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Finding Humanitarian Supply Chain Management Challenges using Uncertain MCDM Methodology

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ABSTRACT

Challenges have emerged for Humanitarian Supply Chain Management (HSCM), a valid and prominent subject today. It primarily focuses on stakeholders, including governments, various non-governmental organisations (NGOs), donors, suppliers, and affected communities. Addressing these challenges enhances disaster response efficiency, resource allocation, and aid delivery. In this work, we have selected several criteria, namely funding, coordination, infrastructure, transparency, logistics, and sustainability. Triangular fuzzy numbers (TFNs) are used as a mathematical tool to handle uncertainty. Data sets are collected from two decision-makers who provide their decisions in linguistic terms, which are then converted into crisp numbers. The weight of the criteria is evaluated using a popular multi-criteria decision-making (MCDM) methodology, specifically the Criteria Importance Through Inter-criteria Correlation (CRITIC) method.

1. Introduction

Humanitarian Supply Chain Management (HSCM) offers an essential role when it comes to delivering relief during emergencies, such as natural disasters, rivalries and pandemics. It encounters different obstacles that impede efficiency and effectiveness. Operations are frequently disrupted by budget limitations, unpredictable demand and infrastructure damage, etc. As coordination among multiple partners, including governments, NGOs, and donor organizations, remains complex, security risks and limited access to disaster-stricken areas further delay relief delivery. Moreover, the limited

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technology and required data management capabilities diminish visibility and real-time decision making in humanitarian logistics. The humanitarian supply chain is crucial for delivering timely aid such as food, water and medicine during emergencies. It helps to save lives and reduce the suffering of people. It ensures efficient use of limited resources and supports coordination among various relief organizations. By enabling real-time tracking and rapid response, it improves the speed and accuracy of aid distribution. It also enhances disaster preparedness and builds community resilience. In addition, it promotes cost-effective and sustainable logistics practices. Thus, the humanitarian supply chain plays a vital role in both immediate relief and long-term recovery efforts.

The above-mentioned facts motivate the construction of this article. In this work, fuzzy sets and fuzzy numbers are taken as mathematical tools. In Particular, Triangular Fuzzy Numbers (TFNs) are used here to identify challenges related to humanitarian supply chain management (HSCM) and an uncertain MCDM methodology is applied. To address the problem of finding criteria weights that consider multiple aspects, here we will apply the MCDM method, namely, the Criteria Importance Through Inter-criteria Correlation (CRITIC) methodology.

1.1 *Motivation of this study*

The primary motivation behind this Humanitarian Supply Chain Management (HSCM) research stems from its significant contributions to protecting lives, alleviating suffering and restoring dignity during and after crises or disasters. There are several reasons to be aware of the HSCM system as follows: Rapid response to any natural and industrial emergency, minimize human suffering, optimization of resources, accountability and transparency, preparedness and resilience, coordination and collaboration, sustainability and long-term recovery, etc. For this reason, we study and evaluate the key criteria for the Humanitarian Supply Chain Management (HSCM) system.

1.2 *Novelties of the work*

The novelties of this work are discussed in this section. The challenges of humanitarian supply chain management (HSCM) are a very demanding and complex subject. The following points indicate the novelty of this work, i.e.,

1. Several challenges are adopted and analysed for Humanitarian Supply Chain Management (HSCM).
2. Various things like funding, coordination, infrastructure, transparency, logistics and sustainability are primarily chosen and elaborately discussed as criteria.
3. The decision-making process is applied to compute the proposed model, namely the CRITIC methodology.
4. Two DMs have been selected to facilitate problem solving by collecting the necessary information.
5. To identify the uncertainty, triangular fuzzy numbers (TFNs) have been considered.

1.3 *Research outline*

Based on the introduction and research motivation, the primary outlines of this paper are represented as follows,

a) To construct the humanitarian supply chain, choose suitable funding, coordination, infrastructure, transparency, logistics and sustainability.

b) Identify the various challenges for finding humanitarian supply chain management and their comparative studies.

c) Create a decision matrix combining criteria and alternatives using Triangular fuzzy numbers (TFN), allowing decision-makers (DMs) to effectively capture and address all forms of ambiguity, uncertainty, and vagueness.

d) Determine the criteria weights using the MCDM method CRITIC. Based on input from decision experts, this step identifies the most important criteria for finding Humanitarian Supply Chain Management.

1.4 *Structure of this study*

This section discusses the total figure of this research. Section 1 explains the introduction and motivation of this study. A brief literature survey of this work is analysed in Section 2. The initials of mathematical tools are explained in Section 3 elaborately. Important criteria selection is shortly expressed in Section 4. The CRITIC based multi-criteria decision making (MCDM) technology is discussed in section 5. The model formulation and data collection are clarified in Section 6. The required numerical illustration and its discussion are laid out in Section 7. Additionally, Section 8 reveals the research implications of this research. Lastly, conclusions and the scope of future research are highlighted in Section 9.

2. Literature survey of this study

This section discusses the literature of this study in detail. First, a detailed discussion on Humanitarian supply chain management, followed by fuzzy set theory and triangular fuzzy numbers in detail. Lastly, discussed the background of the CRITIC based MCDM methodology elaborately.

2.1 *Literature on Humanitarian supply chain management*

Humanitarian Supply Chain Management (HSCM) ensures the efficient flow of goods, services, and information for disaster relief and humanitarian aid. It includes preparedness, response, recovery, and mitigation to support affected populations. Issues like unpredictable demand, infrastructure damage, and funding constraints make HSCM complex. Effective collaboration among NGOs, governments, donors, and logistics providers is very crucial. Innovations like blockchain, AI, and drones improve tracking, delivery, and efficiency. Eco-friendly logistics and long-term resilience are essential for ethical aid distribution. There are many works based on humanitarian supply chain management and some of them are as follows. Kunz, N. et al. [1] proposed a framework of sustainable humanitarian supply chain management (SCM) that can provide more effective performance. Burkart, C. et al. [2] in their work focused on the importance of funding in the humanitarian supply chain interface. YU, D. et al. [3] researched on humanitarian supply chain management and developed a new framework. Anjomshoae, A. et al. [4] provided a literature review and research proposition on the humanitarian supply chain. John, L. et al. [5] critically reviewed and analyzed the major issues that affect humanitarian supply chain management. Paciarotti, C. et al. [6], in their article, focused on standards in humanitarian logistics and supply chain, and also gave a literature review associated with this. Seifert, L. et al. [7] provided a literature review on the management of humanitarian supply chains in response to refugees. A systematic literature review in the field of big data and humanitarian supply chain is provided by Gupta, S. et al. [8] in their paper. Van Wassenhove, L. N. [9] focused on the complexities of managing supply chains in humanitarian settings. John, L. et al. in their article [10] analyze the existing situation to tackle a calamity and suggest some processes to overcome the gaps. More studies on Humanitarian supply chain management are presented in Table 1.

Table 1
Some recent studies on humanitarian supply chain management and their associated data

Authors	Year	Optimization Tools	Application area
[11] Shakibaei, H. et al.	2024	MCDM	Post-disaster HSC using machine learning.
[12] Wang, W. et al.	2024	DEMATEL & MARCOS	HSC analysis integrating with AI-HI
[13] Nain, A. et al.	2024	MCDM	Disaster management of humanitarian operations.
[14] Eligüzel, İ. et al.	2023	Fuzzy MCDM	Humanitarian logistics problems analysis in uncertain environments.
[15] Patil, A. et al.	2022	DEMATEL	Performance measurement HSC during emergency.
[16] Mittal, R. et al.	2023	TOPSIS	Site selection for sustainable warehouse sites.
[17] Kabra, G. et al.	2023	Fuzzy AHP	Analysis of different barriers to information and digital technology adoption in HSC.
[18] Ahmad, M.S. et al.	2024	Delphi & DEMATEL	Determine the key factors for performance measurement of Sustainable HSC.
[19] Büyüközkan, G. et al.	2024	MCDM	Collaboration between MCDM with humanitarian logistics.
[20] Agarwal, S. et al.	2022	BWM	Determine the performance evaluation of humanitarian organizations.
[21] Kabra, G.	2024	DEMATEL	Analysis of critical success criteria of knowledge management on HSC.
This study	2025	CRITIC	Determine the challenges of HSCM.

2.2 *Literature on Fuzzy set theory and Triangular Fuzzy Number*

In 1965 [22], Lotfi A. Zadeh presented fuzzy set theory, a mathematical framework that deals with ambiguity. The concept of uncertainty is very popular these days for statistical and mathematical modelling. This theory is one of the measures of ambiguity in ideologies, which has great relevance within the field of science. We provide some significant key sources on fuzzy set theory, including initial concepts, theories, and examples [23–26]. Further, fuzzy sets are also applied in decision making [27] and differential equations [28].

In this paper, we utilise the Triangular Fuzzy Number (TFN) to achieve a precise representation in uncertain environments throughout the MCDM process. It is demonstrated here that even in an environment of ambiguity, it is possible to exhibit decision-making efficiency under various circumstances and for different reasons. Here, we will discuss some of the research papers that have adopted the concept of TFNs, s.t., Gani, A. N. et al. [29] applied TFNs on fuzzy linear programming problem, Wang, J. et al. [30] applied this fuzzy number in Knowledge management performance evaluation (KMPE) problem, Arora, H. D. et al. [31] measured the distance for TFNs under technique for order of preference with the help of similarity to ideal solution environment, Shanthini, C. [32] applied a new operation with triangular fuzzy number, Dhurai, K. et al. [33] used a new pivotal operation on TFN for solving fully fuzzy linear programming problems. Mukherjee, A. K. et al. [34] provided a detailed analysis of arithmetic operations based on the $\alpha-$cut method. Wang, F. [35] utilized TFNs in a multi-attribute group decision making problem.

Suvetha, R. et al. [36] invented an inventory model in power-pattern demand utilization and Limi, A. et al. [37] applied another inventory model in non-instantaneous decay items with a price-driven demand model. Furthermore, Suvetha, R. et al. [38, 39] developed two inventory models within a circular economy framework and an economic production quantity (EPQ) environment, respectively.

