# Optimizing Horizontal Collaboration in Logistics with Neutrosophic Z-Number Decision Models

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**Abstract:** Horizontal collaboration (HC) has emerged as a strategic approach to improve efficiency, sustainability, and competitive advantage while reducing $CO_2$ emissions in supply chain operations. Despite its potential, HC implementation faces significant challenges, including trust management, strategic alignment, and decision-making complexities. This study proposes an integrated methodology that combines the Delphi technique and the DEMATEL framework, enhanced by Neutrosophic Z-number (NZN) theories, to identify and prioritize critical success factors (CSFs) influencing HC. A case study in Vietnam validates the robustness and practical applicability of the proposed model. The findings highlight economic factors—such as financial stability, data sharing, and innovation adoption—as key drivers of successful HC. Additionally, social factors, including organizational culture and conflict resolution, are found to be intricately linked to economic performance. Environmental factors emphasize the critical role of green practices and resource optimization. This research provides actionable insights for logistics companies and policymakers aiming to promote effective HC, thereby advancing logistics efficiency and sustainability in Vietnam and other developing economies. The proposed framework also offers a valuable foundation for future research and practical innovations in optimizing logistics collaboration.

**Keywords:** Neutrosophic sets, Z-number, MCDM, Delphi, DEMATEL, sustainable horizontal collaboration, logistics, Vietnam

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## 1. Introduction

The logistics industry is vital to the economic framework of many countries, closely connected to economic expansion and the scale of goods movement [1]. This industry is a significant employer and facilitates the movement of products essential for daily economic activities. In the United States, for instance, the logistics sector moves an enormous amount of freight daily, serving numerous manufacturing sites, warehouses, and businesses across the country. The industry also employs millions of workers annually, with substantial job growth. Likewise, in the European Union, the logistics sector accounts for a significant market share and employs a considerable part of the labor force. Globally, the volume of freight movement is expected to continue expanding, driven by factors such as increased international trade and the growth of e-commerce [2].

A significant reason, however, is that even though logistics is of critical importance, inefficiencies abound. For example, whereas most freight is delivered by truck in the U.S., trailers are only 43% full by weight capacity on average. Additionally, 25% of all miles driven have either empty or nearly empty trailers, while the trailers are, on average, only 57% complete during the remaining 75% of miles traveled [3]. The same inefficiencies exist in the European Union, where country-specific data exist for empty truck miles, but studies estimate a range of 15% to 20% [4]. In addition to raising freight transportation costs, these inefficiencies contribute to adverse environmental effects, notably by increasing CO2 emissions from burning fossil fuels. Whereas transportation contributes approximately 29% to CO2 emissions in the United States, freight transportation accounts for about 10% annually [5]. Moreover, increasing congestion on roads and highways aggravates matters and reduces the likelihood of delivery on time, very much so in urban areas; in such a scenario, the implications for the quality of life of a citizen are huge.

At this time, optimizing individual supply chains has reached a point where further improvements yield diminishing returns. Addressing these inefficiencies requires a significant shift in logistics practices; collaborative logistics, precisely HC, offers a promising solution. HC in logistics is defined as partnerships among companies operating at similar levels of the supply chain, focusing on resource-sharing to achieve greater efficiency and lessen ecological effects. This approach differs from vertical collaboration (VC), where coordination occurs across various supply chain tiers, like manufacturers and retailers. HC has demonstrated potential for substantial cost savings and CO2 emissions reductions. Additionally, HC helps firms reduce duplication of efforts and increase load factors, enhancing overall operational efficiency.

The necessity of conducting this research in Vietnam is underscored by the unique challenges and opportunities the country’s logistics sector presents. Vietnam’s logistics sector is notably fragmented, with a significant presence of small and medium-sized enterprises (SMEs) that frequently face limited resources and capabilities, impacting their ability to function effectively and sustainably [6]. As Vietnam continues to integrate economically globally, the demand for efficient logistics services grows. However, these SMEs face significant hurdles, such as inadequate infrastructure, a lack of robust legal frameworks, and deeply ingrained competitive mindsets that hinder collaborative efforts. Furthermore, Vietnam’s rapid urbanization and increasing trade volumes exacerbate congestion and environmental concerns, necessitating innovative solutions to enhance logistics efficiency and sustainability. HC presents a promising strategy to address these issues by enabling resource sharing and reducing operational redundancies. However, the implementation of HC in Vietnam is fraught with challenges, including managing trust among partners and aligning strategic goals, which are particularly complex when partners are competitors. Identifying and prioritizing the CSFs for effective HC is crucial to overcoming these barriers and fostering a more collaborative and efficient logistics environment in Vietnam. This study addresses existing knowledge gaps and offers practical guidance to Vietnamese logistics companies, policymakers, and stakeholders for effective HC adoption. By doing so, it aims to enhance Vietnam's logistics efficiency and strengthen its competitive position in the global market. The objectives of the study are:

*i) Identification and prioritization of CSF contributing to efficiency in LHC.*

*ii) Analysis of the complex inter-relationships and interdependencies between these variables.*

The following research questions are proposed by this current study with respect to the above objectives:

*i) What CSFs lead to efficiency in LHC?*

*ii) What is the nature of interaction and interdependence among these factors in logistic companies?*

To achieve the objectives of this study, which focuses on identifying and prioritizing CSFs in LHC, it is essential to adopt methodologies capable of handling the logistics domain's inherent uncertainty, complexity, and variability[7]. This study employs an MCDM-based Neutrosophic Z-Number (NZN) approach, which integrates Neutrosophic Sets (NS) with Z-Numbers to form a robust framework for decision-making. NS represents a significant advancement over traditional fuzzy sets (FS) by addressing the limitations of existing uncertainty modeling techniques [8]. While FS relies on a single membership grade to quantify uncertainty, NS introduces three independent components: truth, indeterminacy, and falsity. This multifaceted structure enables a more comprehensive representation of real-world scenarios, accommodating not only the degree of membership but also the levels of hesitation and contradiction inherent in uncertain information [9], [10].

Compared to other fuzzy set extensions, such as Triangular Fuzzy Numbers (TFNs) [11], Intuitionistic Fuzzy Sets (IFS) [12], Pythagorean Fuzzy Sets (PFS) [13], and newer variants like Picture Fuzzy Sets [14] and Spherical Fuzzy Sets [15], NS offers unparalleled flexibility. For instance, TFNs are constrained to defining membership degrees within a triangular distribution, making them inadequate for capturing non-membership or hesitation. IFS extends FS by incorporating non-membership degrees but fails to capture indeterminacy explicitly. PFS allows the squared sum of membership and non-membership degrees to total within the range of 0 to 1, which increases flexibility but imposes mathematical constraints that limit real-world applicability [16]. Similarly, Picture and Spherical Fuzzy Sets introduce hesitation degrees but restrict their components (membership, non-membership, and hesitation) to summation or squared constraints within fixed ranges [17]. NS overcomes these limitations by treating truth, indeterminacy, and falsity as independent variables, each ranging freely between 0 and 1, with their combined total spanning from 0 to 3. This independence provides unparalleled flexibility in modeling complex systems, making NS uniquely suited for analyzing the multifaceted challenges of LHC.

While NS provides a robust foundation for handling uncertainty, its effectiveness can be further enhanced by integrating Z-Numbers, which Zadeh [18] introduced to include two components: a fuzzy representation of an uncertain variable (M) and the degree of reliability or confidence in the information source (N). This dual-layer representation of uncertainty addresses the uncertain variable and the trustworthiness of the data or expert judgment. Combining NS and Z-Numbers into the NZN framework creates a robust method for managing ambiguity and assessing source reliability. For example, in Vietnam's logistics sector, diverse stakeholders often provide information with varying levels of reliability [19]. Z-numbers allow for explicitly evaluating these variations in data trustworthiness, complementing NS's ability to handle indeterminacy.

The NZN framework provides a nuanced representation of stakeholder hesitation and conflicting priorities, which are common in LHC. NS captures these complexities through its indeterminacy component, while Z-numbers enhance the analysis by evaluating the reliability of conflicting information. This dual-layer approach ensures that decisions are not only comprehensive but also grounded in the most reliable data [9]. Furthermore, the NZN framework systematically prioritizes CSFs by integrating truth, indeterminacy, and falsity dimensions with reliability evaluations. For example, green practices may have a high truth value (importance), moderate indeterminacy (uncertainty about implementation), and low falsity (minimal contradiction among stakeholders), with a high-reliability score reinforcing its prioritization [8].

The NZN framework is particularly suitable for Vietnam's logistics landscape, characterized by fragmented infrastructure, trust deficits, and conflicting stakeholder objectives. These issues necessitate a framework that can handle the indeterminate and ambiguous nature of stakeholder inputs, accommodate varying levels of data reliability, and systematically prioritize factors influencing collaboration. Combining NS's flexibility in uncertainty modeling with Z-Numbers' ability to evaluate data reliability, the NZN framework offers a comprehensive approach to addressing these challenges. This hybrid approach generates actionable insights and robust prioritizations, fostering successful collaboration in Vietnam's logistics sector and serving as a template for similar developing economies.

This research conducted a comprehensive literature review and expert judgment involving logistics professionals and academics to analyze the interconnections and interdependencies among the identified CSFs. Together, these MCDM tools enable a rigorous evaluation of strategies, enhance decision-making by quantifying qualitative data, and provide actionable recommendations tailored to enhance efficiency and sustainability in Vietnam's logistics sector. Among various MCDM models, the Delphi method facilitates expert consensus-building, crucial for understanding qualitative insights and ensuring comprehensive coverage of factors impacting HC implementation [20]. DEMATEL, on the other hand, provides a structured way to analyze the causal relationships and interdependencies among identified CSFs, offering insights into which factors are pivotal and how they interact [19]. By leveraging Delphi and DEMATEL, this research aims to uncover nuanced insights and foster collaborative frameworks that can effectively address Vietnamese logistics firms' unique challenges, paving the way for improved competitiveness and environmental stewardship in the global logistics landscape.

It can be concluded that a comprehensive understanding of the current operational and strategic CSFs is crucial for the successful implementation of LHC within Vietnam's logistics sector. Additionally, the study proposes practical frameworks and models tailored to the unique challenges faced by Vietnamese logistics firms, particularly SMEs operating in a fragmented market. This research aims to thoroughly analyze LHC's benefits, challenges, and key success factors, offering actionable insights and strategies for logistics firms, policymakers, and relevant stakeholders. These findings can support effective collaboration, boost the efficiency and sustainability of logistics operations in Vietnam, and strengthen the nation's competitive edge within the global logistics market. Integrating NS and Z-Number theory with MCDM techniques, such as Delphi and DEMATEL, will increase the comprehensiveness of expert assessments. This combination allows for the inclusion of zero-level certainty factors in the calculation process, leading to more accurate and reliable results and improving model efficiency. Additionally, incorporating expert weighting and multiplying these weights by the ratings ensures that the outcomes are more comprehensive and realistic. This approach considers experts' varying knowledge and experience across different industries.

The structure of the study is elaborated upon in the subsequent section. Section 2 of this paper provides an in-depth review of the current literature. Section 3 of the document furnishes a comprehensive elucidation of the study process and the methodology employed. This study will explore the discussions and insights from the empirical analysis, mainly focusing on Sections 4 and 5. Section 6 summarizes the key conclusions, implications, limitations, and potential directions for future research.

## 2. Literature Review

### *2.1. Theoretical Foundation*

Mason et al. [20] delineated two primary forms of logistics collaboration: Vertical Collaboration (VC) and Horizontal Collaboration (HC). VC emphasizes fostering advantageous relationships across different supply chain tiers, such as manufacturers, distributors, and retailers, promoting integration and efficiency across stages [21]. Conversely, HC pertains to cooperative arrangements between organizations operating at the same level within the supply chain or within the same industry [21]. Unlike VC, HC unites peers or competitors to address shared challenges and pursue mutual objectives jointly. By leveraging complementary resources and capabilities, HC enables organizations to achieve superior outcomes collectively compared to operating in isolation [22]. HC initiatives encompass various practices, including knowledge sharing, co-developing industry standards, joint research and development (R&D), and sector-wide sustainability programs.

