6,10\|,\mathcal{Z}\|10,11,14\|]$	$[\mathcal{Z}\|11,13,14\|,\mathcal{Z}\|14,15,20\|]$	$[\mathcal{Z}\|2,9,10\|,\mathcal{Z}\|10,11,14\|]$
$rt=2$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|13,15,20\|]$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|9,14,15\|]$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|10,11,16\|]$
$u=1$			

TABLE 27. Carbon emission charge per unit of transportation from the rtth retailer to the bth customer using the uth conveyance for the ath product.

$a=1$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|11,13,20\|]$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|8,10,17\|]$	$[\mathcal{Z}\|8,9,10\|,\mathcal{Z}\|10,11,19\|]$
$rt=2$	$[\mathcal{Z}\|5,10,12\|,\mathcal{Z}\|7,17,20\|]$	$[\mathcal{Z}\|7,9,10\|,\mathcal{Z}\|9,10,20\|]$	$[\mathcal{Z}\|2,10,12\|,\mathcal{Z}\|2,19,20\|]$
$u=2$			
$a=2$	$b=1$	$b=2$	$b=3$
$rt=1$	$[\mathcal{Z}\|6,10,12\|,\mathcal{Z}\|6,14,16\|]$	$[\mathcal{Z}\|7,8,12\|,\mathcal{Z}\|9,10,14\|]$	$[\mathcal{Z}\|10,12,18\|,\mathcal{Z}\|12,14,20\|]$
$rt=2$	$[\mathcal{Z}\|6,10,20\|,\mathcal{Z}\|10,11,23\|]$	$[\mathcal{Z}\|5,6,10\|,\mathcal{Z}\|5,10,13\|]$	$[\mathcal{Z}\|6,10,15\|,\mathcal{Z}\|6,10,19\|]$
$u=2$			

TABLE 28. Selling price per unit for the ath product at the dcth distribution center.

dc	1	2	3
$\left[\xi_{S^1_{L_{dc}}},\xi_{S^1_{R_{dc}}}\right]$	$[\mathcal{Z}\|22,24,28\|,\mathcal{Z}\|28,29,32\|]$	$[\mathcal{Z}\|22,23,24\|,\mathcal{Z}\|22,32,36\|]$	$[\mathcal{Z}\|22,25,28\|,\mathcal{Z}\|24,26,28\|]$
$\left[\xi_{S^2_{L_{dc}}},\xi_{S^2_{R_{dc}}}\right]$	$[\mathcal{Z}\|21,23,24\|,\mathcal{Z}\|22,24,25\|]$	$[\mathcal{Z}\|20,25,30\|,\mathcal{Z}\|33,35,37\|]$	$[\mathcal{Z}\|20,25,30\|,\mathcal{Z}\|24,26,30\|]$

Table 29. Selling price per unit for the ath product at the rtth retailer.

rt	1	2
$\left[\xi_{S^1_{L_{rt}}}, \xi_{S^1_{R_{rt}}}\right]$	$[\mathcal{Z}\|26, 28, 30\|, \mathcal{Z}\|32, 33, 36\|]$	$[\mathcal{Z}\|24, 26, 28\|, \mathcal{Z}\|24, 34, 38\|]$
$\left[\xi_{S^2_{L_{rt}}}, \xi_{S^2_{R_{rt}}}\right]$	$[\mathcal{Z}\|24, 26, 28\|, \mathcal{Z}\|25, 28, 29\|]$	$[\mathcal{Z}\|30, 35, 40\|, \mathcal{Z}\|37, 39, 40\|]$

Table 30. Selling price per unit for the ath product at the bth customer.

b	1	2
$\left[\xi_{S^1_{L_b}}, \xi_{S^1_{R_b}}\right]$	$[\mathcal{Z}\|32, 37, 40\|, \mathcal{Z}\|36, 38, 39\|]$	$[\mathcal{Z}\|28, 29, 30\|, \mathcal{Z}\|26, 37, 40\|]$
$\left[\xi_{S^2_{L_b}}, \xi_{S^2_{R_b}}\right]$	$[\mathcal{Z}\|28, 30, 34\|, \mathcal{Z}\|39, 40, 43\|]$	$[\mathcal{Z}\|40, 45, 48\|, \mathcal{Z}\|48, 50, 51\|]$