2.3 *Literature on Multi-Criterion Decision Making (MCDM) method*

Multi-criteria decision-making (MCDM) is one of the essential decision-making problems which aims to address the perfect decision by selecting more than one criterion in the overall selection process. This decision-making system has various techniques and procedures for evaluating, comparing and prioritizing various alternatives to create the best possible decision by finding out the weight of each criteria. There exist different processes for solving MCDM, such as AHP [40], TOPSIS [41], CRITIC [42], Entropy [43], ELECTRE [44], COPRAS [45], WASPAS [46], CoCoSo [47], MOORA [48], VIKOR [49], DEMATEL [50], etc. These MCDM techniques are crucial in informing decision-makers to handle complex situations by helping them make informed decisions, improving the criteria selected, and enhancing the choice of alternatives and the flexibility and transparency of the process. The decision making process is applicable in different fields, including business, engineering, healthcare and environmental management, where complex decisions require computing multiple factors. This is already used in the location selection of shopping mall [51], site selection for a sustainable health care center in Saudi Arabia [52], location selection for girl's hostel in an educational institute [53], measure the pollution attribute [54], consider the risk factor for COVID-19 [55] etc.

In our study, we will employ the CRITIC method; therefore, we will briefly discuss some applications of this method. The CRITIC method is a mathematical technique that is used for the purpose of finding the weight of each criterion. This methodology was proposed by Diakoulaki et al. [56]in 1995. This is a powerful tool for identifying objective weights in the MCDM problem where multiple conflicting criteria are used for decision-making. This technique is applied to research on various areas of daily life problems. Saraji, M. K. et al. [57] employed the CRITIC method in their work to evaluate challenges to Industry 4.0 adoption for a sustainable digital transformation. Ahmadsaraei, M. S. et al. [58] applied the CRITIC method in their paper to develop a framework for evaluating the sustainable supply chain risk management in the food packaging industry. This method is also used by Saraji, M.K. et al. [59] for evaluating the hurdles to constructing business model innovation for sustainability. Akram, M. et al. [60] attempted to develop a model that combines both the CRITIC and REGIME methods for decision-making using Pythagorean fuzzy rough numbers. Krishnan, A. R. et al. [61] modified the CRITIC method to estimate the objective weights of decision criteria. Zhang, Q. et al. [62] proposed a CRITID method which enhances the CRITIC method with advanced independence testing for robust MCDM. Zhong, S. et al. [63] used the improved CRITIC method to evaluate thermal coal suppliers. Wang, S. et al. [64] associate the GRP and CRITIC method to select a site for hospital construction. The D-CRITIC method in a spherical fuzzy environment is used by Zhang, H. et al. [65] to select a location for establishing charging stations for electric vehicles. Yang, X. et al. [66] applied the CRITIC method and developed a framework in a study of tourism development for tourist satisfaction. Nguyen, T. K. L. et al. [67] applied the CRITIC method and Grey system theory in the study of global electric cars. Shi, H. et al. [68] employed the CRITIC method for a comprehensive evaluation of power quality in microgrids.

3. Preliminaries

In this section, we will discuss the initial concept of fuzzy sets and their extensions. In our study, we utilise the Triangular Fuzzy Number (TFN) to account for the uncertainty and vagueness inherent in the model.

3.1 Fuzzy set

The initial concept of fuzzy sets was first developed by Lotfi A. Zadeh [22] in 1965. The generalization of the classical set is known as the Fuzzy set, where the concept of partial membership of an element in a set is considered. In real-world problems, uncertainty is often incorporated, and fuzzy sets prove to be very effective in dealing with such uncertainty.

Definition 1. ***Fuzzy Set***
Let $\mathscr{X}$ be the universe of discourse. A fuzzy set [69] $\tilde{\mathscr{F}}$ on $\mathscr{X}$ can be defined as follows,

$$\tilde{\mathscr{F}} = \{(\gamma, \mu_{\tilde{\mathscr{F}}}(\gamma)) : \gamma \in \mathscr{X}\} \tag{1}$$

i.e,

$$\tilde{\mathscr{F}} = \left\{ \frac{\mu_{\tilde{\mathscr{F}}}(\gamma)}{\gamma} : \gamma \in \mathscr{X} \right\} \tag{2}$$

where $\mu_{\tilde{\mathscr{F}}}(\gamma) : \mathscr{X} \rightarrow [0, 1]$, represents the membership function corresponding to the fuzzy set $\tilde{\mathscr{F}}$.

Example 1. *Suppose $\mathscr{X} = \{\frac{-1}{5}, 0, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}, 1\}$ be the universal set. Let $\tilde{\mathcal{F}}$ be a fuzzy set having numbers that are closer to 0 and $\mu_{\tilde{\mathcal{F}}}(\gamma) : \mathscr{X} \rightarrow [0, 1]$, is the corresponding membership function. Then, we take the membership values as $\mu_{\tilde{\mathcal{F}}}(-\frac{1}{5}) = 0.2$, $\mu_{\tilde{\mathcal{F}}}(0) = 1$, $\mu_{\tilde{\mathcal{F}}}(\frac{1}{8}) = 0.13$, $\mu_{\tilde{\mathcal{F}}}(\frac{1}{4}) = 0.25$, $\mu_{\tilde{\mathcal{F}}}(\frac{1}{2}) = 0.5$, $\mu_{\tilde{\mathcal{F}}}(1) = 0.1$. Then $\tilde{\mathcal{F}}$ can be represented as,*

$$\tilde{\mathcal{F}} = \left\{ \left(\frac{-1}{5}, 0.2\right), (0, 1), \left(\frac{1}{8}, 0.13\right), \left(\frac{1}{4}, 0.25\right), \left(\frac{1}{2}, 0.5\right), (1, 0.1) \right\}$$

Definition 2. ***α-cut Set & Strong α-cut Set***
Let $\tilde{\mathscr{F}}$ be a fuzzy set defined on the universe of discourse $\mathscr{X}$. A α-cut Set [34] of the fuzzy set $\tilde{\mathscr{F}}$ is symbolized as $\tilde{\mathscr{F}}_\alpha$. The α-cut set $\tilde{\mathscr{F}}_\alpha$ is basically a crisp set, having those elements $\gamma \in \mathscr{X}$ for which the membership function $\mu_{\tilde{\mathscr{F}}_\alpha}(\gamma) \geq \alpha$ and $\alpha \in [0, 1]$.
A α-cut Set of the fuzzy set $\tilde{\mathscr{F}}$ can be expressed as,

$$\tilde{\mathscr{F}}_\alpha = \{\gamma : \mu_{\tilde{\mathscr{F}}_\alpha}(\gamma) \geq \alpha\} \tag{3}$$

In particular, if the values of the membership function $\mu_{\tilde{\mathscr{F}}_\alpha}(\gamma)$ corresponding to the fuzzy set $\tilde{\mathscr{F}}_\alpha$ possess the values that are strictly greater than α, then that fuzzy set is known as the Strong α-cut fuzzy set and symbolized as $\tilde{\mathscr{F}}''_\alpha$. Mathematically, it can be defined as,

$$\tilde{\mathscr{F}}''_\alpha = \{\gamma : \mu_{\tilde{\mathscr{F}}_\alpha}(\gamma) > \alpha\} \tag{4}$$

Definition 3. ***Fuzzy Number***
A fuzzy number [70] $\tilde{\mathscr{F}}$ is basically a fuzzy set having four properties, discussed as follows,

(i) *$\tilde{\mathscr{F}}$ is a normalized fuzzy set. That means there exists some $\gamma \in \mathscr{X}$ for which $\mu_{\tilde{\mathscr{F}}}(\gamma) = 1$ holds.*

(ii) *$\tilde{\mathscr{F}}$ is a convex fuzzy set i.e, $\mu_{\tilde{\mathscr{F}}}(\kappa\gamma_1 + (1-\kappa)\gamma_2) \geq \min\{\mu_{\tilde{\mathscr{F}}}(\gamma_1), \mu_{\tilde{\mathscr{F}}}(\gamma_2)\}$ holds, $\forall \gamma_1, \gamma_2 \in \tilde{\mathscr{F}}$ and $\kappa \in [0,1]$.*

(iii) *The Support of $\tilde{\mathscr{F}}$ must be bounded.*

(iv) *The fuzzy set $\tilde{\mathscr{F}}$ must have a piecewise continuous membership function.*

3.2 Triangular Fuzzy Number (TFN)

There are many extensions of fuzzy numbers. The Triangular Fuzzy Number (TFN) is one such extension. As the membership function represents a triangular shape, that is the reason behind calling it TFN. TFNs are very useful due to their simplicity and flexibility. The definition and properties of Triangular Fuzzy Number (TFN) are discussed as follows:

Definition 4. ***Triangular Fuzzy Number***
A fuzzy number $\tilde{\mathscr{E}} = (\tau_1, \tau_2, \tau_3)$ is known as a Triangular Fuzzy Number, if it's membership function $\mu_{\tilde{\mathscr{E}}}(\gamma)$ is represented as follows,

$$\mu_{\tilde{\mathscr{E}}}(\gamma) = \begin{cases} \frac{\gamma-\tau_1}{\tau_2-\tau_1} & , \quad \text{if } \tau_1 \leq \gamma \leq \tau_2 \\ \frac{\tau_3-\gamma}{\tau_3-\tau_2} & , \quad \text{if } \tau_2 \leq \gamma \leq \tau_3 \\ 0 & , \quad \text{otherwise} \end{cases} \tag{5}$$

where $\tau_1, \tau_2, \tau_3 \in \mathbb{R}$ and $\tau_1 \leq \tau_2 \leq \tau_3$.

Definition 5. ***Positive Triangular Fuzzy Number (TFN)***
If all components of a triangular fuzzy number $\tilde{\mathscr{E}} = (\tau_1, \tau_2, \tau_3)$ are positive, then it is known as Positive Triangular Fuzzy Number [34] i.e, $\tau_i > 0$, for $i = 1, 2, 3$.

Definition 6. ***Negative Triangular Fuzzy Number (TFN)***
A triangular fuzzy number $\tilde{\mathscr{E}} = (\tau_1, \tau_2, \tau_3)$ is called a negative Triangular Fuzzy Number [34] if it's all components are negative, i.e, for $i = 1, 2, 3$, $\tau_i < 0$.

Definition 7. ***Partial Negative Triangular Fuzzy Number (TFN)***
A triangular fuzzy number $\tilde{\mathscr{E}} = (\tau_1, \tau_2, \tau_3)$ is called a partial negative Triangular Fuzzy Number [34] if $\tau_1 < 0 \,\&\, \tau_3 > 0$ holds.

Previously, we have defined the $\alpha-$cut set and here we will show how the $\alpha-$cut of a Triangular fuzzy number is defined.