The potential benefits of HC are substantial, encompassing cost reductions, operational efficiencies, innovation facilitation, and the development of industry-wide solutions. For example, a collaborative effort in Spain's automotive sector successfully reduced the number of freight journeys and associated emissions without compromising delivery lead times [23]. However, implementing HC faces critical challenges, such as fostering participant trust, aligning goals—especially among competitors—and establishing strategic frameworks to guide collaboration. These challenges are particularly pronounced when adopting sustainable HC practices, which are crucial for transitioning the logistics sector towards "green logistics," given the environmental impact of freight transport. Globally, freight transport contributes approximately 5.5% to total emissions, with the need for sustainable practices growing increasingly urgent [24]. In Vietnam, logistics contributes approximately 25% to the national GDP, with transport costs accounting for 50-60% of total logistics expenses, further intensifying emission concerns. These challenges are magnified by Vietnam's vulnerabilities to climate change and its rapidly expanding import-export market. Sustainable HC offers a viable pathway for Vietnamese logistics enterprises—many SMEs—to collaboratively drive green innovations, establish sustainability standards, and achieve economies of scale. Such an approach allows for joint investments in initiatives like route optimization, alternative fuels, and environmental stewardship, accelerating the adoption of green logistics practices while enhancing competitiveness in the global market.

HC can be conceptualized as a strategic supply chain when partnerships exhibit dynamic, operational, and technological integration and maintain long-term adaptability [25]. In this context, HC fosters a structured supply chain environment where collaboration amplifies value creation. Integrating Sustainable Development Theory (SDT) and the Triple Bottom Line (TBL) framework provides a comprehensive lens for understanding and enhancing sustainable HC practices in Vietnam's logistics sector. This theoretical synergy offers valuable insights into the CSFs necessary to facilitate effective partnerships among logistics enterprises while balancing economic, social, and environmental dimensions. Supply chain partnerships often present a social dilemma characterized by a tension between individual short-term gains and collective long-term benefits [26]. A social dilemma arises when individuals must choose between actions that benefit themselves versus those that benefit the group. In fragmented logistics markets like Vietnam, companies might prioritize immediate cost savings over investments in sustainable practices that benefit the broader network. SDT addresses these dilemmas by offering strategies to resolve conflicts, such as fostering trust, enhancing communication, and aligning partner incentives. The TBL framework complements this by advocating for a broader definition of success—encompassing environmental, social, and economic impacts—encapsulated by the principles of "People, Planet, and Profit" [27]. This holistic perspective encourages businesses to align their operations with sustainable development goals, ensuring resource preservation for future generations while uncovering opportunities for growth and innovation beyond purely financial considerations. By integrating SDT and TBL, a robust foundation emerges for identifying CSFs essential for sustainable HC.

### *2.2. Literature Review on CSFs in LHC*

Previous studies employed diverse methodologies to analyze LHC strategies and CSFs. Qualitative techniques like case studies and in-depth interviews provided rich insights into companies' motivations, collaboration processes, and experiences. Quantitative methods were also employed, with analytical hierarchy process (AHP) models and fuzzy logic frameworks used to assess partner compatibility and strategic fit. Process models and conceptual frameworks systematically mapped the stages of collaboration formation, operation, and outcome evaluation. Literature reviews and cross-case analyses synthesized findings across multiple studies to identify common themes, enablers, and barriers to successful collaboration [28]. Quantitative techniques like game and optimization models further analyzed dynamics such as gain/cost-sharing mechanisms, resource allocation strategies, and joint decision-making processes in horizontal alliances. Across these studies, critical factors like achieving monetary gains, future earnings potential, responding to regulatory pressures and customer demands, establishing trust between partners, ensuring strategic alignment and cultural compatibility, developing robust legal and governance frameworks, designing fair gain/risk sharing models, and enabling efficient information sharing have been identified as critical drivers influencing the successful adoption of HC initiatives [29], [30].

Previous research has identified various critical factors that drive companies to participate in HC initiatives, ultimately determining their success or failure. Internal motivations like achieving monetary gains, future earnings potential, and enhancing reputation play a significant role. External factors such as regulatory pressures, customer demands, and competitive forces also act as catalysts [31]. Establishing trust between partners is pivotal, as collaboration involves sharing resources and sensitive information between competing firms with diverse backgrounds. Trust mitigates potential conflicts and opportunistic behavior. Careful partner selection based on strategic alignment, compatible cultures, financial stability, and proven track records is crucial in the formation stage [32]. Other key factors include developing robust legal frameworks, governance mechanisms for joint decision-making, fair gain/risk-sharing models, and efficient information-sharing protocols. The involvement of neutral third parties or "network brokers" can facilitate partner identification, negotiation, and coordination, especially in early collaboration stages. By identifying and prioritizing CSFs, logistics companies can develop strategies that enhance collaboration efficiency and sustainability. These insights are invaluable for policymakers and industry stakeholders aiming to foster a more collaborative and competitive logistics environment. Below are CSF categories encompassing the economic, environmental, and social dimensions that integrate social dilemma theory, which organizations must consider, providing a holistic perspective on ensuring the financial viability, ecological sustainability, and societal impact of HC initiatives, as presented in **Table 1**.

**Table 1.** Potential Factors Affecting HC

| Main Dimensions | Code | Factors | References |
|---|---|---|---|
| Economic | EC1 | Financial Stability | Bahinipati et al. [28] |
| | EC2 | Data Sharing and Integration | Malviya et al. [33] |
| | EC3 | Collaborative Distribution Centers | Malviya et al. [33] |
| | EC4 | Innovation and Technology Adoption Ability | Malviya et al. [33] |
| | EC5 | General Governance Agreements & Commitment to Responsibilities | Karam et al. [34] |
| | EC6 | Consensus on Cost/Profit Sharing Policies | Karam et al. [34] |
| | EC7 | Trust coordination | Malviya et al. [33] |
| | EC8 | Governmental Support | Malviya et al. [33] |
| | EC9 | Cross-Functional Collaboration | Karam et al. [34] |
| Social | SC1 | The consensus on organizational culture | Weare et al. [35] |
| | SC2 | Labor Relations | Chen et al. [36] |
| | SC3 | Supplier Relationship Management | Büyüközkan et al. [37] |
| | SC4 | Community Engagement | Head et al. [38] |
| | SC5 | Coordinate employee training and development programs | Yousuf et al. [39] |
| | SC6 | Clear Conflict Resolution Mechanisms | Karam et al. [34] |
| Environmental | EN1 | General Green Transportation & Packaging Practices | Pomponi et al. [21] |
| | EN2 | Environmental efficiency optimizes coordination | Turki et al. [40] |

| | | |
|---|---|---|
| EN3 | General Waste Reduction and Recycling Mechanisms | Vlajic et al. [41] |
| EN4 | Circular Economy Practices | Sudusinghe et al. [42] |

For the economic dimension, the collaborating partners' financial stability (EC1)s essential, as HC often involves pooling resources, making joint investments in shared assets like distribution centers, and bearing coordination costs [28]. Substantial data sharing and integration capabilities (EC2) enable a seamless exchange of operational information for activities like consolidated shipment planning and order fulfillment coordination. Establishing collaborative distribution centers (EC3) allows partners to consolidate logistics activities, reduce redundancies, and achieve economies of scale. Innovation and technology adoption ability (EC4) ensures collaborating firms can implement process improvements and adopt digital solutions for transparency and efficiency gains. Robust governance agreements (EC5) that clearly define roles and decision rights and ensure commitment to assumed responsibilities provide a solid foundation for collaboration. Reaching consensus on equitable and mutually accepted cost and profit-sharing policies (EC6) is critical to prevent conflicts over the distribution of partnership gains. Building trust and coordination mechanisms (EC7) mitigates risks like free-riding and facilitates alignment of potentially divergent partner interests. Governmental support (EC8) through enabling policies, financial incentives, and investments in logistics infrastructure can greatly facilitate HC initiatives. Finally, effective cross-functional collaboration (EC9) helps align different business units like procurement, operations, and finance within each partner organization behind the collaboration goals. In the social dimension, critical factors include consensus on organizational culture (SC1), supplier relationship management (SC2), coordinated employee training and development programs (SC3), and precise conflict resolution mechanisms (SC4).

In the social dimension, achieving a consensus on organizational cultures (SC1) across the collaborating partners is vital to bridging potential differences in values, management styles, and working methods [39]. Cultural compatibility facilitates effective communication, cooperation, and integration of operations. Strong supplier relationship management capabilities (SC2) enable the extension of collaboration beyond the core partners to upstream suppliers in the supply chain. This unlocks opportunities for broader process integration and sustainability initiatives spanning the end-to-end supply network. Coordinating employee training and development programs (SC3) across partners helps build a skilled joint workforce aligned with the collaboration objectives and protocols. Conflicts and disagreements are inevitable in any collaboration, so precise conflict resolution mechanisms (SC4) are vital for addressing issues through prescribed negotiation, mediation, or arbitration channels. Robust governance and defined escalation paths for conflict resolution prevent disputes from derailing the partnership. By proactively addressing these social factors, collaborating organizations can establish an environment conducive to long-term cooperation, knowledge sharing, and realizing collective goals.

The environmental dimension focuses on factors that enable collaborating organizations to jointly drive sustainability initiatives and reduce their ecological footprint [40]. Adopting general green transportation and packaging practices (EN1), such as using cleaner vehicles/fuels, optimizing routes, and sustainable packaging materials, helps lower carbon emissions and waste from logistics activities. Optimizing coordination between partners to improve environmental efficiency (EN2) minimizes unnecessary product movements and redundant assets like facilities and vehicles, resulting in lower energy use and emissions. Implementing robust waste reduction and recycling mechanisms (EN3) allows collaborating firms to manage reverse logistics flows and reuse/recycle packaging and products in a closed-loop system. Taking this circular approach further, adopting comprehensive circular economy practices (EN4) enables partners to move toward a restorative industrial model by redesigning products and processes for longevity, reuse, refurbishing, and recycling across multiple life cycles. This extends resource productivity and eliminates waste. By collectively focusing on these environmental factors, HC empowers organizations to amplify their sustainability efforts, achieve scale in green initiatives, and transition towards a low-carbon, circular logistics model aligned with environmental stewardship goals.

*2.3. Literature Review on Established Methods*

Evaluating CSFs for sustainable LHC in Vietnam's logistics sector requires addressing various stakeholders, accommodating diverse perspectives, and managing inherent uncertainties. These complexities demand methodological approaches capable of effectively modeling ambiguity, quantifying uncertainty, and capturing the intricate interdependencies among various success factors. In this context, MCDM techniques have emerged as a valuable tool for tackling such challenges. This section reviews established methods, highlighting their applications, strengths, and limitations in evaluating CSFs for sustainable HC.

MCDM techniques, including widely used methods like the AHP [43] and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [44], have gained broad acceptance in logistics and supply chain management. These methods effectively address complex decision-making scenarios, such as supply chain design, sustainable manufacturing, and logistics network planning. For instance, Musumba et al. [45] employed a hybrid Fuzzy AHP-TOPSIS approach to facilitate partner selection for virtual enterprises, showcasing the method’s ability to synthesize diverse stakeholder preferences. Similarly, Zhou et al. [46] developed a hybrid model combining fuzzy DEMATEL, AEW, and FVIKOR techniques to evaluate and select sustainable recycling partners, highlighting the utility of integrating multiple MCDM tools to address multidimensional problems. Prakash et al.[47] applied a fuzzy MCDM framework to assess third-party providers for reverse logistics collaboration, while Lo et al. used a Fuzzy-rough FARE-MABAC approach to incorporate stakeholder insights for selecting sustainable logistics providers [48]. **Table 2** provides a comprehensive summary of these studies and their application areas.