Table 31. The purchasing cost per unit for the ath product at the hth factory.

h	1	2
$\left[\xi_{V^1_{L_h}}, \xi_{V^1_{R_h}}\right]$	$[\mathcal{Z}\|10, 13, 16\|, \mathcal{Z}\|12, 14, 20\|]$	$[\mathcal{Z}\|10, 13, 14\|, \mathcal{Z}\|12, 18, 20\|]$
$\left[\xi_{V^2_{L_h}}, \xi_{V^2_{R_h}}\right]$	$[\mathcal{Z}\|2, 14, 15\|, \mathcal{Z}\|8, 19, 20\|]$	$[\mathcal{Z}\|8, 12, 15\|, \mathcal{Z}\|11, 20, 25\|]$

Table 32. The purchasing cost for the ath product at the dcth distribution center.

dc	1	2	3
$\left[\xi_{V^1_{L_{dc}}}, \xi_{V^1_{R_{dc}}}\right]$	$[\mathcal{Z}\|16, 19, 21\|, \mathcal{Z}\|22, 24, 30\|]$	$[\mathcal{Z}\|9, 10, 11\|, \mathcal{Z}\|11, 15, 19\|]$	$[\mathcal{Z}\|7, 11, 15\|, \mathcal{Z}\|11, 19, 29\|]$
$\left[\xi_{V^2_{L_{dc}}}, \xi_{V^2_{R_{dc}}}\right]$	$[\mathcal{Z}\|6, 9, 22\|, \mathcal{Z}\|22, 25, 29\|]$	$[\mathcal{Z}\|10, 19, 22\|, \mathcal{Z}\|23, 26, 29\|]$	$[\mathcal{Z}\|9, 16, 19\|, \mathcal{Z}\|32, 34, 40\|]$

Table 33. Purchasing cost for the ath product at the rtth retailer.

rt	1	2
$\left[\xi_{V^1_{L_{rt}}}, \xi_{V^1_{R_{rt}}}\right]$	$[\mathcal{Z}\|11, 14, 19\|, \mathcal{Z}\|22, 24, 30\|]$	$[\mathcal{Z}\|17, 19, 22\|, \mathcal{Z}\|22, 23, 29\|]$
$\left[\xi_{V^2_{L_{rt}}}, \xi_{V^2_{R_{rt}}}\right]$	$[\mathcal{Z}\|7, 19, 22\|, \mathcal{Z}\|25, 30, 34\|]$	$[\mathcal{Z}\|10, 13, 14\|, \mathcal{Z}\|21, 28, 30\|]$

TABLE 34. Budget availability at dcth distribution centers.

Bg_1	$[\mathcal{Z}\|1980, 2000, 2020\|, \mathcal{Z}\|1990, 2000, 2010\|]$
Bg_2	$[\mathcal{Z}\|1400, 1500, 1600\|, \mathcal{Z}\|1300, 1500, 1700\|]$
Bg_3	$[\mathcal{Z}\|2000, 2500, 3000\|, \mathcal{Z}\|2400, 2500, 2600\|]$

TABLE 35. Budget availability at rtth retailers.

Bg_1	$[\mathcal{Z}\|2000, 2000, 2010\|, \mathcal{Z}\|2100, 2200, 2300\|]$
Bg_2	$[\mathcal{Z}\|1200, 1700, 1900\|, \mathcal{Z}\|1900, 1950, 2000\|]$

TABLE 36. Budget availability at bth customers.

Bg_1	$[\mathcal{Z}\|1500, 1600, 19000\|, \mathcal{Z}\|1960, 1990, 2000\|]$
Bg_2	$[\mathcal{Z}\|1100, 1200, 1200\|, \mathcal{Z}\|1300, 1450, 1500\|]$

TABLE 37. Optimal results obtained by the Expected Value Model (EVM) and Chance Constrained Model (CCM) for uncertain variables using the Weighted Sum Method.