Definition 8. ***α-cut of Triangular Fuzzy Number (TFN)***
Let $\tilde{\mathscr{E}} = (\tau_1, \tau_2, \tau_3)$ be a TFN, then it's membership function $\mu_{\tilde{\mathscr{E}}}(\gamma)$ is given as follows,

$$\mu_{\tilde{\mathscr{E}}}(\gamma) = \begin{cases} \frac{\gamma-\tau_1}{\tau_2-\tau_1} & , \quad \text{if } \tau_1 \leq \gamma \leq \tau_2 \\ \frac{\tau_3-\gamma}{\tau_3-\tau_2} & , \quad \text{if } \tau_2 \leq \gamma \leq \tau_3 \\ 0 & , \quad \text{otherwise} \end{cases} \tag{6}$$

Then the α-cut of $\tilde{\mathscr{E}}$ is a crisp subset of $\mathbb{R}$ and it is defined as,

$$\tilde{\mathscr{E}}_\alpha = [(\tau_2 - \tau_1)\alpha + \tau_1, -(\tau_3 - \tau_2)\alpha + \tau_3] \tag{7}$$

where $\alpha \in [0, 1]$.

Example 2. *Let $\tilde{\mathscr{E}} = (2, 5, 8)$ be a Triangular Fuzzy Number (TFN). Then the α-cut of this TFN is given as, $\tilde{\mathscr{E}} = [(5-2)\alpha + 2, -(8-5)\alpha + 8]$, $\alpha \in [0, 1]$*
So, $\tilde{\mathscr{E}} = [3\alpha + 2, -3\alpha + 8]$, $\alpha \in [0, 1]$.

3.3 *Some advantages of using Triangular Fuzzy Number (TFN)*

There are several advantages to using Triangular Fuzzy Numbers to address uncertainty that arises during a process. Some of them are given as follows:

(i) Due to only three parameters appearing for representing a Triangular Fuzzy Number (TFN), it becomes very simple to use and understand.

(ii) Triangular Fuzzy Numbers become very useful to tackle uncertainty.

(iii) Triangular Fuzzy Numbers are very useful in the decision-making process as they allow decision experts to express their opinions with flexibility.

3.4 *Some Initial Arithmetic Operations of Triangular Fuzzy Number (TFN):*

The arithmetic operations of Triangular Fuzzy Numbers (TFN) using α-cut approach is described as follows, Let $\tilde{\mathscr{E}}_1 = (\tau_1, \tau_2, \tau_3)$ and $\tilde{\mathscr{E}}_2 = (\delta_1, \delta_2, \delta_3)$ be two TFNs having membership function $\mu_{\tilde{\mathscr{E}}_1}$ and $\mu_{\tilde{\mathscr{E}}_2}$ respectively, where

$$\mu_{\tilde{\mathscr{E}}_1}(\gamma; \tau_1, \tau_2, \tau_3) = \begin{cases} \frac{\gamma - \tau_1}{\tau_2 - \tau_1} & , \quad \text{if } \tau_1 \le \gamma \le \tau_2 \\ \frac{\tau_3 - \gamma}{\tau_3 - \tau_2} & , \quad \text{if } \tau_2 \le \gamma \le \tau_3 \\ 0 & , \quad \text{otherwise} \end{cases} \tag{8}$$

and

$$\mu_{\tilde{\mathscr{E}}_2}(\gamma; \delta_1, \delta_2, \delta_3) = \begin{cases} \frac{\gamma - \delta_1}{\delta_2 - \delta_1} & , \quad \text{if } \delta_1 \le \gamma \le \delta_2 \\ \frac{\delta_3 - \gamma}{\delta_3 - \delta_2} & , \quad \text{if } \delta_2 \le \gamma \le \delta_3 \\ 0 & , \quad \text{otherwise} \end{cases} \tag{9}$$

Then α-cut of $\tilde{\mathscr{E}}_1$ is

$$(\tilde{\mathscr{E}}_1)_\alpha = [(\tau_2 - \tau_1)\alpha + \tau_1, -(\tau_3 - \tau_2)\alpha + \tau_3] \tag{10}$$

where $\alpha \in [0, 1]$.

Then α-cut of $\tilde{\mathscr{E}}_2$ is

$$(\tilde{\mathscr{E}}_2)_\alpha = [(\delta_2 - \delta_1)\alpha + \delta_1, -(\delta_3 - \delta_2)\alpha + \delta_3] \tag{11}$$

$\alpha \in [0, 1]$.

I. **Addition of two TFNs**
α-cut of sum of two TFNs $\tilde{\mathscr{E}}_1$ and $\tilde{\mathscr{E}}_2$ i.e, $(\tilde{\mathscr{E}}_1 \oplus \tilde{\mathscr{E}}_2)$ is defined as,

$$\begin{aligned}\left(\tilde{\mathscr{E}}_1 \oplus \tilde{\mathscr{E}}_2\right)_\alpha &= [\{(\tau_2 - \tau_1) + (\delta_2 - \delta_1)\}\alpha + \tau_1 + \delta_1, -\{(\tau_3 - \tau_2) + (\delta_3 - \delta_2)\}\alpha + \tau_3 + \delta_3] \\ &= [\{(\tau_2 + \delta_2) - (\tau_1 + \delta_1)\}\alpha + (\tau_1 + \delta_1), -\{(\tau_3 + \delta_3) - (\tau_2 + \delta_2)\}\alpha + (\tau_3 + \delta_3)]\end{aligned} \tag{12}$$

Hence, the membership function of $(\tilde{\mathscr{E}}_1 \oplus \tilde{\mathscr{E}}_2)$ can be written as,

$$\mu_{(\tilde{\mathscr{E}}_1 \oplus \tilde{\mathscr{E}}_2)}(\gamma) = \begin{cases} \frac{\gamma-(\tau_1+\delta_1)}{(\tau_2+\delta_2)-(\tau_1+\delta_1)} & \text{, if } (\tau_1+\delta_1) \leq \gamma \leq (\tau_2+\delta_2) \\ \frac{(\tau_3+\delta_3)-\gamma}{(\tau_3+\delta_3)-(\tau_2+\delta_2)} & \text{, if } (\tau_2+\delta_2) \leq \gamma \leq (\tau_3+\delta_3) \\ 0, & \text{, otherwise} \end{cases} \tag{13}$$

So, the sum of two TFNs is defined as,

$$\left(\tilde{\mathscr{E}}_1 \oplus \tilde{\mathscr{E}}_2\right) = (\tau_1+\delta_1, \tau_2+\delta_2, \tau_3+\delta_3) \tag{14}$$

which is also a TFN.

II. **Subtraction of two TFNs**

$\alpha-$cut of difference of two TFN $\tilde{\mathscr{E}}_1$ and $\tilde{\mathscr{E}}_2$ is represented as $(\tilde{\mathscr{E}}_1 \ominus \tilde{\mathscr{E}}_2)$ and it is defined as

$$\begin{aligned}\left(\tilde{\mathscr{E}}_1 \ominus \tilde{\mathscr{E}}_2\right)_\alpha &= [(\tau_2-\tau_1+\delta_3-\delta_2)\alpha+\tau_1-\delta_3, \{(-\tau_3+\tau_2-\delta_2+\delta_1)\}\alpha+\tau_3-\delta_1] \\ &= [\{(\tau_2-\delta_2)-(\tau_1-\delta_3)\}\alpha+(\tau_1-\delta_3), -\{(\tau_3-\delta_1)-(\tau_2-\delta_2)\}\alpha+(\tau_3-\delta_1)]\end{aligned} \tag{15}$$

Hence, the membership function of $(\tilde{\mathscr{E}}_1 \ominus \tilde{\mathscr{E}}_2)$ can be written as,

$$\mu_{(\tilde{\mathscr{E}}_1 \oplus \tilde{\mathscr{E}}_2)}(\gamma) = \begin{cases} \frac{\gamma-(\tau_1-\delta_3)}{(\tau_2-\delta_2)-(\tau_1-\delta_3)} & \text{, if } (\tau_1-\delta_3) \leq \gamma \leq (\tau_2-\delta_2) \\ \frac{(\tau_3-\delta_1)-\gamma}{(\tau_3-\delta_1)-(\tau_2-\delta_2)} & \text{, if } (\tau_2-\delta_2) \leq \gamma \leq (\tau_3-\delta_1) \\ 0 & \text{, otherwise} \end{cases} \tag{16}$$

So, the subtraction of two TFNs is defined as,

$$\left(\tilde{\mathscr{E}}_1 \ominus \tilde{\mathscr{E}}_2\right) = (\tau_1-\delta_3, \tau_2-\delta_2, \tau_3-\delta_1) \tag{17}$$

which is also a TFN.

III. **Multiplication by a crisp number**

Let $\tilde{\mathscr{E}}_1 = (\tau_1, \tau_2, \tau_3)$ be a triangular fuzzy number (TFN) with membership function $\mu_{\tilde{\mathscr{E}}_{11}}$ and k be a positive scalar number. The α-cut of $\tilde{\mathscr{E}}_1$ is

$$(\tilde{\mathscr{E}}_1)_\alpha = [(\tau_2-\tau_1)\alpha+\tau_1, -(\tau_3-\tau_2)\alpha+\tau_3] \tag{18}$$

, where $\alpha \in [0,1]$.

Therefore, $\alpha-$cut of $k\tilde{\mathscr{E}}_1$ is

$$\left(k\tilde{\mathscr{E}}_1\right)_\alpha = [k(\tau_2-\tau_1)\alpha+k\tau_1, -k(\tau_3-\tau_2)\alpha+k\tau_3] \tag{19}$$

where $\alpha \in [0,1]$.

