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One Step Ahead of the Crisis: Evaluating Digital Solutions for Improving Humanitarian Logistics Based on Literature-Informed Insights Relevant to Humanitarian Organizations

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Highlights

Please indicate how your work links to systems science via your contributions to systems practice, theory, and/or methodology.

- The study conceptualizes humanitarian logistics as a complex adaptive socio-technical system relevant to humanitarian organizations, emphasizing interactions, feedback loops, information flows, and adaptive responses to crisis-related disruptions.
- A new hybrid Multi-Criteria Decision-Making (MCDM) model integrating the Criterion Impact Loss (CILOS) method for determining objective criterion weights and the Comprehensive Distance-Based Ranking (COBRA) method for evaluating and ranking digital solutions is developed as a systems-based methodology to support humanitarian organizations in evaluating digital solutions and supporting proactive decision-making in humanitarian logistics.

What are the main findings and/or the implications of the main findings?

- The Internet of Things is identified as the most suitable digital solution for humanitarian organizations, followed by Enterprise Resource Planning systems, mobile technologies, and Big Data technologies.
- The findings show that preparedness, logistics efficiency, and information reliability and security are central to strengthening the adaptive capacity of humanitarian organizations and enabling them to act "one step ahead of the crisis".

Abstract

Digitalization represents an important potential for improving humanitarian logistics (HL) and supporting humanitarian organizations (HOs) in shifting from a reactive to a proactive approach, i.e., acting "one step ahead of the crisis". The aim of this study is to identify the most suitable digital solution for improving HL by considering it as a complex adaptive socio-technical system and applying a new hybrid Multi-Criteria Decision-Making (MCDM) model. The model integrates the CILOS (Criterion Impact Loss) method for determining the objective weights of the criteria and the COBRA (Comprehensive Distance-Based Ranking) method for evaluating and ranking the alternatives. Four digital technologies were analyzed—Internet of Things (IoT), Big Data technologies, Enterprise Resource Planning (ERP) systems, and mobile technologies—based on six criteria: preparedness and resilience, logistics efficiency, integration and adaptability, economic feasibility, reliability and information security, and social acceptability. The results indicate that the Internet of Things

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represents the most suitable solution for HOs, followed by ERP systems, mobile technologies, and Big Data technologies. The main contributions of the study include establishing a new systemic framework for evaluating digital technologies in HL that supports a shift from a reactive to a proactive approach ("one step ahead of the crisis") under conditions of crisis-related uncertainty, as well as introducing a hybrid CILOS-COBRA Multi-Criteria Decision-Making (MCDM) model for evaluating digital solutions in HL. The selection of a digital solution should be based on its contribution to the operational capabilities of HOs, particularly in terms of preparedness, efficiency, reliability, and resilience, thereby supporting a "one step ahead of the crisis" approach.

Keywords: humanitarian logistics; humanitarian organizations; digital solutions; "one step ahead of the crisis"; MCDM; CILOS; COBRA

1. Introduction

Logistics represents an indispensable component of almost all human activities, and its importance becomes particularly evident in conditions of crises, emergencies, and humanitarian disasters. In such circumstances, the part of logistics that encompasses the planning, organization, implementation, and control of the flows of people, materials, information, and other resources is defined as humanitarian logistics (HL) [1]. Approximately 80% of activities related to the provision of assistance in emergencies concern logistics activities, which is why the success of every humanitarian operation largely depends on the efficiency and effectiveness of HL [1,2].

There are different understandings of humanitarian action, but three key principles are most commonly identified at its core: humanity, neutrality, and impartiality. These principles provide the basis for defining and implementing humanitarian operations. Humanity implies the obligation to provide assistance to all persons in need, regardless of the circumstances in which they find themselves. Neutrality implies providing assistance without discriminating against any community, with particular attention given to those whose need for support is greatest and most urgent. At the same time, humanitarian organizations are expected to act impartially in all forms of humanitarian action, meaning that they should not give preference to one group over another simply because a particular group is perceived as "closer" or more closely affiliated with them [3]. Adherence to these principles further emphasizes the importance of effective management of logistics processes, as available resources must be directed to where they are most needed, at the right time, and without unnecessary delays.