**Table 1.** Related Works

| Techniques | Application Area | References |
|---|---|---|
| Fuzzy AHP-TOPSIS | Partner selection in establishing virtual enterprises | Musumba et al. [45] |
| Fuzzy DEMATEL-AEW-FVIKOR | Select a sustainable recycling partner | Zhou et al. [46] |
| Fuzzy MCDM | Evaluating third-party reverse logistics providers | Prakash et al. [47] |

| | | |
|---|---|---|
| Fuzzy-rough FARE-MABAC | Sustainable logistics provider selection | Lo et al. [48] |
| Fuzzy Delphi-AHP | Assess critical criteria in food supply chains | Gupta et al. [49] |
| BWM–VIKOR | Selecting and evaluating sustainable outsourcing partner | Garg et al. [50] |
| Neutrosophic CRITIC | Selecting warehouse management software in sustainable logistics systems | Kara et al. [51] |
| SVNFNPBM | Selecting third-party logistics providers | Ji et al. [52] |
| Neutrosophic TOPSIS | Fourth-party logistics firm assessment | Aydin et al. [53] |
| SVN-CRITIC-CoCoSo | Assessment of sustainable third-party reverse logistic provider | Mishra et al. [54] |

Despite the evident utility of these methods, they exhibit certain limitations when applied to the complexities of sustainable HC in Vietnam's fragmented logistics market. While techniques such as Fuzzy Delphi-AHP and Fuzzy DEMATEL-AEW-FVIKOR have effectively addressed stakeholder divergence and ambiguity, they have primarily relied on fuzzy logic [46]. Integrating NZN theory remains underexplored, representing a critical gap in managing uncertainties more comprehensively [8], [19]. Neutrosophic Sets extend traditional fuzzy logic by accounting for indeterminacy, and Z-number, which incorporates reliability through confidence levels, offers significant potential for enhancing decision-making reliability in HC evaluations [10], [52].

Secondly, existing studies have not sufficiently utilized two-stage models combining the Delphi method and DEMATEL. While the Delphi method excels at achieving expert consensus, DEMATEL is particularly useful for analyzing causal relationships among CSFs. However, the absence of their combined application limits the ability to refine input data through consensus-building and systematically analyze the complex interdependencies among factors [19]. Such an integrated approach would provide a more nuanced understanding of the causal dynamics that underpin successful HC in logistics.

Lastly, the practical application of Neutrosophic-based methods in real-world HC scenarios, particularly in logistics, remains limited. Although approaches like Neutrosophic CRITIC and SVN-CRITIC-CoCoSo have demonstrated utility in evaluating logistics providers, their application to sustainable HC has not been explored in depth [54]. The lack of integration of Neutrosophic Sets with MCDM frameworks leaves a significant gap in understanding how to prioritize and evaluate factors effectively under uncertainty, especially in collaborative logistics settings.

The proposed two-stage approach combines the Delphi method for achieving expert consensus with DEMATEL for analyzing causal relationships among CSFs. By leveraging the strengths of these methodologies, the framework aims to manage uncertainties more effectively, capture the complex interdependencies among factors, and provide actionable insights for logistics enterprises. This approach supports adopting sustainable HC practices in Vietnam's logistics sector, enabling companies to balance economic, environmental, and social considerations while addressing the unique challenges of fragmented market dynamics.

## 3. Proposed Methods

### *3.1 Preliminaries*

Traditional fuzzy sets, while groundbreaking in handling uncertainty, have limitations. They express membership through a single value in [0,1], which fails to capture non-membership or hesitancy often encountered in real-world decisions [55]. Intuitionistic Fuzzy Sets (IFS) extended fuzzy sets by adding non-membership values, but the constraint that their sum must not exceed 1 limits their flexibility in complex scenarios [56]. Type-2 fuzzy sets addressed this by modeling higher uncertainty through secondary membership functions, but their computational complexity made them impractical for real-time use [57].

Z-numbers introduced reliability measures, combining truth values with reliability assessments, but struggled with contradictory information [57]. NS independently model truth, indeterminacy, and falsity, excelling in handling vague or contradictory data, though they lacked a mechanism for expressing the reliability of these values [58]. Picture Fuzzy Sets added a neutral component but did not adequately address reliability [59]. The NZN combines uncertainty and reliability, overcoming the limitations of previous methods and providing a robust tool for complex decision-making scenarios [60].

**Definition 1** [19], [61], [62], [63], [64] A NZN set is defined as Equation (1):

$$\mathrm{NZN_z} = \{[x, a(M,N)(x), b(M,N)(x), c(M,N)(x)] | x \epsilon X\} \tag{1}$$

Where

$\alpha(M,N)(x) = \big(a_M(x), a_N(x)\big)$; $b(M,N)(x) = \big(b_M(x), b_N(x)\big)$; $c(M,N)(x) = \big(c_M(x), c_N(x)\big)$: $X \rightarrow [0,1]^2$.

M represents neutrosophic values corresponding to the universal set X, while N signifies the neutrosophic reliability measures associated with M. Both components follow specific predefined conditions:

$0 \le a_M(x) + b_M(x) + c_M(x) \le 3$ and $0 \le a_N(x) + b_N(x) + c_N(x) \le 3$

$[x, a(M,N)(x), b(M,N)(x), c(M,N)(x)]$ in $N_Z$ is succinctly represented as $N_Z = [a(M,N), b(M,N), c(M,N)] = [(a_M, a_N), (b_M, b_N), (c_M, c_N)]$

**Definition 2** [19], [61], [63], [64], [65]

$\mathrm{NZN_{Z1}} = [a_1(M,N), b_1(M,N), c_1(M,N)] = [(a_{M1}, a_{N1}), (b_{M1}, b_{N1}), (c_{M1}, c_{N1})$ and

$\mathrm{NZN_{Z2}} = [a_2(M,N), b_2(M,N), c_2(M,N)] = [(a_{M2}, a_{N2}), (b_{M2}, b_{N2}), (c_{M2}, c_{N2})$ are two NZNs and $\vartheta > 0$. Then, we give the following relations (Equations (2) – (10)).

1. $$\mathrm{NZN_{Z1}} \supseteq \mathrm{NZN_{Z2}} \Leftrightarrow a_{M1} \ge a_{M2},\ a_{N1} \ge a_{N2},\ b_{M1} \le b_{M2},\ b_{N1} \le b_{N2},\ c_{M1} \le c_{M2} \text{ and } c_{N1} \le c_{N2} \tag{2}$$

2. $NZN_{Z1} = NZN_{Z2} \Leftrightarrow NZN_{Z1} \supseteq NZN_{Z2}$ and $NZN_{Z2} \supseteq NZN_{Z1}$ (3)

3. $NZN_{Z1} \cup NZN_{Z2} \Leftrightarrow [(a_{M1} \vee a_{M2},\ a_{N1} \vee a_{N2}),\ (b_{M1} \wedge b_{M2},\ b_{N1} \wedge b_{N2}), (c_{M1} \wedge c_{M2}, c_{N1} \wedge c_{N2})]$ (4)

3. $NZN_{Z1} \cap NZN_{Z2} \Leftrightarrow [(a_{M1} \wedge a_{M2},\ a_{N1} \wedge a_{N2}),\ (b_{M1} \vee b_{M2},\ b_{N1} \vee b_{N2}), (c_{M1} \vee c_{M2}, c_{N1} \vee c_{N2})]$ (5)

4. $(NZN_{Z1})^C = [(c_{M1}, c_{N1}), (1 - b_{M1}, 1 - b_{N1}), (a_{M1}, a_{N1})]$ (Complement of $NZN_{Z1}$) (6)

5. $NZN_{Z1} \oplus NZN_{Z2} = [(a_{M1} + a_{M2} - a_{M1}a_{M2}, a_{N1} + a_{N2} - a_{N1}a_{N2}), (b_{M1}b_{M2}, b_{N1}b_{N2}), (c_{M1}c_{M2}, c_{N1}c_{N2})$ (7)

6. $NZN_{Z1} \otimes NZN_{Z2} = [(a_{M1}a_{M2}, a_{N1}\alpha_{N2}), (b_{M1} + b_{M2} - b_{M1}b_{M2}, b_{N1} + b_{N2} - b_{N1}b_{N2}), (c_{M1} + c_{M2} - c_{M1}c_{M2}, c_{N1} + c_{N2} - c_{N1}c_{N2})]$ (8)

7. $\vartheta NZN_{Z1} = [(1 - (1 - a_{M1})^{\vartheta}, 1 - (1 - a_{N1})^{\vartheta}), (\beta_{M1}^{\vartheta}, \beta_{N1}^{\vartheta}), (\gamma_{M1}^{\vartheta}, \gamma_{N1}^{\vartheta})]$ (9)

8. $(NZN_{Z1})^{\vartheta} = [\ (a_{M1}^{\vartheta}, a_{N1}^{\vartheta}), (1 - (1 - b_{M1})^{\vartheta}, 1 - (1 - b_{N1})^{\vartheta}), (1 - (1 - c_{M1})^{\vartheta}, 1 - (1 - c_{N1})^{\vartheta})]$ (10)

Defuzzy $NZN_{Z1} = [a_1(M, N), b_1(M, N), c_1(M, N)] = [(a_{M1}, a_{N1}), (b_{M1}, b_{N1}), (c_{M1}, c_{N1})$ Using Equation (11).

$$DEF(NZN_{Z1}) = \frac{2 + a_{M1}\, a_{N1} - b_{M1}\, b_{N1} - c_{M1}\, c_{N1}}{3}, DEF(NZN_{Z1}) \in [0, 1] \quad (11)$$

**Illustrative example 1:**

With two NZN: $NZN_{Z1}$ =[(0,2;0,6);(0,85;0,35);(0,8;0,4)], $NZN_{Z2}$ =[(0,4;0,2);(0,65;0,85);(0,6;0,8)] and $\vartheta = 3$, the results of calculation by use operations (7) - (11) are shown below:

$$NZN_{Z1} \oplus NZN_{Z2} = [(0{,}2; 0{,}6); (0{,}85; 0{,}35); (0{,}8; 0{,}4)] \oplus [(0{,}4; 0{,}2); (0{,}65; 0{,}85); (0{,}6; 0{,}8)]$$
$$= [(0{,}52; 0{,}68); (0{,}5525; 0{,}2975); (0{,}48; 0{,}32)]$$

$$NZN_{Z1} \otimes NZN_{Z2} = [(0{,}2; 0{,}6); (0{,}85; 0{,}35); (0{,}8; 0{,}4)] \otimes [(0{,}4; 0{,}2); (0{,}65; 0{,}85); (0{,}6; 0{,}8)]$$
$$= [(0{,}08; 0{,}12); (0{,}9475; 0{,}9025); (0{,}92; 0{,}88)]$$

$$3 \times NZN_{Z1} = 3 \times [(0{,}2; 0{,}6); (0{,}85; 0{,}35); (0{,}8; 0{,}4)]$$
$$= [(0{,}488; 0{,}936); (0{,}6141; 0{,}0429); (0{,}512; 0{,}064)]$$

$$(NZN_{Z1})^3 = ([(0{,}2; 0{,}6); (0{,}85; 0{,}35); (0{,}8; 0{,}4)]\ )^3$$
$$= [(0{,}008; 0{,}216); (0{,}9966; 0{,}7254); (0{,}992; 0{,}784)]$$

$$DEF(NZN_{Z1})^3 = \frac{2 + 0{,}2 * 0{,}6 - 0{,}85 * 0{,}35 - 0{,}8 * 0{,}4}{3} = 0{,}5008$$

**Definition 3** [19], [61], [62], [63]:

Using Equations (7) and (9) in Definition 2, the equation for the Weighted Aggregation Arithmetic Mean (NZNWAA) for NZNs is derived. Let $NZN_{Zi} = [a_i(M, N), b_i(M, N), c_i(M, N)] = [(a_{Mi}, a_{Ni}), (b_{Mi}, b_{Ni}), (c_{Mi}, c_{Ni})], (i = 1, 2, \dots n)$ be a group of NZN and NZNWAA: $\Omega^n \longrightarrow \Omega$. Subsequently, the NZNWAA equation is formally defined as Equation (12).