Hence, the membership function of $k\tilde{\mathscr{E}}_1$ is

$$\mu_{k\tilde{\mathscr{E}}_1}(\gamma) = \begin{cases} \frac{\gamma-k\tau_1}{k\tau_2-k\tau_1} & \text{, if } k\tau_1 \leq \gamma \leq k\tau_2 \\ \frac{k\tau_3-\gamma}{k\tau_3-k\tau_2} & \text{, if } k\tau_2 \leq \gamma \leq k\tau_3 \\ 0 & \text{, otherwise} \end{cases} \tag{20}$$

Detailed results for the cases where $k \leq 0$ one can go through the paper of Mukherjee, A.K. et al. [34]. So, for any scalar k, the result can be written as,

$$\mu_{k\tilde{\mathscr{E}}_1}(\gamma) = \begin{cases} (k\tau_1, k\tau_2, k\tau_3) & \text{, when } k \geq 0 \\ (k\tau_3, k\tau_2, k\tau_1) & \text{, when } k < 0 \end{cases} \tag{21}$$

IV. **Multiplication of two TFNs**
Let $\tilde{\mathscr{E}}_1 = (\tau_1, \tau_2, \tau_3)$ and $\tilde{\mathscr{E}}_2 = (\delta_1, \delta_2, \delta_3)$ be two positive TFNs having the membership function $\mu_{\tilde{\mathscr{E}}_1}$ and $\mu_{\tilde{\mathscr{E}}_2}$ respectively. Then α-cut of $\tilde{\mathscr{E}}_1$ is

$$\left(\tilde{\mathscr{E}}_1\right)_\alpha = [(\tau_2 - \tau_1)\alpha + \tau_1, -(\tau_3 - \tau_2)\alpha + \tau_3] \tag{22}$$

where $\alpha \in [0, 1]$.
The α-cut of $\tilde{\mathscr{E}}_2$ is

$$\left(\tilde{\mathscr{E}}_2\right)_\alpha = [(\delta_2 - \delta_1)\alpha + \delta_1, -(\delta_3 - \delta_2)\alpha + \delta_3] \tag{23}$$

where $\alpha \in [0, 1]$.
Then α-cut of the product $(\tilde{\mathscr{E}}_1 \otimes \tilde{\mathscr{E}}_2)_\alpha$ can be written as,

$$\left(\tilde{\mathscr{E}}_1 \otimes \tilde{\mathscr{E}}_2\right)_\alpha = [\min\{\xi_1\zeta_1, \xi_1\zeta_2, \xi_2\zeta_1, \xi_2\zeta_2\}, \max\{\xi_1\zeta_1, \xi_1\zeta_2, \xi_2\zeta_1, \xi_2\zeta_2\}] \tag{24}$$

where

$$\begin{cases} \xi_1 = (\tau_2 - \tau_1)\alpha + \tau_1 \\ \xi_2 = -(\tau_3 - \tau_2)\alpha + \tau_3 \\ \zeta_1 = (\delta_2 - \delta_1)\alpha + \delta_1 \\ \zeta_2 = -(\delta_3 - \delta_2)\alpha + \delta_3 \end{cases} \tag{25}$$

As $\tilde{\mathscr{E}}_1$ and $\tilde{\mathscr{E}}_2$ are both positive TFNs, so we can write that $\xi_1 > 0, \xi_2 > 0, \zeta_1 > 0, \zeta_2 > 0$ for any $\alpha \in [0, 1]$, then $\xi_1\zeta_1 > 0, \xi_1\zeta_2 > 0, \xi_2\zeta_1 > 0$ and $\xi_2\zeta_2 > 0$, for all $\alpha \in [0, 1]$.

$$\begin{aligned} \left(\tilde{\mathscr{E}}_1 \otimes \tilde{\mathscr{E}}_2\right)_\alpha &= [\min\{\xi_1\zeta_1, \xi_1\zeta_2, \xi_2\zeta_1, \xi_2\zeta_2\}, \max\{\xi_1\zeta_1, \xi_1\zeta_2, \xi_2\zeta_1, \xi_2\zeta_2\}] \\ &= [\xi_1\zeta_1, \xi_2\zeta_2] \\ &= [\{(\tau_2 - \tau_1)\alpha + \tau_1\}\{(\delta_2 - \delta_1)\alpha + \delta_1\}, \{(\tau_3 - \tau_2)\alpha - \tau_3\}\{(\delta_3 - \delta_2)\alpha - \delta_3\}] \end{aligned} \tag{26}$$

where $\alpha \in [0, 1]$.
This can be written as,

$$\left(\tilde{\mathscr{E}}_1 \otimes \tilde{\mathscr{E}}_2\right)_\alpha = [u_1\alpha^2 + u_2\alpha + u_3, v_1\alpha^3 - v_2\alpha + v_3] \tag{27}$$

where

$$\begin{cases} u_1 = (\tau_2 - \tau_1)(\delta_2 - \delta_1) \\ u_2 = (\tau_2 - \tau_1)\delta_1 + (\delta_2 - \delta_1)\tau_1 \\ u_3 = \tau_1\delta_1 \\ v_1 = (\tau_3 - \tau_2)(\delta_3 - \delta_2) \\ v_2 = (\tau_3 - \tau_2)\delta_3 + (\delta_3 - \delta_2)\tau_3 \\ v_3 = \tau_3\delta_3 \end{cases}$$

Now, after some calculation as mentioned in paper [34] we can represent the membership function of $\left(\tilde{\mathscr{E}}_1 \otimes \tilde{\mathscr{E}}_2\right)$ as,

$$\mu_{\left(\tilde{\mathscr{E}}_1 \otimes \tilde{\mathscr{E}}_2\right)}(\gamma) = \begin{cases} \frac{-u_2 \pm \sqrt{(u_2^2 - 4u_1(u_3 - \gamma))}}{2u_1} & , \text{ when } \tau_1\delta_1 \leq \gamma \leq \tau_2\delta_2 \\ \frac{-v_2 \pm \sqrt{(v_2^2 - 4v_1(v_3 - \gamma))}}{2v_1} & , \text{ when } \tau_2\delta_2 \leq \gamma \leq \tau_3\delta_3 \\ 0 & , \text{ otherwise} \end{cases} \tag{28}$$

So, the multiplication of two positive TFNs is defined as,

$$\left(\tilde{\mathscr{E}}_1 \otimes \tilde{\mathscr{E}}_2\right) = (\tau_1\delta_1, \tau_2\delta_2, \tau_3\delta_3) \tag{29}$$

For other types of TFNs, the result remains the same; for details, refer to the study [34].

V. **Division of two TFNs**
Let $\tilde{\mathscr{E}}_1 = (\tau_1, \tau_2, \tau_3)$ and $\tilde{\mathscr{E}}_2 = (\delta_1, \delta_2, \delta_3)$ be two positive TFNs having the membership function $\mu_{\tilde{\mathscr{E}}_1}$ and $\mu_{\tilde{\mathscr{E}}_2}$ respectively. Then α-cut of $\tilde{\mathscr{E}}_1$ is

$$\left(\tilde{\mathscr{E}}_1\right)_\alpha = [(\tau_2 - \tau_1)\alpha + \tau_1, -(\tau_3 - \tau_2)\alpha + \tau_3] \tag{30}$$

where $\alpha \in [0,1]$ and α-cut of $\tilde{\mathscr{E}}_2$ is

$$\left(\tilde{\mathscr{E}}_2\right)_\alpha = [(\delta_2 - \delta_1)\alpha + \delta_1, -(\delta_3 - \delta_2)\alpha + \delta_3] \tag{31}$$

where $\alpha \in [0,1]$.
Then, the α-cut of the fuzzy number $(\tilde{\mathscr{E}}_1 \oslash \tilde{\mathscr{E}}_2)_\alpha$ can be defined as,

$$\left(\tilde{\mathscr{E}}_1 \oslash \tilde{\mathscr{E}}_2\right)_\alpha = \left[\min\left\{\frac{\xi_1}{\zeta_1}, \frac{\xi_1}{\zeta_2}, \frac{\xi_2}{\zeta_1}, \frac{\xi_2}{\zeta_2}\right\}, \max\left\{\frac{\xi_1}{\zeta_1}, \frac{\xi_1}{\zeta_2}, \frac{\xi_2}{\zeta_1}, \frac{\xi_2}{\zeta_2}\right\}\right] \tag{32}$$

where

$$\begin{cases} \xi_1 = (\tau_2 - \tau_1)\alpha + \tau_1 \\ \xi_2 = -(\tau_3 - \tau_2)\alpha + \tau_3 \\ \zeta_1 = (\delta_2 - \delta_1)\alpha + \delta_1 \\ \zeta_2 = -(\delta_3 - \delta_2)\alpha + \delta_3 \end{cases}$$

As $\tilde{\mathscr{E}}_1$ and $\tilde{\mathscr{E}}_2$ are both positive TFNs, so we can write that $\xi_1 > 0, \xi_2 > 0, \zeta_1 > 0, \zeta_2 > 0$ for any $\alpha \in [0,1]$, then $\frac{\xi_1}{\zeta_1} > 0, \frac{\xi_1}{\zeta_2} > 0, \frac{\xi_2}{\zeta_1} > 0, \frac{\xi_2}{\zeta_2} > 0$.

Now, $\frac{1}{\zeta_1} > \frac{1}{\zeta_2} \implies \frac{\xi_2}{\zeta_1} > \frac{\xi_2}{\zeta_2}$. Again, $\xi_1 < \xi_2 \implies \frac{\xi_1}{\zeta_1} < \frac{\xi_2}{\zeta_1} \& \frac{\xi_1}{\zeta_2} < \frac{\xi_2}{\zeta_2}$.

So, $\frac{\xi_2}{\zeta_1} > \frac{\xi_2}{\zeta_2} > \frac{\xi_1}{\zeta_2}$. Hence,

$$\max\left\{\frac{\xi_1}{\zeta_1}, \frac{\xi_1}{\zeta_2}, \frac{\xi_2}{\zeta_1}, \frac{\xi_2}{\zeta_2}\right\} = \frac{\xi_2}{\zeta_1} \tag{33}$$

We know that $\frac{\xi_1}{\zeta_2} < \frac{\xi_2}{\zeta_2}$ and $\frac{\xi_1}{\zeta_2} < \frac{\xi_2}{\zeta_1}$. As, $\frac{1}{\zeta_1} > \frac{1}{\zeta_2} \implies \frac{\xi_1}{\zeta_1} > \frac{\xi_1}{\zeta_2}$ and $\frac{\xi_2}{\zeta_1} > \frac{\xi_2}{\zeta_2}$, so, $\frac{\xi_1}{\zeta_2} < \frac{\xi_2}{\zeta_2} < \frac{\xi_2}{\zeta_1} \implies \frac{\xi_1}{\zeta_2} < \frac{\xi_2}{\zeta_1}$. Hence,

$$\min\left\{\frac{\xi_1}{\zeta_1}, \frac{\xi_1}{\zeta_2}, \frac{\xi_2}{\zeta_1}, \frac{\xi_2}{\zeta_2}\right\} = \frac{\xi_1}{\zeta_2} \tag{34}$$

So,

$$(\tilde{\mathscr{E}}_1 \oslash \tilde{\mathscr{E}}_2)_\alpha = \left[\frac{\xi_1}{\zeta_2}, \frac{\xi_2}{\zeta_1}\right] \tag{35}$$

After some calculations as mentioned in the paper [34], we get the membership function of $(\tilde{\mathscr{E}}_1 \oslash \tilde{\mathscr{E}}_2)$ as follows,

$$\mu_{(\tilde{\mathscr{E}}_1 \oslash \tilde{\mathscr{E}}_2)}(\gamma) = \begin{cases} \frac{(\gamma\delta_3 - \tau_1)}{(\tau_2 - \tau_1) + \gamma(\delta_3 - \delta_2)} & \text{, if } \frac{\tau_1}{\delta_3} < \gamma < \frac{\tau_2}{\delta_2} \\ \frac{(\delta_3 - \gamma\tau_1)}{(\tau_3 - \tau_2) + \gamma(\delta_2 - \delta_1)} & \text{, if } \frac{\tau_2}{\delta_2} < \gamma < \frac{\tau_3}{\delta_1} \\ 0 & \text{, otherwise} \end{cases} \tag{36}$$

For the division of other types of Triangular Fuzzy Numbers (TFNs), the result will be similar and for details, one can go through the paper [34].