One of the fundamental challenges in HL is unpredictability, as it is often difficult to determine in advance the time, location, and scale of a disaster, both in terms of the number of people affected and the extent of material damage incurred. In addition, the temporal dimension is of particular importance in humanitarian operations. While delays in a commercial supply chain may result in productivity losses or reduced customer satisfaction, delays in the delivery of humanitarian assistance in the most severe situations can be critical to preserving the lives of people affected by a disaster. An additional challenge is the shortage of professional logisticians capable of planning, assessing, and coordinating human and material resources during relief operations. The problem lies not only in attracting qualified personnel but also in retaining them, given the potential for high employee turnover resulting from a lack of clearly defined opportunities for professional development, professional associations, and an appropriate community of practitioners [4]. These challenges indicate that HL operates in a highly complex and dynamic environment

in which traditional response approaches are not always sufficient to achieve a rapid, coordinated, and effective response.

In this context, humanitarian supply chains (HSCs) can be viewed as complex adaptive systems (CASs), characterized by numerous interconnected and interdependent elements whose interactions shape the behavior of the system as a whole. These elements include humanitarian organizations (HOs), donors, logisticians, local communities, and infrastructure, with relationships among them continuously adapting to changes in the environment. The complexity of such systems is further driven by the fact that the decisions and activities of one actor may directly or indirectly affect resource availability, information flows, and the ability of other actors to respond to the needs of the affected population. In such an environment, digital solutions can represent important mechanisms for collecting, sharing, and processing information, as well as for coordinating the activities of different stakeholders. Their potential value, therefore, extends beyond the automation of individual logistics processes to supporting system visibility, decision-making, coordination, and adaptation under dynamic and uncertain conditions. Accordingly, the CAS perspective provides a theoretical lens for understanding why digital solutions may contribute to the adaptability and resilience of HSCs, while the MCDM model developed in this study is used to evaluate and rank digital solutions according to predefined criteria rather than to model the dynamic evolution of the HSC as a CAS.

The primary target group of humanitarian action consists of affected people, whose needs must remain at the center of the processes of planning, decision-making, and aid distribution [5]. For this reason, HOs are tasked with responding to crises rapidly and effectively by providing medical assistance, shelter, food, and water to people affected by disasters. However, the ability to respond successfully does not depend solely on activities undertaken after a disaster occurs. In order to improve their operations, HOs must also invest efforts during periods between crises, when there is an opportunity to analyze existing processes, identify weaknesses, develop capacities, and improve logistics networks [6].

The development of digital technologies creates opportunities to improve the way HOs plan, monitor, and execute their logistics activities. The application of electronic databases, real-time tracking technologies, and automated processes enables HOs to achieve better coordination, greater transparency, and more precise monitoring of resource flows [7]. In this way, technology does not represent merely a means of responding more efficiently once a crisis has already occurred, but also provides a foundation for building capacities that enable HOs to prepare for future unpredictable events.

It is precisely this need for the timely identification of risks, preparedness of capacities, and improvement of response capabilities before a crisis occurs that underpins the "one step ahead of the crisis" approach. In this context, being "one step ahead of the crisis" should not be understood as predicting specific future events, nor as a substitute for preparedness or resilience. Rather, it refers to a proactive orientation in which HOs continuously identify potential vulnerabilities, anticipate emerging operational challenges, assess available solutions, and strengthen their capacity to respond before identified risks escalate into more severe disruptions. While preparedness primarily focuses on developing capacities and arrangements to address anticipated hazards, and resilience refers to the ability of organizations and systems to absorb, adapt to, and recover from disruptions, the "one step ahead" approach emphasizes the continuous identification of vulnerabilities and the timely enhancement of response capabilities as risks emerge and evolve. From this perspective, being "one step ahead" involves developing the capacity of HOs to identify potential weaknesses in a timely manner, assess available solutions, and select those that can contribute to faster, more efficient, transparent, and sustainable humanitarian assis-

tance. In this regard, innovations in HL represent a potential response to the limitations of traditional approaches; however, their value cannot be assessed solely in terms of technological sophistication. For HOs, it is particularly important that digital solutions address the actual needs of users, remain applicable under complex crisis conditions, contribute to the efficient use of limited resources, and can be integrated into existing logistics processes.