$$NZNWAA(\mathrm{NZN_{Z1}}, \mathrm{NZN_{Z2}}, \ldots, \mathrm{NZN_{Zn}}) = \sum_{i=1}^{n} \vartheta_i \, \mathrm{NZN_{Zi}} = \left[1 - \prod_{i=1}^{n}(1 - a_{Mi})^{\vartheta_i}, 1 - \prod_{i=1}^{n}(1 - a_{Ni})^{\vartheta_i}), (\prod_{i=1}^{n} b_{Mi}{}^{\vartheta_i}, \prod_{i=1}^{n} b_{Ni}{}^{\vartheta_i}), (\prod_{i=1}^{n} c_{Mi}{}^{\vartheta_i}, \prod_{i=1}^{n} c_{Ni}{}^{\vartheta_i})\right] \tag{12}$$

where $\vartheta_i (i = 1, 2..n)$ is the weight of $\mathrm{NZN_{Zi}}$, $0 \leq \vartheta_i \leq 1$ and $\sum_{i=1}^{n} \vartheta_i = 1$

The equation for calculating the weighted aggregation through the geometric mean (NZNWAGM) is as follows: $\mathrm{NZN_{Zi}} = [a_i(M,N), b_i(M,N), c_i(M,N)] = [(a_{Mi}, a_{Ni}), (b_{Mi}, b_{Ni}), (c_{Mi}, c_{Ni})], (i = 1, 2, \ldots n)$ be a group of NZN and NZNWGA: $\Omega^n \longrightarrow \Omega$. The NZNWGA equation is formally defined as shown in Equation (13).

$$NZNWGA(\mathrm{NZN_{Z1}}, \mathrm{NZN_{Z2}}, \ldots, \mathrm{NZN_{Zn}}) = \prod_{i=1}^{n} (\mathrm{NZN_{Zi}})^{\vartheta_i} = [(\prod_{i=1}^{n} (a_{Mi})^{\vartheta_i}, \prod_{i=1}^{n} (a_{Ni})^{\vartheta_i}), (1 - \prod_{i=1}^{n}(1 - b_{Mi})^{\vartheta_i}, 1 - \prod_{i=1}^{n}(1 - b_{Ni})^{\vartheta_i}), 1 - \prod_{i=1}^{n}(1 - c_{Mi})^{\vartheta_i}, 1 - \prod_{i=1}^{n}(1 - c_{Ni})^{\vartheta_i}) \tag{13}$$

where $\vartheta_i (i = 1, 2..n)$ is the weight of $\mathrm{NZN_{Zi}}$ with $0 \leq \vartheta_i \leq 1$ and $\sum_{i=1}^{n} \vartheta_i = 1$

**Illustrative example 2:**

With set S include 3 NZN number S = {[(0,2;0,6);(0,85;0,35);(0,8;0,4)], [(0,4;0,2);(0,65;0,85);(0,6;0,8)], [(0,4;0,4);(0,65;0,65);(0,6;0,6)]} and corresponding weights $\vartheta_i = \{0{,}5; 0{,}4; 0{,}1\}$, the agreed results obtained using the NZNWAA and NZNWGA methods are summarized as follows:

NZNWAA (S) = [(0,3072;0,4503);(0,7433;0,531);(0,6928;0,5497)]

NZNWGA (S) = [(0,2828;0,3713);(0,7709;0,6601);(0,7172;0,6287)]

**Definition 4** [19], [66]: Metrics for assessing distance and similarity within NZN ts

Let $\mathrm{NZN_{Z1}} = \{\mathrm{NZN_{Z11}}, \mathrm{NZN_{Z12}} \ldots, \mathrm{NZN_{Z1n}}\}$ and $\mathrm{NZN_{Z2}} = \{\mathrm{NZN_{Z21}}, \mathrm{NZN_{Z22}} \ldots, \mathrm{NZN_{Z2n}}\}$, where $\mathrm{NZN_{Z1k}} = [a_{1k}(M,N), b_{1k}(M,N), c_{1k}(M,N)] = [(a_{M1k}, a_{N1k}), (b_{M1k}, b_{N1k}), (c_{M1k}, c_{N1k})]$, and $\mathrm{NZN_{Z2k}} = [a_{2k}(M,N), b_{2k}(M,N), c_{2k}(M,N)] = [(a_{M2k}, a_{N2k}), (b_{M2k}, b_{N2k}), (c_{M2k}, c_{N2k})]$ are two NZNs, set $\theta \geq 1$ as any integer, and the corresponding weights of n pairs of NZN $\vartheta_k = (\vartheta_1, \vartheta_2, \ldots \vartheta_n), \sum_{k=1}^{n} \vartheta_k = 1$. Subsequently, the generalized distance between $\mathrm{NZN_{Z1}}$ and $\mathrm{NZN_{Z2}}$ is calculated by the Equation (14):

$$\mathrm{DIS}_{w_\theta}(\mathrm{NZN_{Z1}}, \mathrm{NZN_{Z2}}) = \frac{1}{2}\left\{\sqrt[\theta]{\frac{1}{3}\sum_{k=1}^{n} \vartheta_k(|a_{M1k} - a_{M2k}|^{\vartheta} + |b_{M1k} - b_{M2k}|^{\vartheta} + |c_{M1k} - c_{M2k}|^{\vartheta})} + \sqrt[\theta]{\frac{1}{3}\sum_{k=1}^{n} \vartheta_k(|a_{N1k} - a_{N2k}|^{\vartheta} + |b_{N1k} - b_{N2k}|^{\vartheta} + |c_{N1k} - c_{N2k}|^{\vartheta})}\right\} \tag{14}$$

When $\theta = 1$, the generalized distance formula reduces to the Hamming distance formula $\mathrm{DIS_{w1}}$, as shown in Equation (15).

$$\mathrm{DIS_{w1}}(\mathrm{NZN_{Z1}},\mathrm{NZN_{Z2}}) = \frac{1}{6}\left\{\sum_{k=1}^{n}\vartheta_k\left(|a_{M1k}-a_{M2k}| + |b_{M1k}-b_{M2k}| + |c_{M1k}-c_{M2k}|\right) + \sum_{k=1}^{n}\vartheta_k\left(|a_{N1k}-a_{N2k}| + |b_{N1k}-b_{N2k}| + |c_{N1k}-c_{N2k}|\right)\right\} \tag{15}$$

When $\theta = 2$, this generalized distance formula simplifies to the Euclidean distance formula $\mathrm{DIS_{w2}}$, shown in Equation (16).

$$\mathrm{DIS_{w2}}(\mathrm{NZN_{Z1}},\mathrm{NZN_{Z2}}) = \frac{1}{2}\left\{\sqrt{\frac{1}{3}\sum_{k=1}^{n}\vartheta_k\left(|a_{M1k}-a_{M2k}|^2 + |b_{M1k}-b_{M2k}|^2 + |c_{M1k}-c_{M2k}|^2\right)} + \sqrt{\frac{1}{3}\sum_{k=1}^{n}\vartheta_k\left(|a_{N1k}-a_{N2k}|^2 + |b_{N1k}-b_{N2k}|^2 + |c_{N1k}-c_{N2k}|^2\right)}\right\} \tag{16}$$

**Illustrative example 3**

With two sets NZN: $SNZN_{Z1}$ ={[(0,2;0,6);(0,85;0,35);(0,8;0,4)], [(0,4;0,2);(0,65;0,85);(0,6;0,8)]} and $SNZN_{Z2}$ ={[(0,8;0);(0,15;1);(0,2;1)]; [(0,4;0,6);(0,65;0,35);(0,6;0,4)]}with corresponding weights $\vartheta_2 = (0{,}7; 0{,}3)$, the Euclidean distance between these two NZN sets is calculated using Equation (16):

$$DIS_{w2}(SNZN_{Z1},SNZN_{Z2}) = \frac{1}{2}\left\{\sqrt{\frac{1}{3}\begin{bmatrix}0{,}7(|0{,}2-0{,}8|^2 + |0{,}85-0{,}15|^2 + |0{,}8-0{,}2|^2)\\ +\,0{,}3(|0{,}4-0{,}4|^2 + |0{,}65-0{,}4|^2 + |0{,}6-0{,}6|^2)\end{bmatrix}} + \sqrt{\frac{1}{3}\begin{bmatrix}0{,}7(|0{,}6-0|^2 + |0{,}35-1|^2 + |0{,}4-1|^2)\\ +\,0{,}3(|0{,}2-0{,}6|^2 + |0{,}85-0{,}35|^2 + |0{,}8-0{,}4|^2)\end{bmatrix}}\right\} = 0{,}5501$$

*3.2 Research Procedure*

This study presents a two-stage MCDM approach combining NZN with the Delphi and DEMATEL methods, as shown in **Figure 1**. In the first phase, the NZN-Delphi method gathers expert opinions via a structured Delphi survey, where logistics experts identify and refine the CSFs for LHC. The iterative process ensures consensus and clarity on these factors, while NZN captures uncertainties and improves the reliability of expert judgments. In the second phase, the NZN-DEMATEL approach explores the causal relationships between the identified factors. DEMATEL creates influence relation maps to visualize the cause-and-effect dynamics and interdependencies among CSFs. By integrating NZN, the approach handles data uncertainty and provides a more accurate analysis, enabling a reliable prioritization of the success factors based on their impact and interconnections.

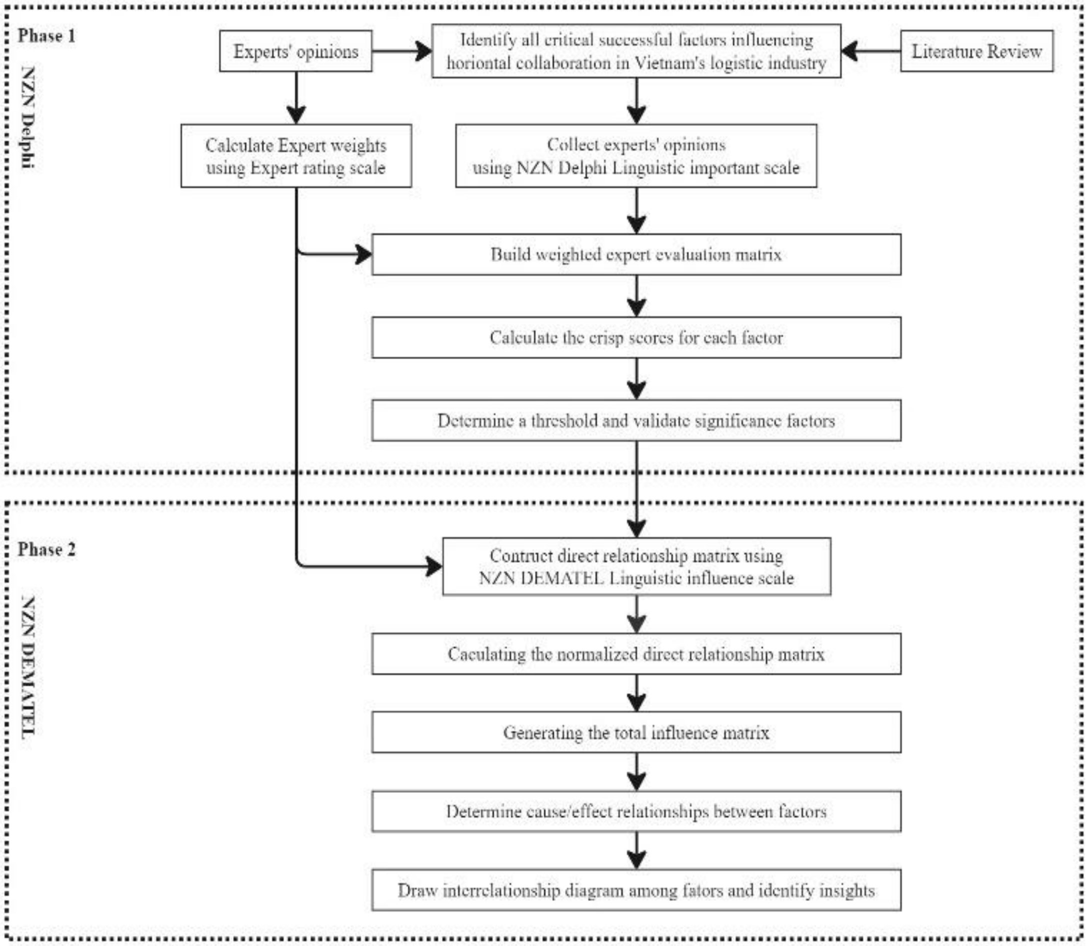


**Figure 1.** Proposed research framework

*3.3 NZN Delphi Model*

Suppose k experts provide evaluations for n factors. Each expert assesses the significance of these factors using a linguistic scale, which is subsequently converted to NZN numbers using NZN sets. Furthermore, experts are weighted according to their education and years of experience.