Example 3. *Let $\tilde{\mathscr{A}} = (2, 4, 7)$ and $\tilde{\mathscr{B}} = (3, 5, 8)$ be two positive TFNS and the membership functions are $\mu_{\tilde{\mathscr{A}}}$ and $\mu_{\tilde{\mathscr{B}}}$ respectively, where*

$$\mu_{\tilde{\mathscr{A}}}(\gamma) = \begin{cases} \frac{\gamma-2}{2} & \text{, if } 2 \leq \gamma \leq 4 \\ \frac{7-\gamma}{3} & \text{, if } 4 \leq \gamma \leq 7 \\ 0 & \text{, otherwise} \end{cases} \tag{37}$$

and

$$\mu_{\tilde{\mathscr{B}}}(\gamma) = \begin{cases} \frac{\gamma-3}{2} & \text{, if } 3 \leq \gamma \leq 5 \\ \frac{8-\gamma}{3} & \text{, if } 5 \leq \gamma \leq 8 \\ 0 & \text{, otherwise} \end{cases} \tag{38}$$

Now, the α-cut of $\tilde{\mathscr{A}}$ is

$$\tilde{\mathscr{A}}_\alpha = [2\alpha + 2, -3\alpha + 7] \tag{39}$$

where $\alpha \in [0, 1]$.
The α-cut of $\tilde{\mathscr{B}}$ is

$$\tilde{\mathscr{B}}_\alpha = [2\alpha + 3, -3\alpha + 8] \tag{40}$$

where $\alpha \in [0, 1]$.

(i) ***Addition:***
Then α-cut of $(\tilde{\mathscr{A}} \oplus \tilde{\mathscr{B}})$ is

$$\left(\tilde{\mathscr{A}} \oplus \tilde{\mathscr{B}}\right)_\alpha = [4\alpha + 5, -6\alpha + 15] \tag{41}$$

where $\alpha \in [0, 1]$.
The membership function of $(\tilde{\mathscr{A}} \oplus \tilde{\mathscr{B}})$ can be represented as

$$\mu_{\tilde{\mathscr{A}} \oplus \tilde{\mathscr{B}}}(\gamma) = \begin{cases} \frac{\gamma-5}{4} & \text{, if } 3 \leq \gamma \leq 5 \\ \frac{15-\gamma}{6} & \text{, if } 5 \leq \gamma \leq 8 \\ 0 & \text{, otherwise} \end{cases} \tag{42}$$

So, $(\tilde{\mathscr{A}} \oplus \tilde{\mathscr{B}}) = (2 + 3, 4 + 5, 7 + 8) = (5, 9, 15)$.

(ii) ***Subtraction:***
Then α-cut of $(\tilde{\mathscr{A}} \ominus \tilde{\mathscr{B}})$ is

$$\left(\tilde{\mathscr{A}} \ominus \tilde{\mathscr{B}}\right)_\alpha = [5\alpha - 6, -5\alpha + 4] \tag{43}$$

where $\alpha \in [0, 1]$.
The membership function of $\left(\tilde{\mathscr{A}} \ominus \tilde{\mathscr{B}}\right)$ can be represented as

$$\mu_{\tilde{\mathscr{A}} \ominus \tilde{\mathscr{B}}}(\gamma) = \begin{cases} \frac{\gamma-6}{5} & \text{, if } -6 \leq \gamma \leq -1 \\ \frac{4-\gamma}{5} & \text{, if } -1 \leq \gamma \leq 4 \\ 0 & \text{, otherwise} \end{cases} \tag{44}$$

So, $(\tilde{\mathscr{A}} \ominus \tilde{\mathscr{B}}) = (2 - 8, 4 - 5, 7 - 3) = (-6, -1, 4)$.

(iii) ***Multiplication by a crisp number:***
Let $k=3$ be a scalar. The α-cut of $3\tilde{\mathscr{A}}$ is

$$\left(3\tilde{\mathscr{A}}\right)_\alpha=[6\alpha+6,-9\alpha+21] \tag{45}$$

where $\alpha\in[0,1]$.
Hence, the membership function of $3\tilde{\mathscr{A}}$ is of the form

$$\mu_{3\tilde{\mathscr{A}}}(\gamma)=\begin{cases}\frac{\gamma-6}{6} & \text{, if } 6\leq\gamma\leq12\\ \frac{21-\gamma}{9} & \text{, if } 12\leq\gamma\leq21\\ 0 & \text{, otherwise}\end{cases} \tag{46}$$

So, $3\tilde{\mathscr{A}}=(3\times2,3\times4,3\times7)=(6,12,21)$.

(iv) ***Multiplication of two TFNs:***
The α-cut of $(\tilde{\mathscr{A}}\otimes\tilde{\mathscr{B}})$ is

$$\begin{aligned}\left(\tilde{\mathscr{A}}\otimes\tilde{\mathscr{B}}\right)_\alpha&=[(2\alpha+2)(2\alpha+3),(3\alpha-7)(3\alpha-8)]\\&=\left[4\alpha^2+10\alpha+6,9\alpha^2-45\alpha+56\right]\end{aligned} \tag{47}$$

where $\alpha\in[0,1]$.
Thus, the membership function related to $\left(\tilde{\mathscr{A}}\otimes\tilde{\mathscr{B}}\right)$ is

$$\begin{aligned}\mu_{\left(\tilde{\mathscr{A}}\otimes\tilde{\mathscr{B}}\right)}&=\begin{cases}\frac{-10\pm\sqrt{4^2-4\times4\times(6-\gamma)}}{2\times4} & \text{, when } 6\leq\gamma\leq20\\ \frac{-45\pm\sqrt{(45)^2-4\times9\times(56-\gamma)}}{2\times9} & \text{, when } 20\leq\gamma\leq56\\ 0 & \text{, otherwise}\end{cases}\\&=\begin{cases}\frac{-10\pm\sqrt{(16\gamma-80)}}{8} & \text{, when } 6\leq\gamma\leq20\\ \frac{-45\pm\sqrt{(36\gamma+9)}}{18} & \text{, when } 20\leq\gamma\leq56\\ 0 & \text{, otherwise}\end{cases}\end{aligned} \tag{48}$$

So,

$$(\tilde{\mathscr{A}}\otimes\tilde{\mathscr{B}})=(2\times3,4\times5,7\times8)=(6,20,56) \tag{49}$$

(v) ***Division of two TFNs:***
The α-cut of $(\tilde{\mathscr{A}}\oslash\tilde{\mathscr{B}})$ is represented as

$$\left(\tilde{\mathscr{A}}\oslash\tilde{\mathscr{B}}\right)_\alpha=\left[\frac{(2\alpha+2)}{(-3\alpha+8)},\frac{(-3\alpha+7)}{(2\alpha+3)}\right] \tag{50}$$

where $\alpha\in[0,1]$. The membership function corresponding to $(\tilde{\mathscr{A}}\oslash\tilde{\mathscr{B}})$ is

$$\mu_{(\tilde{\mathscr{A}}\oslash\tilde{\mathscr{B}})}(\gamma)=\begin{cases}\frac{(8\gamma-2)}{(2+3\gamma)} & \text{, when } \frac{1}{4}<\gamma<\frac{4}{5}\\ \frac{(8-2\gamma)}{(3+2\gamma)} & \text{, when } \frac{4}{5}<\gamma<\frac{7}{3}\\ 0 & \text{, otherwise}\end{cases} \tag{51}$$

So,

$$\left(\tilde{\mathscr{A}}\oslash\tilde{\mathscr{B}}\right)=\left(\frac{2}{8},\frac{4}{5},\frac{7}{3}\right)=\left(\frac{1}{4},\frac{4}{5},\frac{7}{3}\right). \tag{52}$$

3.5 Proposed de-fuzzification method

In mathematics, de-fuzzification is a technique to compute the crisp value of every fuzzy set. The de-fuzzification methodology provides a crisp number for every fuzzy number. Since there is no order relation between the fuzzy set and the triangular fuzzy number. The de-fuzzification of a TFN is not a proper crisp value for a TFN. For the same TFNs, various de-fuzzification techniques can provide several de-fuzzified values. In this study, we consider de-fuzzified process, which is explained below.

Definition 9. *Let us choose,* $\tilde{\mathscr{A}} = \{\langle b, (\tau_1, \tau_2, \tau_3); \mu_{\tilde{\mathscr{A}}}(b)\rangle : b \in \mathbb{R}\}$ *be a Triangular Fuzzy Number(TFN). Therefore, the defuzzification value of* $\tilde{\mathscr{A}}$*, defined as* $\mathcal{D}(\tilde{\mathscr{A}})$*, i.e.,*

$$\mathcal{D}(\tilde{\mathscr{A}}) = \frac{\tau_1 + 2\tau_2 + \tau_3}{4} \tag{53}$$

Example 4. *Let,* $\tilde{\mathscr{A}} = \{\langle b, (2, 4, 6); \mu_{\tilde{\mathscr{A}}}(b)\rangle : b \in \mathbb{R}\}$ *and* $\tilde{\mathscr{I}} = \{\langle b', (7, 9, 11); \mu_{\tilde{\mathscr{I}}}(b')\rangle : b' \in \mathbb{R}\}$ *are two Triangular Fuzzy Numbers (TFNs). Therefore, the defuzzification values* $\mathcal{D}(\tilde{\mathscr{A}})$ *and* $\mathcal{D}(\tilde{\mathscr{I}})$ *of* $\tilde{\mathscr{A}}$ *and* $\tilde{\mathscr{I}}$*, respectively. So,*

$$\begin{aligned}\mathcal{D}(\tilde{\mathscr{A}}) &= \frac{2 + (2 \times 4) + 6}{4} \\ &= \frac{16}{4} = 4\end{aligned}$$

and

$$\begin{aligned}\mathcal{D}(\tilde{\mathscr{I}}) &= \frac{7 + (2 \times 9) + 11}{4} \\ &= \frac{36}{4} = 9\end{aligned}$$