The aim of this study is to identify and rank the most suitable digital solution for improving HL by applying a new hybrid Multi-Criteria Decision-Making (MCDM) model, with a focus on the proactive "one step ahead of the crisis" approach relevant to HOs. Given that the proposed evaluation framework is developed from insights derived from the existing literature rather than from primary empirical data, the study also examines whether such literature-informed insights can provide a structured and multidimensional basis for the comparative evaluation of digital solutions in HL. Based on the research problem and the literature-informed decision-support approach adopted in this study, four research hypotheses are formulated:

H1. *Literature-informed insights can provide a structured basis for evaluating digital solutions relevant to HOs and HL.*

H2. *Findings from the existing literature can be translated into a multi-dimensional set of criteria reflecting the priorities and needs of HOs for the comparative evaluation of digital solutions in HL.*

H3. *A literature-informed MCDM approach can distinguish the relative suitability of different digital solutions for HL within a decision framework relevant to HOs.*

H4. *The relative suitability of digital solutions for HL depends on the simultaneous consideration of operational, informational, organizational, economic, and social dimensions relevant to HOs.*

The study first examines the theoretical foundations of HL and digital technologies. Subsequently, the research methodology is presented. Next, the alternatives and evaluation criteria are defined based on insights from the existing literature and their relevance to HOs. The proposed MCDM model is then applied, and the obtained results are presented and analyzed, including a sensitivity analysis. Finally, concluding remarks and directions for future research are presented.

2. Toward Sustainable and Digitalized Humanitarian Logistics

In the context of increasingly complex humanitarian crises, limited resources, and growing demands for a rapid, efficient, and resilient response, HOs face the need to improve their logistics, organizational, and technological capacities. In this regard, this chapter reviews the relevant literature through four interconnected thematic areas: (i) the role and involvement of HOs in HL, with a focus on the importance of trust, coordination, logistics network organization, cross-sector partnerships, and organizational capacity development; (ii) sustainability and (iii) digitalization of HL, addressing opportunities to improve the efficiency, flexibility, visibility, and resilience of HSCs, as well as challenges associated with the implementation of sustainable and digital solutions; and (iv) the application of MCDM methods, which are incorporated into the proposed hybrid MCDM model. This structure provides a foundation for evaluating digital solutions based on insights from the existing literature and their relevance to HOs, with the aim of identifying solutions that can contribute to a more efficient, flexible, and resilient response to future crises and, consequently, to achieving a "one step ahead of the crisis" approach.

2.1. Role and Involvement of Humanitarian Organizations in Humanitarian Logistics

HOs represent one of the key actors in organizing and implementing HL, particularly in the context of natural disasters, crises, and other emergency events. Their role encompasses not only the direct provision of assistance to affected populations but also resource planning and management, supply chain organization, coordination among different actors, and capacity development for future crises. In this regard, modern HL increasingly requires a shift from a reactive approach toward proactive action, in which HOs develop capacities, partnerships, and logistics solutions in advance in order to remain "one step ahead of the crisis".

One of the fundamental prerequisites for the successful functioning of HOs is stakeholder trust. Trust provides a basis for improved coordination among the various actors involved in HL. When trust exists among participants, conditions are created for better coordination, information and resource sharing, mutual learning, and the development of a participatory environment in which participants can express their opinions and views more freely. Cooperation and coordination further foster reciprocity, fairness, and trust, thereby creating conditions for improving HL performance. On the other hand, a lack of trust, cultural differences, and an unequal distribution of power can hinder cooperation among actors. The occurrence of corruption further undermines public trust, which is particularly important for HOs because a large proportion of their funding is provided through public donations. Therefore, building and maintaining trust represents one of the important prerequisites for the long-term sustainability of HOs. Public trust is more pronounced in local communities where HOs operate continuously and exchange information with the population, further highlighting the importance of direct communication and the local presence of HOs [8].