Weights			EVM			CCM					
						cl_1			cl_2		
λ_1	λ_2	λ_3	$E[Z_1]$	$E[Z_2]$	$E[Z_3]$	Z_1	Z_2	Z_3	Z_1	Z_2	Z_3
0.4	0.4	0.2	[269, 1.1351]	[33, 58]	[72.5, 100]	[275, 1165]	[31, 70]	[70, 100]	[215, 1000]	[30, 40]	[70, 80]
0.2	0.4	0.4	[269, 1.1351]	[33, 58]	[72.5, 100]	[270, 1160]	[30, 90]	[75, 80]	[95, 1025]	[30, 40]	[70, 80]
0.4	0.2	0.4	[269, 1.1351]	[33, 58]	[72.5, 100]	[270, 1160]	[30, 90]	[75, 80]	[85, 1005]	[25, 30]	[70, 75]
0.5	0.25	0.25	[269, 1.1351]	[33, 58]	[72.5, 100]	[270, 1160]	[30, 90]	[75, 90]	[95, 1025]	[30, 40]	[70, 80]
0.25	0.5	0.25	[269, 1.1351]	[33, 58]	[72.5, 100]	[270, 1025]	[30, 90]	[75, 80]	[95, 1025]	[30, 40]	[70, 80]
0.25	0.25	0.5	[269, 1.1351]	[33, 58]	[72.5, 100]	[270, 1160]	[30, 90]	[75, 80]	[95, 10250]	[30, 40]	[70, 90]
0.1	0.1	0.8	[225, 1175]	[29.8, 60.8]	[75.3, 100]	[270, 1160]	[30, 90]	[75, 80]	[95, 1025]	[30, 40]	[70, 80]
0.1	0.8	0.1	[225, 1175]	[29.8, 60.8]	[75.3, 100]	[225, 1175]	[49, 58]	[70, 110]	[85, 1005]	[25, 30]	[70, 75]
0.8	0.1	0.1	[225, 1175]	[29.8, 60.8]	[75.3, 100]	[225, 1175]	[49, 58]	[70, 110]	[85, 1005]	[25, 30]	[70, 75]

Table 38. Results obtained by the EVM.

Name of method	Z^1	Z^2	Z^3
Weighted Sum Method	$[269, 1135]$,	$[30, 55]$,	$[73, 125]$
Fuzzy Programming Method	$[269, 1135]$,	$[30, 55]$,	$[73, 125]$
Goal Programming Method	$[223, 970]$,	$[32, 59]$,	$[75, 130]$

Table 39. Results obtained by CCM class 1.

Name of method	Z^1	Z^2	Z^3
Weighted Sum Method	$[224, 782]$,	$[36, 59]$,	$[73, 125]$
Fuzzy Programming Method	$[285, 1032]$,	$[36, 55]$,	$[72, 75]$
Goal Programming Method	$[285, 1032]$,	$[36, 55]$,	$[72, 75]$

9. Results and discussion

In this section, we present the results obtained from both models:

- EVM.
- CCM.

Subsequently, deterministic models were solved using three distinct methodologies:

- Linear Weighted method.
- Fuzzy Programming.
- Goal Programming.

Results for EVM and CCM, along with their corresponding transportation plans, are provided. In the case of CCM, cl_1 includes chance levels from 0 to 0.5, while cl_2 includes chance levels from 0.5 to 1.

For cl_1, chance level values are set as:

$$\begin{aligned}&\forall a, h, dc, rt, b, u, \quad \alpha_1 = \alpha_2 = \alpha_3 = 0.4;\\&\beta_{a^a_{L_h}} = \beta_{b^a_{L_h}} = \beta_{b^a_{R_h}} = \beta_{e^1_{L_u}} = \beta_{e^1_{R_u}} = \beta_{e^2_{L_u}} = \beta_{e^2_{R_u}} = \beta_{e^3_{L_u}} = \beta_{e^3_{R_u}} = \beta_{Ms_{L^a_{hdcu}}} = \beta_{Ms_{R^a_{hdcu}}} = \beta_{Ms_{L^a_{dcrtu}}}\\&= \beta_{Ms_{R^a_{dcrtu}}} = \beta_{Ms_{L^a_{rtbu}}} = \beta_{Ms_{R^a_{rtbu}}} = \beta_{Bg_{dc}} = \beta_{Bg_{rt}} = \beta_{Bg_b} = 0.45.\end{aligned}$$