4. Important challenges of humanitarian supply chain management

Human lives and even the economy of a nation are badly affected by any type of disaster. Therefore, it is essential to provide relief materials in a timely manner to those in need and to rescue them from their situation. For conducting such a process, humanitarian organizations have to be prepared to take action rapidly and manage the whole situation with proper coordination. Different types of challenges arise that these humanitarian organizations have to face during their field work. Some of these obstacles include funding, supply chain resilience, coordination, infrastructure, logistics, transparency, sustainability, security and safety risks, environmental impact and low capacity. There are numerous research studies that identify the criteria important for humanitarian supply chain management. Kabra, G. et al. [71] in their work divide the barriers of humanitarian supply chain management into 5 categories, such as management barriers, technological barriers, cultural barriers, people barriers and organizational barriers and further consider some sub-criteria belonging to these categories. Momena, A. F. et al. [72] in their research work consider 5 criteria, namely supply chain disruptions, logistics challenges, demand and supply imbalances, technological and cybersecurity issues, sustainability and ethical sourcing and their corresponding sub-criteria, which are important for humanitarian supply chain management. Gardner, T.A. et al. [73] discussed the importance of transparency and sustainability in their research on supply chain management. After studying various research works and articles, we have decided to consider 6 criteria such as funding $(\mathcal{C}_1)$, coordination $(\mathcal{C}_2)$, infrastructure $(\mathcal{C}_3)$, transparency $(\mathcal{C}_4)$, logistics $(\mathcal{C}_5)$, sustainability $(\mathcal{C}_6)$, to address the challenges of humanitarian supply chain management. Figure 1 illustrates the graphical representation of the various challenges in the Humanitarian Supply Chain Management system. In this section, we will provide a brief description of these criteria.

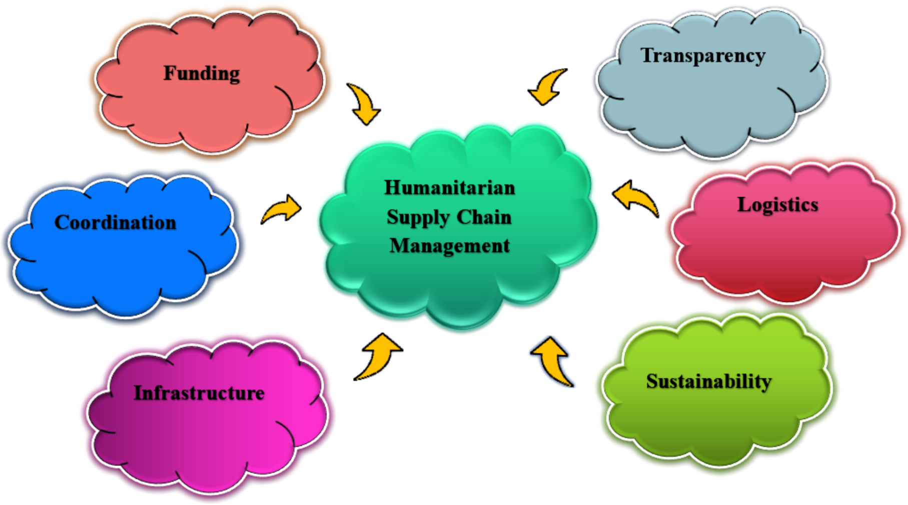

Fig. 1. Associated criteria related to the proposed model

4.1 *Funding* $(\mathcal{C}_1)$

Funding [74, 75] is one of the primary challenges in the sustainable management of the humanitarian supply chain. The accessibility, acquisition, and distribution of necessary resources are directly influenced by the factor of funding. In some situations, especially during prolonged crises, insufficient and unpredictable financial assistance can become a reason for delays, resource deficiencies and inadequate aid delivery. For developing the infrastructure, a sufficient amount of funds is required. Even factors such as acclimation to technology and manpower capacity are also affected by the inconsistent supply of funding. Without a sufficient amount of financial aid, it is not possible to manage and carry out such relief tasks properly. For the smooth conduct of the supply process, there is a need for a continuous source of funding, as relying on short-term donor contributions can generate inconsistency. It also emphasizes that there is a need for a diversified, sustainable financial model which can guarantee continuous and effective humanitarian operations.

4.2 *Coordination* $(\mathcal{C}_2)$

Coordination [3, 76] is a main problem related to the sustainable management of the humanitarian supply chain. In a crisis situation, many NGOs, donors, governments and private organizations work together with good coordination to ensure the timely delivery of aid. If there is poor coordination between group members, it may result in the wastage of resources, an increase in operational costs and a delay in reaching relief. Thus, the entire process of providing aid will slow down and become more expensive to implement. In some situations, decision-making becomes very complicated due to the scarcity of a standardized process and the lack of rapid information sharing. Therefore, it becomes very challenging to maintain a proper supply chain and meet the needs of the people. To construct a flexible and sustainable humanitarian supply chain, it is necessary to enhance coordination [77] through rapid data integration and seamless communication.

4.3 Infrastructure $(\mathcal{C}_3)$

Infrastructure [75, 78] is a crucial criterion of sustainable management of the humanitarian supply chain. Several factors, including inadequate roads, ports, poor communication networks and a shortage of warehouses, can hinder the timely delivery of aid. The infrastructure of disaster-affected or remote areas is very poor. In many areas, the conditions of the roads are very bad and sometimes the roads are not wide enough, causing a delay in transportation. It also created problems in storing and distributing supplies. Due to the lack of safe houses near the disaster-affected area, it takes time to evacuate people safely from that place. Even though there is a lack of reliable energy sources and clean water, this makes the situation worse. To improve the process of delivering aid, it is essential to focus on establishing robust infrastructure, including sustainable energy solutions, a sufficient number of safe housing facilities and a reliable internet connection. This also helps to produce a more effective supply chain, which reduces the harmful environmental impact and ensures long-term support in crisis-prone regions.

4.4 Transparency $(\mathcal{C}_4)$

Transparency [73, 79] plays a major role in the sustainable management of the humanitarian supply chain. The absence of clarity in working mode can result in exploitation, inadequacy, and inaccurate allocation of assets. There is a need to properly monitor the entire process of utilising funds; otherwise, there may arise some risks of duplicity and corruption, which can interrupt the process. Through establishing proper coordination between organizations for sharing their data and providing updates consistently about the situation, it will be easy to make suitable decisions and use resources effectively. To ensure transparency in the distribution of resources, digital solutions such as real-time tracking, blockchain, and open data platforms can be utilised effectively. These technologies also help identify those in need and properly distribute relief funds and other resources. This ultimately strengthens the supply chain and makes it more sustainable.

4.5 Logistics $(\mathcal{C}_5)$

Logistics [72, 76, 78] is one of the main criteria of sustainable management of the humanitarian supply chain. The process through which we can plan, organize and manage the movement of articles, information and services is known as logistics. In disaster-affected areas, a well-functioning transportation system is crucial for delivering aid smoothly and quickly. In disaster-stricken regions, the transportation system is often disrupted, which causes difficulty in delivering aid of relief. Lack of sufficient storage, inconsistent fuel supply, and inefficient transportation can contribute to increased expenses and environmental pollution. Thus, to develop a fast, reliable, and sustainable solution for humanitarian supply chains and minimise waste, we must focus especially on the use of environmentally friendly transportation, local supplies, and better routes.

4.6 Sustainability $(\mathcal{C}_6)$

Sustainability [72, 73, 77] is identified as one of the main criteria for resolving the challenges related to humanitarian supply chain management. Sustainability helps to utilise resources in a proper way, ensuring they do not affect the needs of future generations. When we seek a humanitarian approach in our work, the concept of sustainability concerns not only balancing immediate assistance to affected people but also ensuring it meets the environmental, economic and social needs of those affected for a long duration. It also helps us mitigate the environmental consequences, manage waste effectively and use resources ethically, thereby strengthening the community. Thus, humanitarian organizations intensify their working procedure and provide their contribution towards our community effectively, by integrating sustainability [80] into the supply chain process.

5. A MCDM based Methodology: CRITIC Method

Multi-criteria decision making (MCDM) [72] is a complex decision-making optimisation technique that deals with several conflicting criteria, sub-criteria, alternatives and decision-makers simultaneously. In this paper, we have employed the Criteria Importance Through Inter-criteria Correlation (CRITIC) methodology [66, 67], a highly effective MCDM technique. In this section, we will provide a detailed description of the CRITIC method. This technique works quite well for finding the weight of individual criteria. This methodology was first introduced by Diakoulaki, D. et al. [42] in 1995. Due to its straightforward calculation and reduced processing requirements, this evaluation process is easy to complete. Correlation of criteria and variability are the two main dimensions of this method.

In this study, we have considered M number of criteria and there are N number of alternatives that can be chosen for ranking. L number of decision makers (DMs) provide their opinions based on these criteria for determining the criteria weight. The process of the CRITIC methodology is given graphically through Figure 2. The method is explained step by step elaborately as follows:

(a) **Formation of decision matrices in terms of Triangular Fuzzy Number (TFN):**
First of all, every decision maker (DM) provides their wise decision in linguistic terms and then transfers it to a Triangular Fuzzy Number (TFN). The decision matrix structured by κ^{th} decision maker is denoted by $\tilde{\mathcal{D}}_\kappa$ and is represented as

$$\tilde{\mathcal{D}}_\kappa = \begin{bmatrix} \left(\tilde{\mathcal{R}}_{11}\right)_\kappa & \left(\tilde{\mathcal{R}}_{12}\right)_\kappa & \dots & \left(\tilde{\mathcal{R}}_{1q}\right)_\kappa & \dots & \left(\tilde{\mathcal{R}}_{1M}\right)_\kappa \\ \left(\tilde{\mathcal{R}}_{21}\right)_\kappa & \left(\tilde{\mathcal{R}}_{22}\right)_\kappa & \dots & \left(\tilde{\mathcal{R}}_{2q}\right)_\kappa & \dots & \left(\tilde{\mathcal{R}}_{2M}\right)_\kappa \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \left(\tilde{\mathcal{R}}_{p1}\right)_\kappa & \left(\tilde{\mathcal{R}}_{p2}\right)_\kappa & \dots & \left(\tilde{\mathcal{R}}_{pq}\right)_\kappa & \dots & \left(\tilde{\mathcal{R}}_{pM}\right)_\kappa \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \left(\tilde{\mathcal{R}}_{N1}\right)_\kappa & \left(\tilde{\mathcal{R}}_{N2}\right)_\kappa & \dots & \left(\tilde{\mathcal{R}}_{Nq}\right)_\kappa & \dots & \left(\tilde{\mathcal{R}}_{NM}\right)_\kappa \end{bmatrix}_{N\times M} \tag{54}$$

Now, the Equation (54) can be also described as,

$$\tilde{\mathcal{D}}_\kappa = \left[\left(\tilde{\mathcal{R}}_{pq}\right)_\kappa\right]_{N\times M} = \left[\left\{\left(\tau_{1\tilde{\mathcal{R}}_{pq}}\right)_\kappa, \left(\tau_{2\tilde{\mathcal{R}}_{pq}}\right)_\kappa, \left(\tau_{3\tilde{\mathcal{R}}_{pq}}\right)_\kappa\right\}\right]_{N\times M} \tag{55}$$

where $q = 1, 2, \dots, M$, $p = 1, 2, \dots, N$ and $\kappa = 1, 2, \dots, L$.