In addition to trust, the structure and organization of the HL network have a significant impact on the efficiency of response in crisis situations. Centralized and decentralized logistics network structures are particularly relevant, as they differ in terms of inventory management, resource allocation, and the location of decision-making. Centralized models enable risk pooling and generally provide advantages in terms of safety stock levels and economies of scale. On the other hand, decentralized models enable shorter delivery times and are, therefore, well aligned with the humanitarian sector's need for rapid response. A rapid response is of critical importance to affected populations, but it can also contribute to positive media coverage, which may influence the acquisition of additional financial resources. Historically, HOs have often approached the reorganization of their HL networks in a relatively opportunistic manner. They have located inventories in places where they already had operations or selected suitable locations based on proximity to airports, as well as specific customs and tax benefits available in certain countries. This approach indicates the need for more systematic and strategic logistics network planning, which should be based on an assessment of risks, expected needs, and available capacities rather than solely on existing infrastructure and the current availability of locations [6].

Partnerships between HOs and the business sector represent significant potential for improving HL. Modern humanitarian supply chains require diverse resources, knowledge, and capacities, meaning that almost no HO can independently respond to all needs arising in crisis situations. Cooperation between the humanitarian and business sectors can provide access to additional logistics capacities, expertise, technologies, transport infrastructure, and other resources. Partnerships between HOs and the business sector can also play an important role in the development of digital solutions. By combining the experience of HOs with the technological, organizational, and logistics capacities of the business sector, new models of cooperation and more efficient approaches to humanitarian supply chain management can be developed. In this way, cross-sector partnerships can contribute not

only to addressing problems after a crisis occurs but also to improving the preparedness of HOs and their ability to respond to future challenges in a timely manner. A comprehensive assessment of their value requires further investigation of the outcomes of such partnerships and their impact on HL performance [9].

Among the significant problems faced by HOs in emergencies are insufficient information flow, inadequate preparedness for humanitarian operations, and the unavailability of the required quantities of humanitarian assistance. A particular challenge is the shortage of qualified and trained personnel. Field operations often involve logisticians who have not received formal training but have acquired their knowledge and experience through practical work. Therefore, it is necessary to establish and support competency development and capacity-building programs aimed at raising the knowledge and skills of humanitarian logisticians to a more professional level. This includes appropriate training programs, as well as certification and accreditation systems [10].

In addition to human capacity development, one of the key directions for improving HL concerns digitalization. Investment in communication and information technologies is of critical importance for addressing crises and mitigating their consequences. Digital solutions can contribute to more efficient information exchange, better coordination among actors, and improved resource management. Therefore, HOs should recognize the importance of supply chain management and logistics in the effective provision of humanitarian assistance [10].

2.2. Sustainability of Humanitarian Logistics

The sustainability of HL represents an increasingly important component of modern HSCs, particularly considering the need to simultaneously improve the efficiency, resilience, and accountability of humanitarian operations. The concept of sustainable, or green, HSCs involves the integration of environmental principles into the planning, organization, and implementation of humanitarian activities, with the aim of reducing the negative environmental impact of operations while maintaining the ability of the HL system to respond to the needs of affected populations in a timely manner. In this context, particular attention is paid to reducing carbon dioxide emissions, using resources rationally, reducing waste, and developing more sustainable transportation and warehousing solutions [11,12].