*Step 1: Compute the experts' weights.*

Expert weights will be determined using NZN numbers, comprising two key components: MM, representing the evaluation level based on the expert's experience and educational background, and NN, indicating the certainty level derived from the research team's understanding of the expert. These NZN values, reflecting the expert's rating, will be combined using Equation (7) and converted into a precise score via Equation (11). **Table 3** presents the expert assessments and corresponding linguistic scales [64].

**Table 3.** Expert rating scale

| Education (A) | Experience (A) | Linguistic scale (C) | NZN | Code |
|---|---|---|---|---|
| Doctor | Over 20 years | Very high | (0.8,0.15,0,2) | VH |
| Master | 10 – 20 years | High | (0.6,0.35,0.4) | H |
| Bachelor | 5 – 10 years | Medium | (0.4,0.65,0.6) | M |
| Under Bachelor | Under five years | Low | (0.2,0.85,0.8) | L |
| | | Very low | (0,1,1) | VL |

Calculate the evaluation value for k experts, obtaining k values EXK: $exk_j = \{exk_1, exk_2, \ldots exk_k\}$. The weight of expert EXW: $exw_j = \{exw_1, exw_2, \ldots exw_k\}$ is calculated as Equation (17) below:

$$exw_j = \frac{exk_j}{\sum_{j=1}^{k} exk_j} \tag{17}$$

*Step 2: Construct a matrix that incorporates weighted evaluations from experts.*

Experts will assess the importance of n factors, initially presented in linguistic form and then converted to NZN numbers. This process forms a matrix $\otimes EM = [em_{ij}]_{nxk}$, where n is a number of factors and k is several experts. The evaluation linguistic scale and corresponding NZN are detailed in **Table 4**.

**Table 4.** NZN Delphi linguistic significant scale

| Important level | Code | Membership | | |
|---|---|---|---|---|
| | | **α** | **β** | **γ** |
| Very low | VL | 0 | 1 | 1 |
| Low | L | 0.2 | 0.85 | 0.8 |
| Medium | M | 0.4 | 0.65 | 0.6 |
| High | H | 0.6 | 0.35 | 0.4 |
| Very high | VH | 0.8 | 0.15 | 0.2 |

The weighted expert evaluation matrix $\otimes EMW = [emw_{ij}]_{nxk}$ is created using Equation (18) below.

$$emw_{ij} = em_{ij} \otimes exw_j \tag{18}$$

with $i = 1, 2, \ldots n$ and $j = 1, 2, \ldots k$; $exw_j = \{exw_1, exw_2, \ldots exw_k\}$ is the expert's j of weight.

*Step 3: Determine the threshold and verify the variables.*

A panel of k experts evaluates each factor, with Equation (12) consolidating these assessments into aggregated results for n factors in NZN format. These ratings are then transformed into precise crisp scores using Equation (11), producing \( n \) EV values: $epv_i = \{epv_1, epv_2, \ldots evp_n\}$. The threshold value is calculated using Equation (19):

$$\delta = \frac{\sum_{i=1}^{n} epv_i}{n} \tag{19}$$

If value $epv_i \geq \delta$, then factor i is accepted. If value $epv_i < \delta$, then factor i is rejected.

*3.4 NZN DELMATEL Model*

Assume there are k experts, each assigned a specific weigh ew , assessing the reciprocal influence among n factors. These assessments are initially provided in linguistic terms, then translated into NZN. Table 5 displays the rating scale along with its associated NZN values [64].

**Table 5.** NZN DEMATEL linguistic influence scale

| Influence level | Code | Membership | | |
|---|---|---|---|---|
| | | **a** | **b** | **c** |
| Equal influence | EI | 0 | 1 | 1 |
| Week influence | WI | 0.2 | 0.85 | 0.8 |
| Fair influence | FI | 0.4 | 0.65 | 0.6 |
| Very influence | VI | 0.6 | 0.35 | 0.4 |
| Absolute influence | AI | 0.8 | 0.15 | 0.2 |

Once the assessments are transformed into NZN numbers, the data undergoes analysis through the DEMATEL method, with the calculation steps outlined below.

*Step 1: Calculating direct relationship matrix $\otimes DR$*

The assessments of the mutual influence among n factors - where factor i impacts factor j - as provided by k experts and denoted as$\mathrm{dr}_{ij}^{k}$, are transformed into NZN - based on the corresponding expert weights $\mathrm{exw}_t$. These transformed evaluations are then aggregated using equation (20), yielding the direct influence matrix $\otimes \mathrm{DR} = [\otimes \mathrm{dr}_{ij}]_{nxn}$, where:

$$\mathrm{dr}_{ij} = \mathrm{NZNWAA}\left(\mathrm{dr}_{ij}^{1}, \mathrm{dr}_{ij}^{2}, \dots, \mathrm{dr}_{ij}^{k}\right) = \sum_{t=1}^{k} \mathrm{exw}_t \mathrm{dr}_{ij}^{k} \tag{20}$$

where $i = 1, 2, \dots n$, $j = 1, 2, \dots n$, t = 1, 2.. k;

$\otimes \mathrm{d}_{ij} = \left[\left(\mathrm{dr}_{ij}^{a_E}, \mathrm{dr}_{ij}^{a_R}\right), \left(\mathrm{dr}_{ij}^{b_E}, \mathrm{dr}_{ij}^{b_R}\right), \left(\mathrm{dr}_{ij}^{c_E}, \mathrm{dr}_{ij}^{c_R}\right)\right]$. The diagonal elements in the matrix are 0, i.e, $\otimes \mathrm{dr}_{ij} = 0$ (when i = j).

*Step 2:Determining the normalized form of the direct relationship matrix $\otimes DR^{*}$*

Matrix $\otimes \mathrm{DR} = [\otimes \mathrm{dr}_{ij}]_{nxn}$ is transformed into a normalized form, represented as $\otimes \mathrm{DR}^{*} = [\otimes \mathrm{dr}_{ij}^{*}]_{nxn}$ by applying Equation (21) below:

$$\mathrm{dr}_{ij}^{*} = (\theta_E, \theta_R) . \mathrm{dr}_{ij} = \left[\left(\theta_E \mathrm{dr}_{ij}^{a_E}, \theta_R \mathrm{dr}_{ij}^{a_R}\right), \left(\theta_E \mathrm{dr}_{ij}^{b_E}, \theta_R \mathrm{dr}_{ij}^{b_R}\right), \left(\theta_E \mathrm{dr}_{ij}^{c_E}, \theta_R \mathrm{dr}_{ij}^{c_R}\right)\right] \tag{21}$$

where $\otimes \mathrm{dr}_{ij}^{*} = \left[\left(\mathrm{dr}_{ij}^{*a_E}, \mathrm{dr}_{ij}^{*a_R}\right), \left(\mathrm{dr}_{ij}^{*b_E}, \mathrm{dr}_{ij}^{*b_R}\right), \left(\mathrm{dr}_{ij}^{*c_E}, \mathrm{dr}_{ij}^{*c_R}\right)\right]$

$$\theta_A = \mathrm{Min}\left\{\frac{1}{\sum_{j=1}^{n} \mathrm{dr}_{ij}^{a_E}}; \frac{1}{\sum_{j=1}^{n} \mathrm{dr}_{ij}^{b_E}}; \frac{1}{\sum_{j=1}^{n} \mathrm{dr}_{ij}^{c_E}}\right\}$$

$$\theta_C = \mathrm{Min}\left\{\frac{1}{\sum_{j=1}^{n} \mathrm{dr}_{ij}^{a_R}}; \frac{1}{\sum_{j=1}^{n} \mathrm{dr}_{ij}^{b_R}}; \frac{1}{\sum_{j=1}^{n} \mathrm{dr}_{ij}^{c_R}}\right\} \tag{22}$$

*Step 3: Constructing the comprehensive influence matrix ⊗O*

The normalized direct relationship matrix $\otimes O$ is calculated to form the total influence matrix, incorporating both direct and indirect connections aggregated from minimal to maximal impact over an infinite range. The steps are detailed in Equations (23)-(24).

$$\otimes O = \left[\otimes o_{ij}\right]_{nxn}, \; i = j = 1, 2, \dots n \tag{23}$$

where $\otimes o_{ij} = \left[\left(o_{ij}^{a_E}, o_{ij}^{a_R}\right), \left(o_{ij}^{b_E}, o_{ij}^{b_R}\right), \left(o_{ij}^{c_E}, o_{ij}^{c_R}\right)\right]$

$$\begin{aligned} \otimes O &= \otimes DR^{*} + \otimes DR^{*2} + \dots + \otimes DR^{*\infty} \\ &= \otimes O(I + \otimes DR^{*} + \otimes DR^{*2} + \dots + \otimes DR^{*\infty-1}) \\ &= \otimes DR^{*}(I - \otimes DR^{*\infty})(I - \otimes DR^{*})^{-1} = \otimes D^{*}(I - \otimes DR^{*})^{-1} \end{aligned} \tag{24}$$

where $\otimes O^{\infty} = [0]_{nxn}$ and I is the identity matrix

Equation (11) is used to convert the NZN into crisp values, forming matrix $\otimes O^{*} = \left[\otimes o_{ij}^{*}\right]_{nxn}$

*Step 4: Establish cause-effect relationships between factors and compute weights as given in Equations (25)-(28)*

$\otimes r, \otimes c$ is calculated as below, with "superscript T" is the transpose of the matrix:

$$\otimes r = [\otimes r_i]_{nx1} = (\otimes r_1, \otimes r_2, \dots, \otimes r_{i,} \dots, \otimes r_n) \tag{25}$$

$$[\otimes r_i]_{nx1} = \left[\sum_{j=1}^{n} \otimes o_{ij}^{*}\right]_{nx1} \tag{26}$$

$$\otimes c = [\otimes c_i]_{1xn} = (\otimes c_1, \otimes c_2, \dots, \otimes c_{j,}, \dots, \otimes c_n)^{T} \tag{27}$$

$$\left[\otimes c_j\right]_{1xn} = \left[\sum_{i=1}^{n} \otimes o_{ij}^{*}\right]_{1xn} = [\otimes c_i]_{nx1}^{T} \tag{28}$$

The index of the strength of influences imparted and received is $\otimes r_i + \otimes c_i$. The net influence is represented by $\otimes r_i - \otimes c_i$. A higher $\otimes r_i + \otimes c_i$ indicates that criterion i has a more significant influence on the evaluation system. If $\otimes r_i - \otimes c_i > 0$, indicator i significantly influences others. If $\otimes r_i - \otimes c_i < 0$, indicator other indicators influence me. In general, it denotes the overall effect of the indicator on the assessment system. The indicator's impact weight is calculated using Equation (29).

$$w_i = \frac{(r_i + c_i)}{\sum_{i=1}^{n}(r_i + c_i)} \tag{29}$$

## 4. Results and Discussions

The research was conducted within the Vietnamese context to address specific issues in the country's logistics industry. Vietnam's logistics sector, a critical component of its economy, faces significant challenges related to efficiency, sustainability, and collaboration. This study focused on identifying and prioritizing CSFs for sustainable HC among logistics companies to investigate these challenges.

### *4.1. Experts Panel Selection*

In this study, purposive sampling was utilized to carefully select experts with substantial expertise in logistics and supply chain management, as this approach is well-suited to the specialized requirements of the research. This non-probability sampling method allows for the deliberate selection of individuals who meet specific criteria, ensuring that the data collected is relevant and insightful. Experts were chosen based on their significant professional experience (at least ten years), educational background (holding at least a bachelor's degree, with many having master's or doctoral degrees), and their professional roles (lecturers, researchers from renowned universities, or leaders from prominent logistics corporations in Vietnam). The experts were all 35 years and above, ensuring mature and experienced viewpoints. Potential experts were identified through professional networks, industry associations, and academic institutions, with personalized invitations to encourage participation. Both online methods (JotForm surveys and virtual interviews via Zoom and Microsoft Teams) and offline methods (face-to-face interviews and paper-based surveys) were used to ensure comprehensive data collection. Before the final distribution, a pilot test with five logistics professionals who were not part of the final panel was conducted to refine the questionnaire based on clarity, relevance, and comprehensiveness feedback.