The input $\tilde{\mathcal{R}}_{pq}$ represents the κ^{th} decision maker's opinion about p^{th} alternative on the basis of q^{th} criteria and it is given as

$$\left(\tilde{\mathcal{R}}_{pq}\right)_\kappa = \left\{\left(\tau_{1\tilde{\mathcal{R}}_{pq}}\right)_\kappa, \left(\tau_{2\tilde{\mathcal{R}}_{pq}}\right)_\kappa, \left(\tau_{3\tilde{\mathcal{R}}_{pq}}\right)_\kappa\right\} \tag{56}$$

(b) **Aggregate the above described Decisions Matrices:**
The total L numbers of decision matrices are aggregated to obtain a single decision matrix by using the following equation,

$$\begin{aligned}\tilde{\mathcal{R}}_{pq} &= \left\{\tau_{1\tilde{\mathcal{R}}_{pq}}, \tau_{2\tilde{\mathcal{R}}_{pq}}, \tau_{3\tilde{\mathcal{R}}_{pq}}\right\} \\ &= \left\{\sum_{\kappa=1}^{L}\left(\tau_{1\tilde{\mathcal{R}}_{pq}}\right)_{\kappa}, \sum_{\kappa=1}^{L}\left(\tau_{2\tilde{\mathcal{R}}_{pq}}\right)_{\kappa}, \sum_{\kappa=1}^{L}\left(\tau_{3\tilde{\mathcal{R}}_{pq}}\right)_{\kappa}\right\}\end{aligned} \tag{57}$$

Now, the Aggregated Decision Matrix $(\tilde{\mathcal{D}}^{\mathscr{A}})$ is

$$\tilde{\mathcal{D}}^{\mathscr{A}} = \left[\tilde{\mathcal{R}}_{pq}\right]_{N\times M} = \left[\left\{\tau_{1\tilde{\mathcal{R}}_{pq}}, \tau_{2\tilde{\mathcal{R}}_{pq}}, \tau_{3\tilde{\mathcal{R}}_{pq}}\right\}\right]_{N\times M} \tag{58}$$

where $q = 1, 2, \ldots, M$, $p = 1, 2, \ldots, N$.

(c) **De-fuzzification of the aggregated decision matrices:**
Using the Equation (53), the aggregated decision matrix $(\tilde{\mathcal{D}}^{\mathscr{A}})$ is de-fuzzified. The de-fuzzified aggregated decision matrix is denoted by $(\mathcal{D})$ and is defined as

$$\mathcal{D} = [(\mathcal{R}_{pq})]_{N\times M} \tag{59}$$

where, $\mathcal{R}_{pq}$ is the de-fuzzification value corresponding to the TFN $\tilde{\mathcal{R}}_{pq}$, $q = 1, 2, \ldots, M$, $p = 1, 2, \ldots, N$.

(d) **Normalization of the de-fuzzified Decision Matrix:**
We will compute the Normalized decision matrix $(\mathcal{D}_{\mathscr{N}})$ from the de-fuzzified decision matrix $\mathcal{D}$. For this purpose, we will use the formula that is given below

$$\tilde{\mathcal{R}}_{pq}^{'} = \frac{\tilde{\mathcal{R}}_{pq} - \tilde{\mathcal{R}}_{q}^{worst}}{\tilde{\mathcal{R}}_{q}^{best} - \tilde{\mathcal{R}}_{q}^{worst}} \tag{60}$$

and here

$$\begin{cases}\tilde{\mathcal{R}}_{q}^{best} = \max\limits_{p=1,2,\ldots,N} \tilde{\mathcal{R}}_{pq} \\ \tilde{\mathcal{R}}_{q}^{worst} = \min\limits_{p=1,2,\ldots,N} \tilde{\mathcal{R}}_{pq}\end{cases}$$

(e) **Evaluating Standard deviation (σ_q) for each criterion:**
For calculating the standard deviation (σ_q) of each criterion, the following formula is used

$$\sigma_q = \sqrt{\frac{\sum\limits_{q=1}^{M}\left(\mathcal{R}_q - \bar{\mathcal{R}}_q\right)}{M-1}} \tag{61}$$

where $\bar{\mathcal{R}}_q$ represents the population mean, M is the number of criteria (i.e., size of the population) and $q = 1, 2, \ldots, M$.

(f) **Determining the Linear Correlation Coefficient $(\theta_{qq'})$ between the criterion c_q and the criterion $c_{q'}$:**
Here, we will construct the $N \times M$ symmetric matrix with elements $\mathcal{R}_{pq}^{'}$, which is the Linear Correlation Coefficient between $\mathcal{R}_q$ and $\mathcal{R}_q^{'}$. The Correlation Coefficient between the criteria c_q and $c_{q'}$ is denoted by $\theta_{qq'}$.

(g) **Measure of the Conflict $(\mathscr{R}_q)$ created by the criteria:**
The measure of the conflict $(\mathcal{R}_q)$ created by q^{th} criterion with respect to the decision situation defined by the remaining criteria is calculated with the help of the following formula

$$\mathscr{R}_q = \sum_{q'=1}^{M} \left(1 - \theta_{qq'}\right) \tag{62}$$

(h) **Evaluating the Quality of information $(\mathscr{Q}_q)$:**
The quality of the information $(\mathscr{Q}_q)$ in relation to each criterion is evaluated by applying the following formula

$$\mathscr{Q}_q = \sigma_q \times \mathscr{R}_q \tag{63}$$

where criteria $q = 1, 2, \ldots, M$.

(i) **Finding the criteria weight $(\mathcal{W}_q)$:**
The weight of q^{th} criterion is symbolized as $\mathcal{W}_q$ and defined as

$$\mathcal{W}_q = \frac{\mathscr{Q}_q}{\sum_{q=1}^{M} \mathscr{Q}_q} \tag{64}$$

Thus, we can evaluate the weight of each criterion for $q = 1, 2, \ldots, M$.

Screenshot 2025-04-05 211047.png

Fig. 2. Structural flowchart of the CRITIC method

6. Model formulation and data collection

For proper management of the humanitarian supply chain, it is necessary that all organizations work together with proper coordination. In a disaster-affected area, it is crucial to send all types of aid and rescue people without causing casualties. Many agencies, local people, and the disaster management team all try their best to bring the situation under control. We have gone through many articles related to this study. We have observed that Kovács, G. et al. [81] in their paper consider 6 alternatives and further Venkatesh, V. G. et al. [82] mention this article and worked based on this article. Here, we have also consider these 6 alternatives such as Donors $(\mathcal{A}_1)$, Aid agencies $(\mathcal{A}_2)$, Government $(\mathcal{A}_3)$, NGOs $(\mathcal{A}_4)$, Military $(\mathcal{A}_5)$, Logistics Providers $(\mathcal{A}_6)$ for our further calculation.

In this research work, we have considered 6 criteria to develop a model for finding the challenges of humanitarian supply chain management and 6 alternatives, which are mentioned above. A detailed description of the criteria is given in Section 4. To collect the dataset, we considered the opinions of four experts. Thus, we will get four 6×6 order decision matrices and use them for our further mathematical calculations. The Figure 3 provides a clear view of the formulated model.

Humanitarian supply chain managment new.png

Fig. 3. Hierarchical structure of the proposed model

In this paper, we have considered the opinions of 4 decision makers who are excellent in their field and they are

DM_1 : One professor in the social science department.

DM_2 : A government officer with ten years experiences.

DM_3 : A senior researcher work on humanitarian supply chain management.

DM_4 : A social workers work on a Non-governmental organization (NGO) with fifteen years of experience.

Table 2
Comparison table between linguistic terms and the set of considered crisp numbers

Linguistic Terms	Triangular Fuzzy Number (TFN)	De-fuzzified Value
Absolutely Important Inference (AII)	$(7, 8, 9)$	8
Strongly Important Inference (SII)	$(6, 7, 8)$	7
Mostly Important Inference (MII)	$(5, 6, 7)$	6
Equally Important Inference (EII)	$(4, 5, 6)$	5
Little Important Inference (LII)	$(3, 4, 5)$	4
Below Important Inference (BII)	$(2, 3, 4)$	3
Poorly Important Inference (PII)	$(1, 2, 3)$	2

Decision makers (DMs) provide their opinion in linguistic terms and the decision matrices formed in linguistic terms are shown in Table 3. This dataset is further converted to Triangular Fuzzy Numbers (TFNs) using the information in Table 2.

7. Numerical illustration

In this section, we will elaborate on the numerical calculations. In this paper, we have applied one of the most popular MCDM methods, namely CRITIC [66, 67], to evaluate the weight corresponding to each criterion. Here, we have considered the data in linguistic terms, which are given in Table 3. After that, we have converted the linguistic term into Triangular Fuzzy Number (TFN) with the help of Table 2. Thus, we have obtained four decision matrices and further converted them into a single Aggregated Decision matrix $(\tilde{\mathcal{D}}^{\mathscr{A}})$ with the help of Equation (58). Then, by using the Equation (53), we have derived the de-fuzzified decision matrix $(\mathcal{D})$, which is shown in Table 4. After that, we have normalized the de-fuzzified Decision with the help of Equation (60) and it is given in Table 5. Furthermore, we have calculated the Standard Deviation (σ_q) corresponding to each criterion using the Equation (61) and these values are represented in the Table 6. Then we have evaluated the Correlation Coefficient between the criterion shown in Table 7 and applied Equation (62) to find the Measure of Conflict $(\mathscr{R}_q)$ and the values are given in Table 8. Further, the quality of the information $(\mathscr{Q}_q)$ corresponding to each criterion is calculated with the help of Equation (63) and using the values given in Table 6 and Table 8. The Table 9 represents the quality of the information corresponding to each criterion. Lastly, we have applied the Equation (64) to find the weight $(\mathcal{W}_q)$ of each criterion and the values are represented in Table 10.