For cl_2, chance level values are set as:

$$\begin{aligned}&\forall a, h, dc, rt, b, u, \quad \alpha_1 = \alpha_2 = \alpha_3 = 0.8;\\&\beta_{a^a_{L_h}} = \beta_{b^a_{L_h}} = \beta_{b^a_{R_h}} = \beta_{e^1_{L_u}} = \beta_{e^1_{R_u}} = \beta_{e^2_{L_u}} = \beta_{e^2_{R_u}} = \beta_{e^3_{L_u}} = \beta_{e^3_{R_u}} = \beta_{Ms_{L^a_{hdcu}}} = \beta_{Ms_{R^a_{hdcu}}} = \beta_{Ms_{L^a_{dcrtu}}}\\&= \beta_{Ms_{R^a_{dcrtu}}} = \beta_{Ms_{L^a_{rtbu}}} = \beta_{Ms_{R^a_{rtbu}}} = \beta_{Bg_{dc}} = \beta_{Bg_{rt}} = \beta_{Bg_b} = 0.85.\end{aligned}$$

The Weighted Sum Method results for the EVM and CCM using varied weights λ_1, λ_2, and λ_3 are summarized in Table 37. Optimal values for EVM and CCM vary according to specified λ_1, λ_2, and λ_3 values, reflecting adaptation to decision-maker preferences. Notably, results from EVM and CCM remain non-dominated, highlighting the impact of diverse weight configurations.

Tables 38–41 present the results of the deterministic equivalent of the EVM and CCM employing three methodologies (Weighted Sum Method, fuzzy programming, and goal programming). For the Weighted Sum Method, λ_1, λ_2, and λ_3 remain constant.

TABLE 40. Results obtained by CCM class 2.

Name of method	Z^1	Z^2	Z^3
Weighted Sum Method	$[85, 1005]$,	$[25, 30]$,	$[70, 75]$
Fuzzy Programming Method	$[85, 1005]$,	$[25, 30]$,	$[70, 75]$
Goal Programming Method	$[85, 1005]$,	$[25, 30]$,	$[70, 75]$

TABLE 41. Results obtained by the CCM for zigzag uncertain variables.

Chance levels			Zigzag uncertain variables		
			Objective values of model		
α_1	α_2	α_3	Z_1	Z_2	Z_3
0.1	0.1	0.1	$[300, 1165]$	$[40, 70]$	$[75, 100]$
0.2	0.2	0.2	$[275.9, 1175]$	$[45, 60]$	$[70, 110]$
0.3	0.3	0.3	$[195, 1225]$	$[30, 65]$	$[70, 80]$
0.4	0.4	0.4	$[225, 1195]$	$[40, 70]$	$[70, 110]$
0.5	0.5	0.5	$[190, 1220]$	$[40, 70]$	$[70, 100]$
0.6	0.6	0.6	$[185, 1215]$	$[60, 70]$	$[80, 120]$
0.7	0.7	0.7	$[180, 1215]$	$[40, 50]$	$[70, 90]$
0.8	0.8	0.8	$[115, 1065]$	$[25, 40]$	$[70, 75]$
0.9	0.9	0.9	$[75, 933]$	$[20, 30]$	$[65, 75]$

Table 38 presents EVM results. The fuzzy method and the weighted sum method produce same non-dominated solutions, both are different from the goal programming method.

Table 39 presents results for CCM cl_1. In this case, the fuzzy method and the goal programming method produce same solutions, which are not dominated by the solutions from the weighted sum method.

Table 40 presents results for cl_2 and emphasizes that solutions generated by these three methods are the same.

Across Tables 38–40, the linear weighted method shows better computational efficiency relative to fuzzy programming and goal programming for both EVM and CCM. It provides solutions that are in harmony with the decision-maker's preferences.

In conclusion, based on the data in Tables 37–40, an increase in transportation time is likely to associate with higher pollution levels. It is essential to find a balance between the need to minimize transport costs for financial gain and the need to consider environmental concerns to optimize profits while implementing pollution control measures in the context of transport issues. This requires strategic decision-making to maximize economic benefits while ensuring responsible and sustainable practices in the transport sector.