Linking the concepts of sustainability and innovation is particularly important for the "one step ahead of the crisis" approach. HOs are increasingly faced with crises that require not only a rapid response but also the ability to manage limited resources effectively over the long term. For this reason, digital solutions in the areas of transportation, warehousing, inventory management, and energy use can provide a foundation for developing HL systems that are simultaneously flexible, resilient, and environmentally responsible. From a literature-informed perspective relevant to HOs, the value of such innovations is reflected not only in their environmental impact but also in their potential to improve operational efficiency and reduce the vulnerability of HL systems in future crises.

Nevertheless, the implementation of sustainable solutions in HL faces numerous limitations. High initial implementation costs of environmentally friendly technologies, insufficiently developed capacities for monitoring and measuring environmental impacts, and limited availability of infrastructure in crisis-affected areas represent significant barriers to their wider adoption. An additional challenge arises from the need to establish a balance between long-term sustainability objectives and the requirements for urgent action. In situations where the lives and health of the population are under immediate threat, the priority of HOs is the speed and reliability of aid delivery, which means that environmental considerations may sometimes be given lower priority [12].

The importance of institutional support becomes evident in the development and implementation of such solutions. The activities of the European Union provide an important example of how strategic investments, an institutional framework, and the development of innovative capacities can contribute to improving HL. An evaluation of the activities of the European Commission's Directorate-General for European Civil Protection and Humanitarian Aid Operations shows that investments in logistics capacities were timely and effective, particularly during the COVID-19 pandemic and the war in Ukraine. Programs such as the European Humanitarian Air Bridge, the Humanitarian Aid Facility, the European Humanitarian Response Capacity, as well as the partnership with the United Nations Humanitarian Air Service, have enabled faster mobilization of resources, improved logistics coordination, and more efficient distribution of assistance to affected populations [12,13]. The development of such capacities provides a foundation for integrating sustainable principles into humanitarian operations, as it enables better resource utilization planning, the rationalization of logistics processes, and the development of solutions capable of reducing the long-term environmental and operational impact of humanitarian activities. In this regard, institutional support contributes not only to the ability of HOs to respond to existing crises but also to their capacity to develop and implement digital solutions that enhance the resilience and sustainability of HL systems in future crises.

In addition to European Union institutional initiatives, international organizations and national actors are increasingly developing policies and practices that promote sustainable planning, technological innovation, and more efficient resource management in HL. This approach indicates that sustainability should not be viewed as an additional requirement imposed on HOs after the establishment of basic logistics processes but rather as an integral element of their long-term development. The integration of sustainable practices can contribute to reducing operational costs, improving resource efficiency, and increasing the resilience of humanitarian missions, thereby creating conditions for a more reliable response to future crises [11].

2.3. Digitalization of Humanitarian Logistics

Digitalization of HSCs represents one of the key directions for improving the efficiency, transparency, flexibility, and resilience of HL. The complexity of contemporary crisis situations, demand uncertainty, limited resources, and the need for a rapid response require HOs to have access to timely, reliable, and interconnected information. In this context, digitalization enables the real-time collection, processing, analysis, and exchange of data, the monitoring of aid and resource flows, more accurate needs planning, and more effective coordination among different HSC actors [14,15]. Its value is particularly evident in HL, where the quality and speed of decision-making can directly affect the lives and health of affected populations [7]. In this regard, it is useful to consider digitalization through the various functional capabilities it provides to HL, rather than solely through the application of individual digital solutions. Table 1 summarizes the key opportunities offered by digitalization in HL and indicates their potential contribution to improving the efficiency, agility, and resilience of HSCs, as well as their role in enhancing the ability of HOs to respond in a timely manner to changes in needs and the conditions under which humanitarian operations are conducted.

Table 1. Key opportunities offered by digitalization in humanitarian logistics.