Table 3
Decision matrix in linguistic terms given by DMs

	Criteria vs Alternatives	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
DM 1	Donor $(\mathcal{A}_1)$	EII	MII	AII	SII	AII	SII
	Aid agencies $(\mathcal{A}_2)$	MII	EII	LII	SII	AII	MII
	Government $(\mathcal{A}_3)$	AII	MII	EII	LII	SII	SII
	NGOs $(\mathcal{A}_4)$	LII	SII	BII	EII	MII	LII
	Military $(\mathcal{A}_5)$	AII	SII	SII	MII	EII	SII
	Logistics Providers $(\mathcal{A}_6)$	MII	SII	AII	MII	AII	EII
	Criteria vs Alternatives	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
DM 2	Donor $(\mathcal{A}_1)$	EII	SII	AII	AII	AII	MII
	Aid agencies $(\mathcal{A}_2)$	MII	EII	MII	SII	AII	LII
	Government $(\mathcal{A}_3)$	SII	LII	EII	BII	AII	SII
	NGOs $(\mathcal{A}_4)$	MII	SII	BII	EII	SII	BII
	Military $(\mathcal{A}_5)$	SII	AII	AII	LII	EII	SII
	Logistics Providers $(\mathcal{A}_6)$	MII	MII	SII	MII	SII	EII
	Criteria vs Alternatives	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
DM 3	Donor $(\mathcal{A}_1)$	EII	MII	SII	AII	AII	SII
	Aid agencies $(\mathcal{A}_2)$	LII	EII	SII	MII	AII	LII
	Government $(\mathcal{A}_3)$	AII	MII	EII	LII	AII	MII
	NGOs $(\mathcal{A}_4)$	MII	MII	PII	EII	MII	LII
	Military $(\mathcal{A}_5)$	AII	AII	SII	MII	EII	AII
	Logistics Providers $(\mathcal{A}_6)$	SII	MII	MII	LII	SII	EII
	Criteria vs Alternatives	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
DM 4	Donor $(\mathcal{A}_1)$	EII	MI	AII	AII	SII	AII
	Aid agencies $(\mathcal{A}_2)$	MII	EII	MII	AII	MII	LII
	Government $(\mathcal{A}_3)$	AII	LII	EII	BII	SII	SII
	NGOs $(\mathcal{A}_4)$	LII	AII	BII	EII	MII	BII
	Military $(\mathcal{A}_5)$	AII	SII	AII	LII	EII	SII
	Logistics Providers $(\mathcal{A}_6)$	MII	MII	SII	LII	SII	EII

Table 4
De-fuzzified aggregated decision matrix

Criteria vs Alternatives	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
Donor $(\mathcal{A}_1)$	5.00	6.25	7.75	7.75	7.75	7.00
Aid agencies $(\mathcal{A}_2)$	5.50	5.00	5.75	7.00	7.50	4.50
Government $(\mathcal{A}_3)$	7.75	5.00	5.00	3.25	7.50	6.75
NGOs $(\mathcal{A}_4)$	5.00	7.00	2.38	5.00	6.25	3.25
Military $(\mathcal{A}_5)$	7.75	7.50	7.50	5.00	5.00	7.25
Logistics Providers $(\mathcal{A}_6)$	6.25	6.25	7.00	5.00	7.25	5.00
Best Performance	7.75	7.50	7.75	7.75	7.75	7.25
Worst Performance	5.00	5.00	2.38	3.25	5.00	3.25

Table 5
Normalized de-fuzzified aggregated decision matrix

Criteria vs Alternatives	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
Donor $(\mathcal{A}_1)$	0.000	0.500	1.000	1.000	1.000	0.938
Aid agencies $(\mathcal{A}_2)$	0.182	0.000	0.628	0.833	0.909	0.313
Government $(\mathcal{A}_3)$	1.000	0.000	0.488	0.000	0.909	0.875
NGOs $(\mathcal{A}_4)$	0.000	0.800	0.000	0.389	0.455	0.000
Military $(\mathcal{A}_5)$	1.000	1.000	0.953	0.389	0.000	1.000
Logistics Providers $(\mathcal{A}_6)$	0.455	0.500	0.860	0.389	0.818	0.438

Table 6
Standard Deviation (SD) (σ_q) for each criterion

Criteria	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
Standard Deviation (SD)	0.4650	0.4082	0.3763	0.3600	0.3846	0.4046

Table 7
Linear Correlation Coefficient $(\theta_{qq'})$ between the criteria c_q and $c_{q'}$

Criteria vs Alternatives	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
Donor $(\mathcal{A}_1)$	1.000	-0.003	0.252	-0.718	-0.393	0.601
Aid agencies $(\mathcal{A}_2)$	-0.003	1.000	0.065	-0.008	-0.811	0.030
Government $(\mathcal{A}_3)$	0.252	0.065	1.000	0.389	0.054	0.732
NGOs $(\mathcal{A}_4)$	-0.718	-0.008	0.389	1.000	0.299	-0.033
Military $(\mathcal{A}_5)$	-0.393	-0.811	0.054	0.299	1.000	-0.069
Logistics Providers $(\mathcal{A}_6)$	0.601	0.030	0.732	-0.033	-0.069	1.000

Table 8
Measure of the Conflict $(\mathscr{R}_q)$ among the criteria

Criteria vs Alternatives	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
Donor $(\mathcal{A}_1)$	0.000	1.003	0.748	1.718	1.393	0.399
Aid agencies $(\mathcal{A}_2)$	1.003	0.000	0.935	1.008	1.811	0.970
Government $(\mathcal{A}_3)$	0.748	0.935	0.000	0.611	0.946	0.268
NGOs $(\mathcal{A}_4)$	1.718	1.008	0.611	0.000	0.701	1.033
Military $(\mathcal{A}_5)$	1.393	1.811	0.946	0.701	0.000	1.069
Logistics Providers $(\mathcal{A}_6)$	0.399	0.970	0.268	1.033	1.069	0.000

Table 9
Quality of information $(\mathscr{Q}_q)$

Criteria	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
Sum	5.261	5.726	3.508	5.071	5.920	3.739
Quantity of Information	2.447	2.338	1.320	1.826	2.277	1.513

Table 10
Criteria weight $(\mathcal{W}_q)$ evaluated by CRITIC method

Criteria	Funding $(\mathcal{C}_1)$	Coordination $(\mathcal{C}_2)$	Infrastructure $(\mathcal{C}_3)$	Transparency $(\mathcal{C}_4)$	Logistics $(\mathcal{C}_5)$	Sustainability $(\mathcal{C}_6)$
Weight	0.209	0.199	0.113	0.156	0.194	0.129

Pi diagram.png

Fig. 4. Pi diagram of the criteria weight evaluated by the CRITIC method

Remark 1. *From Table 10, we can observe that the criterion Funding* $(\mathcal{C}_1)$ *obtains the highest weight of* 0.209 *among all the criteria. The criterion Coordination* $(\mathcal{C}_2)$ *takes the weight* 0.199 *and the criterion Logistics* $(\mathcal{C}_5)$ *obtains the weight* 0.194*, which are the second and third highest weights, respectively. The criterion Infrastructure* $(\mathcal{C}_3)$ *has a weight of* 0.113*, which is the lowest among all criteria. Here, we have provided a Pie diagram in Figure 4 to visualise and gain a clear understanding of the weight obtained by each criterion.*

8. Research Implication

This research has significant implications for educational and implementation purposes in the area of Humanitarian Supply Chain Management (HSCM) systems. Triangular fuzzy numbers integrated with Multi-Criteria Decision-Making (MCDM) methodology; this study sequentially recognised important criteria as considered challenges in humanitarian settings. From a theoretical viewpoint, the MCDM model with uncertainty (i.e., fuzzy sets, grey numbers, neutrosophic numbers, linguistic terms, or probabilistic numbers) constructs an extraordinarily complex model to capture the uncertainty and vagueness of real-world problems and measures the opinions of experts more accurately. These mathematical decision-making models make a significant contribution to achieving HSCM and provide a roadmap for a more robust evaluation foundation for future work.

From a practical standpoint, this study contributes to the humanitarian organizations, government officials, NGOs and policy makers to focus their resources, rescue operations and strategic efforts on the most urgent issues such as infrastructure fragility, disruptions of information flow and unproductive coordination. By considering these important issues in an uncertain environment, decision-makers can adopt more realistic, resistant and efficient supply chain strategies. Additionally, this structural model can be utilised as a replicable decision-support tool for determining operational risks and limitations in various humanitarian contexts, thereby opening the door for more intelligent and flexible supply chain interventions.

9. Conclusions and Future Research Scope

This research has the goal of determining and prioritising the challenges of Humanitarian Supply Chain Management (HSCM) using an uncertain Multi-Criteria Decision-Making (MCDM) technique. Taking into consideration the ambiguity and unpredictability in humanitarian operations, the combination of uncertainty in the MCDM approach allowed for a more realistic and trustworthy assessment of professional judgement.

The numerical results are described in the numerical illustration section. The Funding (C_1) criteria are the most challenging criterion, followed by Coordination (C_2) criteria for Humanitarian Supply Chain Management (HSCM) research. These results can be attributed to coordination among stakeholders, limited infrastructure, insufficient funding, and poor information sharing, which significantly hinder the effectiveness of humanitarian supply chains. The fuzzy MCDM method effectively captures the complexity of these difficulties by accommodating uncertainty, vague and imprecise inputs, reflecting the dynamic nature of the humanitarian supply chain.

In conclusion, this research contributes to the corpus of knowledge by presenting a model formulation and an uncertain framework for identifying the key challenges in HSCM. This study provides practical advice for aid organisations, decision-makers, enabling them to prioritize and address the most pressing challenges to upgrade reactivity, efficiency and fortitude in humanitarian supply chains.

In future research, researchers can expand on this study by considering specific disaster scenarios to further enhance the HSCM system. Further research can extend this study by incorporating stakeholders' opinions to develop a more realistic and efficient model formulation. Additionally, this study can be re-evaluated by taking more challenges as criteria and sub-criteria for building a realistic model formulation.

Author Contributions

Conceptualization, methodology, and software, K.H.G., A.B., T.B., A.G., and S.P.M.; validation, K.H.G., and A.B.,; writing—original draft preparation, writing—review and editing, and visualization, K.H.G., A.B., T.B., A.G., and S.P.M.; supervision, S.P.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability

All the necessary data are cited in the article.

Conflicts of Interest

The authors declare that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper. There are no conflicts of interest between authors.

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