10. Sensitivity analysis

Sensitivity analysis is essential for understanding the consequences of changing the coefficients of objective functions in optimization problems. Table 41 shows the results of sensitivity analysis for CCM, using the linear weighted sum. The same values are assigned to λ_1, λ_2, and λ_3, and varying the chance levels α_1, α_2, and α_3.

When α_1, α_2, and α_3 are in the interval $[0, 0.5]$, the other parameters are fixed:

$$\beta_{a^a_{L_h}} = \beta_{b^a_{L_h}} = \beta_{b^a_{R_h}} = \beta_{e^1_{L_u}} = \beta_{e^1_{R_u}} = \beta_{e^2_{L_u}} = \beta_{e^2_{R_u}} = \beta_{e^3_{L_u}} = \beta_{e^3_{R_u}} = \beta_{Ms_{L^a_{hdcu}}} = \beta_{Ms_{R^a_{hdcu}}} = \beta_{Ms_{L^a_{dcrtu}}}$$
$$= \beta_{Ms_{R^a_{dcrtu}}} = \beta_{Ms_{L^a_{rtbu}}} = \beta_{Ms_{R^a_{rtbu}}} = \beta_{Bg_{dc}} = \beta_{Bg_{rt}} = \beta_{Bg_b} = 0.45 \text{ for all } h, dc, rt, b, u, a.$$

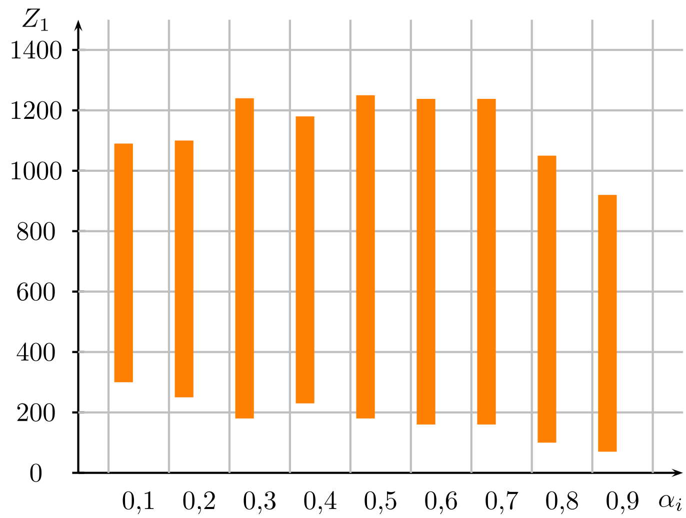

FIGURE 1. The chance constrained model (CCM) at various chance levels α_1, α_2, α_3 concerning Z_1.

When α_1, α_2, and α_3 are in the interval $(0.5, 1]$, the other parameters are fixed:

$$\beta_{a^a_{L_h}} = \beta_{b^a_{L_h}} = \beta_{b^a_{R_h}} = \beta_{e^1_{L_u}} = \beta_{e^1_{R_u}} = \beta_{e^2_{L_u}} = \beta_{e^2_{R_u}} = \beta_{e^3_{L_u}} = \beta_{e^3_{R_u}} = \beta_{Ms_{L^a_{hdcu}}} = \beta_{Ms_{R^a_{hdcu}}} = \beta_{Ms_{L^a_{dcrtu}}}$$
$$= \beta_{Ms_{R^a_{dcrtu}}} = \beta_{Ms_{L^a_{rtbu}}} = \beta_{Ms_{R^a_{rtbu}}} = \beta_{Bg_{dc}} = \beta_{Bg_{rt}} = \beta_{Bg_b} = 0.85 \text{ for all } h, dc, rt, b, u, a.$$

Table 38 shows the difference between optimal solutions, which are not dominated by each other. The considerable impact of parameter values on the quality of solutions underlines the importance of sensitivity analysis in guiding well-informed decision-making.

Obviously, the values assigned to the parameters have a considerable influence on the quality of the model's solutions. Consequently, the implementation of a sensitivity analysis becomes imperative for decision-makers in their decision processes. In both models, as the values of α_1, α_2 and α_3 increase, the stability of Z_1 (to be maximized) is generally observed, though with a small decrease. Conversely, the values of Z_2 and Z_3 (to be minimized) decrease as these parameters increase.