According to Nguyen et al. [65], a minimum of 10 to 18 experts is sufficient for this type of research to ensure diverse and reliable data collection. In this study, 35 survey invitations were sent, and 30 valid responses were received. All participating experts had at least ten years of experience, including lecturers, researchers from renowned universities, and leaders from prominent logistics corporations. The expert panel comprised 30 individuals, including five aged 35-40 years (16.6%), 19 aged 40-60 years (63.3%), and six aged over 60 years (20%). Gender representation included 13 males (43.3%), 14 females (46.6%), and three individuals identifying as other (10%). Educationally, one expert held a bachelor's degree (3.3%), 22 had a master's degree (73.3%), and 7 had a doctorate (23.3%). Professionally, the panel included seven government officials (23.3%), 12 researchers/professors (40%), and 11 managers/directors (36.7%). Regarding experience, 24 experts had 10-20 years (80%), while 6 had more than 20 years (20%). This meticulous selection process and data collection method underscore the robustness and validity of the research findings, offering valuable insights into the CSFs for sustainable HC in the Vietnamese logistics industry. **Table 6** provides detailed information about the experts' profiles.

**Table 6.** Experts's Profiles

| Criteria | | Number of experts | Percentage |
|---|---|---|---|
| Age (years old) | 35 – 40 | 5 | 16.6 % |
| | 40 – 60 | 19 | 63.3 % |
| | More than 60 | 6 | 20 % |
| Gender | Male | 13 | 43.3 % |
| | Female | 14 | 46.6 % |
| | Other | 3 | 10 % |
| Education | Bachelor | 1 | 3.3% |
| | Master | 22 | 73.3 % |
| | Doctor | 7 | 23.3 % |
| Work | Government Officials | 7 | 23.3 % |

| | | | |
|---|---|---|---|
| | Researchers/Professors | 12 | 40 % |
| | Managers/Directors | 11 | 36.7 % |
| Experience (years) | 10 - 20 | 24 | 80 % |
| | More than 20 | 6 | 20 % |

*4.2. Results of NZN Delphi*

In this study, the practical HC factors identified through the literature review encompass 20 factors distributed across three dimensions. Experts have judged these factors for their suitability in the form of linguistic scales, which were converted into Z numbers in Table 4. Expert evaluations on each factor were synthesized, and relevant indexes were calculated. Results of NZN Delphi analysis are given in Table 7 below, indicating whether the factor is retained or rejected. It compares each (***Vc***) value obtained for every factor with a given threshold value and selects three factors that did not meet the threshold criteria and were therefore rejected: SC2, SC4, and EN5. The comprehensive evaluation ensures that only the most relevant and suitable factors are carried forward for further analysis in Phase 2, enhancing the robustness and validity of the study's findings on effective HC in the logistics sector.

**Table 7**. The NZN Delphi method results

| Factor | Aggregate | Score | Validate |
|---|---|---|---|
| EC1 | [(0.7397;0.6093);(0.218;0.3499);(0.2603;0.3907)] | 0.7576 | Accepted |
| EC2 | [(0.7021;0.5536);(0.2614;0.4271);(0.2979;0.4464)] | 0.7147 | Accepted |
| EC3 | [(0.69;0.5235);(0.2737;0.4613);(0.31;0.4765)] | 0.6957 | Accepted |
| EC4 | [(0.6987;0.5222);(0.2651;0.462);(0.3013;0.4778)] | 0.6995 | Accepted |
| EC5 | [(0.729;0.6338);(0.2287;0.331);(0.271;0.3662)] | 0.7624 | Accepted |
| EC6 | [(0.6663;0.5748);(0.3006;0.3917);(0.3337;0.4252)] | 0.7078 | Accepted |
| EC7 | [(0.6735;0.7102);(0.2898;0.2448);(0.3265;0.2898)] | 0.7709 | Accepted |
| EC8 | [(0.6967;0.5109);(0.2629;0.4744);(0.3033;0.4891)] | 0.6943 | Accepted |
| EC9 | [(0.731;0.6119);(0.2299;0.3518);(0.269;0.3881)] | 0.754 | Accepted |
| SC1 | [(0.7762;0.562);(0.1779;0.4207);(0.2238;0.438)] | 0.7545 | Accepted |
| **SC2** | [(0.2323;0.5091);(0.8114;0.47);(0.7677;0.4909)] | 0.4533 | **Rejected** |
| SC3 | [(0.6971;0.6271);(0.2683;0.335);(0.3029;0.3729)] | 0.7448 | Accepted |
| **SC4** | [(0.2268;0.5621);(0.8218;0.4147);(0.7732;0.4379)] | 0.4827 | **Rejected** |

| | | | |
|---|---|---|---|
| SC5 | [(0.7579;0.6027);(0.1987;0.3588);(0.2421;0.3973)] | 0.7631 | Accepted |
| SC6 | [(0.6978;0.5553);(0.2601;0.4159);(0.3022;0.4447)] | 0.715 | Accepted |
| EN1 | [(0.7097;0.5034);(0.2475;0.4675);(0.2903;0.4966)] | 0.6991 | Accepted |
| EN2 | [(0.7083;0.496);(0.2509;0.4843);(0.2917;0.504)] | 0.6943 | Accepted |
| EN3 | [(0.6544;0.5646);(0.3112;0.3984);(0.3456;0.4354)] | 0.6983 | Accepted |
| EN4 | [(0.7277;0.6198);(0.2324;0.3441);(0.2723;0.3802)] | 0.7558 | Accepted |
| **EN5** | [(0.2747;0.4627);(0.756;0.5062);(0.7253;0.5373)] | 0.4516 | **Rejected** |
| | **Threshold (*Vc*)** | **0.68847** | |

*4.3 Results of NZN DEMATEL*

After the validation and acceptance of factors during the NZN DEMATEL phase, an analysis of the interrelationships among these factors shall be undertaken. The cohort of thirty experts will participate in the second phase of the investigation, wherein they will evaluate the impact relationships between factors pairwise. The evaluation results obtained from the thirty experts will be synthesized through a process involving the calculation of averages, standardization, and defuzzification. **Table 8** shows the total-influence matrix, elucidating the interrelationships among the factors under consideration.

**Table 8**. Total influence matrix

| | **EC1** | **EC2** | **EC3** | **EC4** | **EC5** | **EC6** | **EC7** | **EC8** | **EC9** | **SC1** | **SC3** | **SC5** | **SC6** | **EN1** | **EN2** | **EN3** | **EN4** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **EC1** | 0.621 | 0.598 | 0.635 | 0.615 | 0.625 | 0.635 | 0.621 | 0.615 | 0.621 | 0.593 | 0.637 | 0.617 | 0.626 | 0.634 | 0.619 | 0.630 | 0.634 |
| **EC2** | 0.576 | 0.625 | 0.627 | 0.621 | 0.587 | 0.588 | 0.612 | 0.576 | 0.636 | 0.584 | 0.629 | 0.592 | 0.589 | 0.625 | 0.612 | 0.610 | 0.637 |
| **EC3** | 0.590 | 0.642 | 0.642 | 0.632 | 0.639 | 0.617 | 0.624 | 0.607 | 0.646 | 0.615 | 0.651 | 0.605 | 0.632 | 0.638 | 0.622 | 0.623 | 0.609 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **EC4** | 0.579 | 0.624 | 0.641 | 0.631 | 0.608 | 0.592 | 0.584 | 0.580 | 0.629 | 0.604 | 0.620 | 0.626 | 0.595 | 0.631 | 0.628 | 0.627 | 0.637 |
| **EC5** | 0.590 | 0.622 | 0.627 | 0.621 | 0.636 | 0.631 | 0.626 | 0.633 | 0.638 | 0.627 | 0.652 | 0.645 | 0.643 | 0.627 | 0.624 | 0.609 | 0.639 |
| **EC6** | 0.611 | 0.598 | 0.606 | 0.613 | 0.611 | 0.629 | 0.619 | 0.601 | 0.601 | 0.592 | 0.636 | 0.616 | 0.626 | 0.632 | 0.641 | 0.641 | 0.643 |
| **EC7** | 0.590 | 0.646 | 0.651 | 0.634 | 0.642 | 0.641 | 0.632 | 0.593 | 0.649 | 0.616 | 0.652 | 0.635 | 0.633 | 0.609 | 0.639 | 0.609 | 0.613 |
| **EC8** | 0.631 | 0.623 | 0.627 | 0.635 | 0.631 | 0.618 | 0.598 | 0.629 | 0.625 | 0.640 | 0.630 | 0.635 | 0.633 | 0.639 | 0.638 | 0.624 | 0.650 |
| **EC9** | 0.581 | 0.627 | 0.643 | 0.627 | 0.595 | 0.595 | 0.588 | 0.582 | 0.636 | 0.607 | 0.634 | 0.617 | 0.613 | 0.642 | 0.618 | 0.616 | 0.632 |
| **SC1** | 0.559 | 0.579 | 0.603 | 0.577 | 0.573 | 0.574 | 0.565 | 0.561 | 0.613 | 0.606 | 0.605 | 0.608 | 0.594 | 0.585 | 0.584 | 0.581 | 0.585 |
| **SC3** | 0.543 | 0.568 | 0.575 | 0.566 | 0.564 | 0.562 | 0.555 | 0.545 | 0.574 | 0.555 | 0.614 | 0.569 | 0.564 | 0.575 | 0.573 | 0.572 | 0.576 |
| **SC5** | 0.562 | 0.585 | 0.607 | 0.599 | 0.577 | 0.577 | 0.571 | 0.567 | 0.628 | 0.603 | 0.610 | 0.618 | 0.597 | 0.591 | 0.588 | 0.585 | 0.592 |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SC6** | 0.601 | 0.630 | 0.645 | 0.628 | 0.613 | 0.614 | 0.621 | 0.605 | 0.620 | 0.611 | 0.624 | 0.618 | 0.634 | 0.623 | 0.622 | 0.620 | 0.621 |
| **EN1** | 0.548 | 0.570 | 0.578 | 0.573 | 0.567 | 0.567 | 0.562 | 0.551 | 0.576 | 0.563 | 0.583 | 0.573 | 0.569 | 0.615 | 0.617 | 0.574 | 0.579 |
| **EN2** | 0.564 | 0.583 | 0.590 | 0.583 | 0.578 | 0.577 | 0.574 | 0.566 | 0.590 | 0.576 | 0.594 | 0.587 | 0.582 | 0.617 | 0.622 | 0.623 | 0.629 |
| **EN3** | 0.552 | 0.575 | 0.580 | 0.574 | 0.569 | 0.569 | 0.562 | 0.557 | 0.577 | 0.563 | 0.584 | 0.575 | 0.572 | 0.597 | 0.595 | 0.611 | 0.580 |
| **EN4** | 0.605 | 0.621 | 0.626 | 0.619 | 0.616 | 0.616 | 0.612 | 0.606 | 0.623 | 0.613 | 0.627 | 0.621 | 0.620 | 0.649 | 0.646 | 0.645 | 0.641 |

**Table 9** presents $\otimes$ r, $\otimes$ c, $\otimes$ r $+\otimes$ c, and $\otimes$ r, $-\otimes$ c scores and weights of each CFS after defuzzy. If $\otimes$ r $-\otimes$ c connection is positive, then a factor is causal, that is, the cause factor; on the other hand, when the connection is negative, the factor is affected, that is, the effect factor. Following defuzzification, each factor is assigned a weight representing its relative significance within the causal framework. These weights quantify the magnitude of influence exerted by each factor on the overall system dynamics. Figure 2 illustrates significant causal relationships among factors.