To illustrate this relationship visually, Figures 1–3 graphically show the variations in Z_1, Z_2, and Z_3 across different α_1, α_2, and α_3 values, respectively.

11. Conclusion and future research scopes

The proposed model introduces an innovative approach to addressing complex challenges in transportation systems globally. It integrates uncertain interval programming into a multi-stage, multi-objective framework tailored for robust transport logistics. The model stands out by simultaneously optimizing profit, time efficiency, and environmental impact, specifically carbon emissions' reduction. It incorporates budgetary constraints and safety considerations, aligning with real-world practicalities for transportation planners. Notably, the model's ability to manage uncertainty, including weather fluctuations and unexpected incidents, makes it a valuable tool for risk evaluation and mitigation. Emphasizing sustainability, the model supports environmentally-friendly practices in supply chain management, contributing to global sustainable development goals and compliance with environmental regulations. As a robust decision support system, it provides actionable insights by elucidating trade-offs among objectives, facilitating informed decision-making across diverse industries. The model

Figure 2. The CCM at various chance levels α_1, α_2, α_3 concerning Z_2.

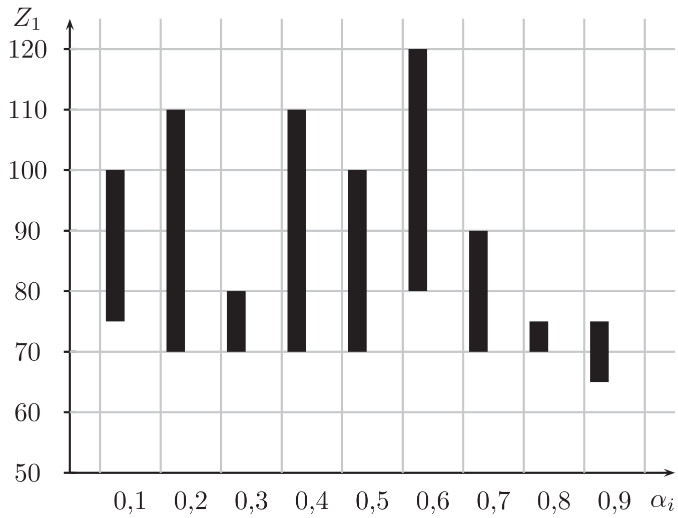

Figure 3. The CCM at various chance levels α_1, α_2, α_3 concerning Z_3.

represents a significant advancement in creating resilient, efficient, and sustainable transportation systems, offering a transformative approach to complex challenges in various sectors.

This research formulates and resolves two distinctive models: the EVM and the CCM. Employing varied solution techniques, including the Linear Weighted method, fuzzy programming, and goal programming, the study investigates the efficacy of these models. A thorough assessment is performed using a comprehensive numerical example, and the results are rigorously compared. Additionally, a sensitivity analysis is conducted to discern and interpret the implications of changes in objective function coefficients.

In the context of this study, several limitations have been identified, each suggesting specific avenues for future research. Firstly, given the absence of real scenario data, a potential future direction would involve developing a comprehensive documentation system that integrates real-time data, potentially utilizing IoT devices and exploring blockchain technology for secure and transparent data management. Concerning algorithms specifically designed for small instances, a relevant future orientation would be to work on improving their scalability to larger instances, focusing on advances in parallel computing, distributed systems, and integrating adaptive tuning mechanisms based on machine learning techniques. To extend the study to optimal route selection within the supply chain, a promising future perspective would involve the integration of real-time tracking, predictive analytics, and machine learning algorithms, thereby creating a dynamic model capable of adapting to changing conditions and forecasting potential disruptions.

The model's capacity to address a wide array of applications is truly striking. Whether it's enhancing waste management practices, fine-tuning pharmaceutical distribution, managing the complexities of perishable goods logistics, tackling supplier selection challenges, optimizing inventory control, or delving into portfolio optimization – the model emerges as a versatile powerhouse. The potential implications across various sectors are undeniably exciting. Aligning with future research paths, customization for specific industries through in-depth case studies, collaboration with industry stakeholders, and integrating feedback loops becomes crucial. This approach ensures continuous refinement and relevance in dynamic business environments, making the model not just versatile but also finely tuned to meet the unique demands of specific sectors.

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