**Table 9**. NZN DEMATEL Results

| Criteria | $\otimes$ r | $\otimes$ c | $\otimes$ r $+\otimes$ c | w | Rank | $\otimes$ r $-\otimes$ c | Relation |
|---|---|---|---|---|---|---|---|
| **EC1** | 10.57 | 9.90 | 20.47 | 0.05836 | 12 | 0.6739 | **Cause** |
| **EC2** | 10.33 | 10.32 | 20.64 | 0.05884 | 10 | 0.0118 | **Cause** |
| **EC3** | 10.63 | 10.50 | 21.14 | 0.06024 | 1 | 0.1317 | **Cause** |
| **EC4** | 10.44 | 10.35 | 20.78 | 0.05924 | 7 | 0.0882 | **Cause** |
| **EC5** | 10.69 | 10.23 | 20.92 | 0.05963 | 4 | 0.4575 | **Cause** |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **EC6** | 10.51 | 10.20 | 20.72 | 0.05905 | 8 | 0.3109 | **Cause** |
| **EC7** | 10.68 | 10.12 | 20.81 | 0.05931 | 6 | 0.5578 | **Cause** |
| **EC8** | 10.71 | 9.97 | 20.68 | 0.05894 | 9 | 0.7326 | **Cause** |
| **EC9** | 10.45 | 10.48 | 20.93 | 0.05966 | 3 | -0.0303 | Effect |
| **SC1** | 9.95 | 10.17 | 20.12 | 0.05734 | 17 | -0.2162 | Effect |
| **SC3** | 9.65 | 10.58 | 20.23 | 0.05767 | 15 | -0.9294 | Effect |
| **SC5** | 10.06 | 10.36 | 20.42 | 0.05819 | 13 | -0.2995 | Effect |
| **SC6** | 10.55 | 10.32 | 20.87 | 0.05948 | 5 | 0.2264 | **Cause** |
| **EN1** | 9.76 | 10.53 | 20.29 | 0.05784 | 14 | -0.7643 | Effect |
| **EN2** | 10.03 | 10.49 | 20.52 | 0.05849 | 11 | -0.4522 | Effect |
| **EN3** | 9.79 | 10.40 | 20.19 | 0.05754 | 16 | -0.6076 | Effect |
| **EN4** | 10.61 | 10.50 | 21.10 | 0.06015 | 2 | 0.1087 | **Cause** |

Most economic factors denoted as EC1 to EC8, are identified as primary causes within the logistics system, exerting significant influence on other factors. Collaborative Distribution Centers (EC3), Financial Stability EC1), and General Governance Agreements (EC5) play pivotal roles in shaping logistics firms' strategic decisions and overall performance. Specifically in HC, these economic factors are essential for aligning goals, reducing operational costs, and realizing economies of scale. The centrality of economic factors in strategic planning underscores their role as key drivers within the system. Effective HC implementation necessitates substantial investments in technology, infrastructure, and process optimization, all inherently linked to economic considerations. As such, economic factors assume a causative role, influencing both the adoption and success of HC initiatives. Furthermore, economic factors directly impact operational efficiency and productivity. For example, enhancements in financial stability or market competitiveness can result in more streamlined logistics operations, influencing other interconnected factors within the system.

Unlike other economic factors, cross-functional collaboration (EC9) is influenced by the organization's effectiveness in implementing existing economic strategies and social dynamics. Its success often depends on the foundational economic conditions and the quality of interdepartmental relationships.

Social factors within the logistics sector, consensus on organizational culture (SC1), supplier relationship management (SC3), and Coordinated employee training and development programs (SC5) are often influenced by economic stability and performance. Economic optimization sets the stage for positive social outcomes. Broader economic conditions and policies shape these social factors. For example, cost efficiency and market competitiveness improvements can lead to better working conditions and increased stakeholder engagement. In other instances, organizations achieving financial stability are more likely to invest in employee development and conflict resolution mechanisms.

One exception is SC6 (Clear Conflict Resolution Mechanisms), categorized as a cause factor. Effective conflict resolution mechanisms can enhance organizational efficiency and cohesion, impacting social and economic outcomes. When managed effectively, conflicts contribute to smoother operations and optimal resource utilization, thus causatively influencing other factors.

This study analyzes environmental sustainability factors through a cause-effect lens to clarify their significance within the logistics ecosystem. Circular Economy Practices (EN4) is considered as a cause factor. By adopting circular economy principles, circular Economy Practices involve proactive strategies such as resource optimization and waste minimization, making them critical drivers in logistics sustainability. Logistics entities initiate transformative changes to align with sustainability goals, positioning themselves as proactive agents in environmental stewardship.

General Green Transportation and Packaging Practices (EN1) and Environmental Efficiency Optimization Coordination (EN2) are shown as Effect Factors. These factors emerge as outcomes influenced by broader environmental initiatives. They represent tangible manifestations of sustainability efforts, reflecting the downstream impacts of proactive interventions. General Waste Reduction and Recycling Mechanisms (EN3) is also an Effect Factor. These mechanisms epitomize reactive measures enacted in response to sustainability goals. As logistics enterprises embrace circular economy paradigms, waste reduction and recycling mechanisms become integral components of environmental management frameworks.

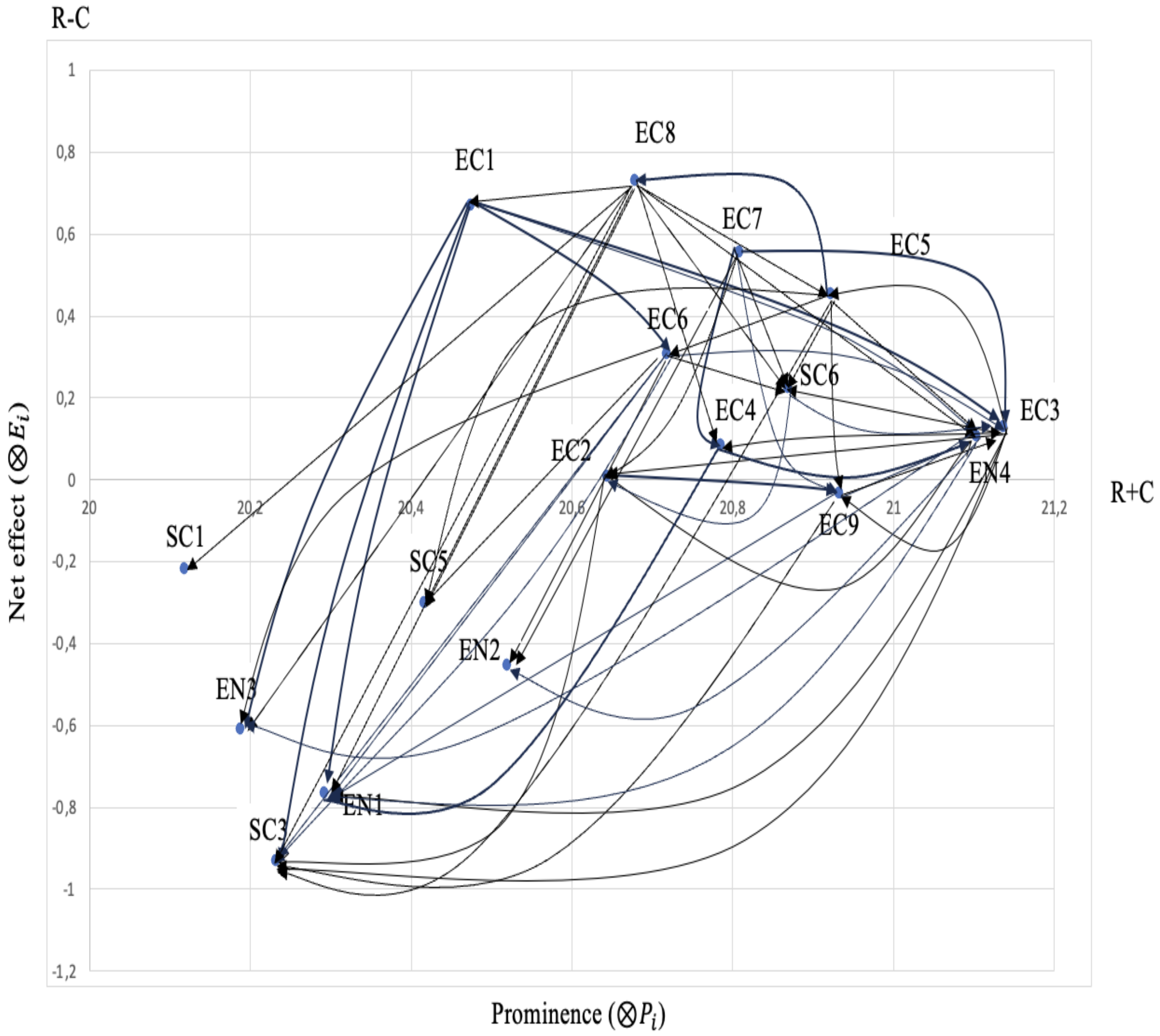


**Figure 2.** Influential Maps of significant relationships among factors

*4.4 Discussions*

The hybrid application of neutrosophic sets and Z-numbers in conjunction with Delphi and DEMATEL methods creates an advanced decision-making framework. This integration successfully addresses the complexities and uncertainties in HC, providing a multi-faceted analytical lens that traditional methods often overlook. The dual application enhances reliability in expert assessments and decision criteria, significantly advancing over previous studies. Our findings underscore critical factors for successful horizontal logistics collaboration, which are aligned with the previous studies. Comparatively, similar studies have often employed traditional fuzzy set theories or singular methodological approaches, lacking the hybrid analytical depth provided by our framework. For instance, Ferrell et al.[66] explored opportunities for improved logistics planning through HC using standard fuzzy set theory and conventional survey methods, highlighting the potential but needing to address the complexities of uncertainty and indeterminacy in the decision-making process.

Conversely, our study leverages neutrosophic sets to manage the indeterminacy, thus providing a more robust and flexible evaluation framework. This approach aligns with the recent advancements Zadeh [67] suggested, enhancing the decision-making framework's credibility and robustness. However, they needed to integrate advanced fuzzy logic techniques, thereby limiting the analytical precision regarding the uncertainties inherent in logistics collaborations. Our methodology surpasses this limitation by incorporating Z-numbers, which offer a more nuanced handling of uncertainty and reliability in expert judgments.

After the NZN-Delphi phase, several factors were eliminated based on their aggregated scores not meeting the predetermined threshold. Factors such as SC2, SC4, and EN5 were rejected. This elimination process involved rigorous expert evaluations, converted into NZN to handle uncertainty and ensure reliability. The exclusion of these factors does not necessarily imply their irrelevance within the context of Vietnam. Instead, their exclusion reflects that, based on the Delphi method and subsequent evaluations using the NZN Set MCDM model, these factors did not meet the predetermined threshold for criticality in driving the effectiveness and sustainability of HC in the logistics industry. The rigorous expert evaluations and the use of NZN were employed to handle uncertainty and ensure the reliability of the decision-making process regarding which factors to prioritize. Factors that did not meet the threshold criteria were deemed less critical than those that were retained. This selective process aims to concentrate efforts and resources on the most influential factors likely to have the highest impact on the success of HC. Therefore, while SC2, SC4, and EN5 may still be relevant to the logistics industry in Vietnam, their exclusion suggests that they are perceived to have less immediate influence or may not be as pivotal in driving the desired outcomes of HC compared to other retained factors. Thus, the study focuses on what are believed to be the most significant drivers of success, ensuring a targeted approach to enhancing collaboration effectiveness and sustainability in the logistics sector in Vietnam.

The DEMATEL analysis offers significant insights into HTC's CSF. Among the most prominent factors identified are those related to economic aspects and firm-level concerns, underscoring the crucial role that individual companies and financial considerations play in HTC initiatives. This finding aligns with existing literature emphasizing the importance of firm-level dynamics and economic motivations in collaborative logistics efforts [23], [68]. The most critical factor identified is EC3, which pertains to Collaborative Distribution Centers as Partners. This highlights the complexity of establishing leadership and management structures within HTC, as partners may harbor distrust regarding equitable treatment. The challenge of selecting a neutral, trustworthy party to lead the collaboration emerges as a primary concern, resonating with findings from various studies [4], [68]. Closely following in importance is EN4, focusing on Circular Economy Practices. This factor's high ranking suggests a growing recognition among companies of the need to adopt sustainable practices, potentially driving the push toward HTC. The prominence of this environmental factor amidst predominantly economic considerations indicates an emerging shift towards sustainability in the logistics sector. This aligns with research by Torres et al.[69] on the importance of green logistics practices. Governance and trust-related factors also emerged as significant factors, including General Governance Agreements and Commitment to Responsibilities (EC9) and Clear Conflict Resolution Mechanisms (EC5), which rank high, underscoring the need for robust contractual frameworks and conflict management strategies. These findings resonate with research by Raue et al. [70], which stresses the importance of formal agreements in ensuring partner commitment and accountability.

Trust coordination presents a critical challenge, given the inherent competitive nature of potential HTC partners. The reluctance to share sensitive information and concerns about the fairness of benefit/cost-sharing methods can significantly impede collaboration. This aligns with studies by Islam et al. [71], highlighting trust issues in competitive collaborations. Innovation and technology adoption ability are also prominent among the top CSFs. This factor reflects the dual challenge of overcoming misconceptions about information security risks and addressing smaller companies' financial barriers in adopting collaborative decision support systems (CDSSs). The findings align with Basso et al.[72], which identifies technology-related concerns as significant hurdles in HTC implementation. Interestingly, while factors related to cost/profit-sharing policies and data sharing and integration are recognized as necessary, they are not among the top-ranked CSFs. This suggests that while these aspects pose challenges, they may be more manageable than trust, governance, and technology adoption. The existence of ride-sharing applications in Vietnam demonstrates that technological solutions for logistics optimization are feasible when there is a determined effort to implement HTC.

In conclusion, the DEMATEL analysis highlights the interplay between economic, technological, governance, and trust-related aspects. The results suggest that the successful implementation of HTC requires a multifaceted approach that addresses firm-level challenges, particularly in trust-building, governance structuring, and technology adoption. While economic factors remain paramount, the growing importance of sustainability practices indicates a potential shift towards more environmentally conscious collaboration in the logistics sector. Future HTC initiatives should focus on developing robust governance frameworks, fostering trust among partners, and leveraging technology to overcome collaboration barriers while integrating circular economy practices to enhance overall sustainability.

## 5. Conclusions

This study utilized the combined NZN Delphi and NZN DEMATEL model to identify and analyze the CSFs for logistics HC. The findings highlight key factors influencing the HC process and their interrelationships, offering valuable strategies and priorities for enhancing HC in the logistics industry. Methodologically, the study demonstrates the benefits of integrating neutrosophic and Z-number theories, effectively addressing real-world challenges both mathematically and linguistically. By combining Delphi and DEMATEL techniques with advanced fuzzy set theories, this research provides a comprehensive framework for understanding and optimizing logistics HC.

## 6. Implications

### *6.1 Theoretical implications*

This study on the CSFs for sustainable LHC in Vietnam's logistics industry using the NZN Set MCDM model offers significant theoretical implications that extend beyond its immediate context. Firstly, the use of Neutrosophic and Z-number theories addresses the inherent uncertainty and imprecision in human judgment, providing a more nuanced approach to decision-making processes in logistics by simultaneously capturing truth, indeterminacy, and falsity degrees while incorporating both restriction and reliability components. This methodological advancement could be extended to other fields where decision-making under uncertainty is critical, such as healthcare (treatment protocol evaluation), finance (risk assessment), and urban planning (infrastructure development). Secondly, combining Delphi and DEMATEL techniques with these contemporary fuzzy set theories provides a structured approach to expert consensus-building and causal relationship analysis through multiple rounds of expert consultation and systematic convergence of opinions. The Delphi method ensures comprehensive coverage of factors impacting HC through iterative rounds of expert consultation, while DEMATEL offers insights into the interdependencies and causal relationships among these factors, enabling the development of impact-relation maps and the identification of critical nodes in the factor network. This integrated approach can inform future studies aiming to explore complex, interrelated phenomena in various domains, promoting a deeper understanding of underlying mechanisms and enhancing the rigor of MCDM models. The findings also underscore the importance of adopting a holistic perspective when examining CSFs for HC, incorporating economic dimensions (cost efficiency, resource optimization), social aspects (stakeholder engagement, community impact), and environmental considerations (carbon footprint reduction, waste management). This aligns with the principles of the TBL framework, which broadens the scope of organizational success beyond financial metrics to include social responsibility and environmental sustainability. By integrating TBL with SDT, the study provides a comprehensive theoretical framework for analyzing the dynamics of collaborative efforts among competing firms, addressing both short-term competitive advantages and long-term collaboration benefits. SDT highlights the conflict between immediate self-interest and longer-term collective interest, a common challenge in HC while offering insights into partner selection criteria and resource-sharing mechanisms. The identification and prioritization of CSFs using this integrated framework contribute to the theoretical understanding of collaboration dynamics in the logistics sector, emphasizing the importance of trust-building mechanisms (information sharing protocols, joint problem-solving approaches), robust governance structures (formal contracts and informal relationship management), and technology adoption (integration platforms, data sharing systems). These findings support existing theories on collaboration and governance, reinforcing the significance of trust and transparency in cooperative ventures, while the emphasis on sustainability practices reflects a growing theoretical shift towards integrating environmental considerations into logistics and supply chain management, aligning with the broader agenda of green logistics and sustainable development through eco-friendly transportation, green warehousing, and circular economy initiatives.

*6.2 Practical implications*

The practical implications of this study on the CSFs for sustainable HC in Vietnam's logistics industry are substantial and multifaceted, offering actionable insights for various stakeholders across the logistics ecosystem. Firstly, logistics companies can leverage the identified CSFs to design and implement more effective collaboration strategies, with a particular emphasis on trust-building mechanisms that serve as foundational elements for successful collaboration through the implementation of comprehensive trust-development programs, including regular partner satisfaction surveys, joint problem-solving sessions, and transparent performance reporting systems. Companies should invest in developing transparent communication channels through multiple synchronized touchpoints (such as daily operational briefings, weekly coordination meetings, monthly strategic reviews, and quarterly performance assessments), establishing clear and fair governance structures (including detailed standard operating procedures, multi-level conflict resolution mechanisms, escalation matrices, and joint decision-making protocols), and fostering a culture of mutual respect and reliability among partners through structured joint training programs, cross-functional teams, shared innovation initiatives, and regular cultural alignment workshops. Practical steps include implementing regular joint meetings with structured agendas covering operational updates, performance reviews, and strategic planning, supported by detailed documentation and follow-up action items; developing shared performance metrics encompassing both individual and collective KPIs (such as on-time delivery rates, cost savings achieved, carbon footprint reduction, customer satisfaction scores, and sustainability targets met), with automated reporting systems and real-time dashboards; and deploying integrated technology platforms to facilitate real-time information sharing across partners, including blockchain-based transaction tracking, IoT-enabled asset monitoring, and AI-powered analytics for optimization. The study's emphasis on robust governance frameworks translates into specific, actionable measures, including the establishment of joint oversight committees with clearly defined roles, responsibilities, and authority matrices, the implementation of standardized decision-making processes using weighted scoring models and multi-criteria evaluation frameworks, and the development of comprehensive partnership agreements covering aspects such as resource allocation, risk sharing, profit distribution, intellectual property rights, data ownership, and exit strategies. These governance structures should be supported by detailed documentation, including service level agreements (SLAs), operating manuals, compliance guidelines, and contingency plans, while incorporating flexibility mechanisms to adapt to changing market conditions through regular review and revision processes. Technology adoption emerges as a CSF, with specific recommendations for implementing blockchain solutions for transparent transaction tracking, automated smart contracts, and immutable audit trails; deploying IoT sensors for real-time asset monitoring, predictive maintenance, and environmental condition tracking; and utilizing AI algorithms for route optimization, demand forecasting, resource allocation, and predictive analytics, supported by machine learning models for continuous improvement. Companies should also consider implementing cloud-based collaboration platforms that integrate various technological solutions, enabling seamless data sharing and analysis while maintaining robust security protocols and privacy standards through encrypted communications and role-based access controls. The sustainability dimension requires practical initiatives such as joint investment in electric vehicle fleets with shared charging infrastructure, energy-efficient warehousing facilities equipped with solar panels and smart energy management systems, and collaborative last-mile delivery solutions that optimize routes and reduce environmental impact through consolidated shipments and reverse logistics programs. Companies should establish specific environmental targets (e.g., 20% reduction in carbon emissions within two years, 50% reduction in packaging waste, 100% renewable energy usage), implement joint recycling and waste management programs with circular economy principles, and develop shared green logistics infrastructure including eco-friendly packaging systems and carbon offset programs. For SMEs, the study recommends specific collaboration models such as forming regional logistics clusters with shared resources and capabilities, participating in shared technology platforms to reduce individual investment costs through pay-per-use models, and establishing joint training programs for capability development in areas such as digital skills, sustainability practices, and operational excellence. These initiatives should be supported by detailed implementation roadmaps with clear milestones and deliverables, resource allocation plans including financial and human resource requirements, and performance monitoring systems with regular audits and improvement cycles. Additionally, the study provides comprehensive guidance for policymakers to create enabling environments through specific policy measures such as tax incentives for collaborative logistics initiatives, streamlined regulations for data sharing and joint operations, investment in digital infrastructure to support logistics collaboration, and development of industry standards for sustainable logistics practices. This includes developing standardized frameworks for logistics partnerships with legal templates and guidelines, establishing industry-wide data-sharing protocols with cybersecurity standards, and creating financial support mechanisms for sustainable logistics initiatives through green bonds and sustainability-linked loans, while also addressing change management aspects through stakeholder engagement strategies, comprehensive communication plans, and training programs to ensure successful adoption of collaborative practices across the entire logistics ecosystem.

### *6.3 Limitations and Future Work*

This study on the CSFs for sustainable HC in Vietnam's logistics industry, utilizing the NZN Set MCDM model, offers valuable insights but also has several limitations that should be addressed in future research. A key limitation is the potential subjectivity in expert evaluations. While expert judgment is crucial in Delphi and DEMATEL techniques, it may introduce biases that influence the findings. Experts' perspectives and experiences can shape the consensus and impact the analysis. The study's sample size is limited, mainly focusing on experts within Vietnam's logistics sector. This geographic and industry-specific focus may not fully reflect the diversity needed to generalize the findings across other regions and industries. Future research should aim for a broader and more diverse sample to enhance the generalizability of the results. Another limitation is the dynamic nature of CSFs. The factors identified are based on the current logistics industry landscape and prevailing environmental, economic, and social conditions. However, these factors can change over time due to technological advancements, market shifts, regulatory updates, and evolving sustainability norms. Therefore, periodic reevaluation of the identified CSFs will be necessary to ensure their relevance.

Additionally, while this study integrates qualitative insights with quantitative data through NZN theories, the quantitative aspect remains limited by the precision and reliability of the initial expert inputs. These inputs' inherent fuzziness and uncertainty pose challenges in achieving absolute accuracy.

Future research could enhance the methodological approach by incorporating more advanced statistical techniques and machine learning algorithms to analyze expert inputs better and validate findings. Combining traditional MCDM methods with advanced analytics would offer deeper insights and improve result reliability. Expanding the geographic scope of the study is also crucial. Including a broader range of countries and regions will provide a more comprehensive understanding of how CSFs for HC vary across logistics markets and cultural contexts, potentially identifying universal factors and region-specific nuances.

Longitudinal studies would also be valuable in capturing the evolving nature of CSFs over time. Tracking the development of collaboration practices and success factors in logistics could provide more up-to-date recommendations and allow for observing long-term impacts on sustainability and performance. Exploring HC in other sectors, such as healthcare, manufacturing, and finance, would also offer insights into the similarities and differences in CSFs across industries, supporting the development of more targeted strategies for collaboration and sustainability.

As technology advances, future research should investigate the role of emerging technologies like blockchain, AI, and IoT in facilitating HC. Understanding how these technologies can be integrated into collaboration strategies would provide practical insights for logistics companies seeking to improve their operations and sustainability. Finally, further research is needed on the role of policy and regulatory frameworks in supporting HC. Analyzing the effectiveness of current policies and proposing new regulatory measures could help promote collaboration and sustainability in the logistics industry, addressing incentive structures, compliance mechanisms, and the impact of international regulations on local practices.

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