Dimension of Digitalization	Opportunities in HL	Contribution	References
Forecasting and decision-making	Analysis of data on needs, resources, and flows; demand forecasting and support for HL planning	Shift from reactive to anticipatory management; faster and more accurate decisions	[7,14–18]

Table 1. *Cont.*

Dimension of Digitalization	Opportunities in HL	Contribution	References
Visibility and traceability	Digital tracking of inventories, shipments, equipment, and resources	Greater transparency; fewer errors; improved control of HL flows and inventories	[19–29]
Transparency and coordination	Exchange and verification of data on resources, transactions, and aid distribution	Better coordination among actors; more transparent HL flows; reduced information asymmetry	[30–33]
Spatial and situational visibility	Processing of spatial data; damage and needs assessment; identification of priority areas	More accurate planning of locations, needs, and resource allocation	[34–39]
Flexibility and accessibility of aid	Support for aid delivery and information collection in hard-to-reach areas	Shorter response time; greater accessibility and flexibility; potentially lower emissions	[40–43]
Simulation and risk management	Integration of data and simulations of HL processes and scenarios	Earlier identification of disruptions; vulnerability assessment; improved risk management	[14,44,45]
Procurement and production flexibility	Decentralization of selected HL activities and local production of required resources	Shorter procurement lead times; reduced dependence on distant suppliers; greater flexibility	[39,46–48]
Organizational preparedness and security	Development of digital competencies, infrastructure, and data protection	More sustainable implementation of digitalization and more secure information exchange	[49–51]

Although these opportunities indicate the significant potential of digitalization, its implementation in HL faces numerous limitations. Digital transformation does not merely involve the acquisition and implementation of appropriate solutions but also requires changes in the way HOs collect information, make decisions, coordinate activities, and manage resources. High initial investments, underdeveloped infrastructure, unstable internet connections, and disruptions in energy supply can significantly limit the implementation of digital solutions, particularly in crisis-affected and remote areas. Additional challenges include a shortage of qualified personnel, the need for employee training, and the development of new digital competencies [49,50]. A particular challenge concerns the quality, availability, and interoperability of data. Digital systems can improve decision-making only if they have access to timely, accurate, and relevant information. Incompatible data formats, different standards across organizations, fragmented information systems, and limited data sharing can reduce the benefits of digitalization. Furthermore, a higher degree of digital connectivity increases exposure to risks related to data protection, privacy, and cybersecurity. Therefore, it is necessary to develop appropriate security protocols, standardized procedures, and data protection mechanisms, particularly when processing information that may be sensitive to humanitarian aid recipients or the HOs themselves [51].

It follows that the value of digitalization in HL cannot be assessed solely on the basis of the technological sophistication of a particular solution. Its practical value depends on whether digital support corresponds to the specific needs of HOs, the conditions in which the organization operates, and the phase of the humanitarian operation in which it is applied. A technologically advanced solution that requires infrastructure, data, or professional capacities unavailable to an HO may have less practical value than a simpler and more reliable solution that can be implemented under real-world conditions. In this regard, the digitalization of HL should be viewed as a means of developing logistics capabilities rather than as an end in itself. Its fundamental value lies in its ability to connect information, resources, processes, and actors in a way that enables the timely

identification of needs, better anticipation of changes, more efficient resource allocation, greater visibility of logistics flows, and improved decision-making. This is precisely where the connection between digitalization and the "one step ahead of the crisis" approach becomes evident. The essence of this approach is not for HOs to implement the greatest possible number of new technologies but rather to develop, based on high-quality data, appropriate digital support, and organizational preparedness, the ability to identify changes in a timely manner, anticipate needs, prepare resources, and adapt logistics processes before a disruption reaches critical levels. This research gap provides the starting point for this study, which develops a systemic framework for evaluating and selecting the most suitable digital solution for HOs by applying a hybrid MCDM model. The substantive decision problem addressed is how HOs can systematically select digital solutions according to their potential contribution to preparedness, efficiency, coordination, reliability, and resilience, rather than merely evaluating individual technologies based on isolated criteria. Existing MCDM approaches provide valuable tools for technology evaluation, but they often focus on specific technologies, criteria, or operational contexts and, therefore, offer limited guidance for this broader, capability-oriented selection problem. The CAS perspective serves as a theoretical lens for recognizing the interconnected, adaptive, and dynamic nature of HSCs and for understanding the potential role of digital solutions in supporting coordination, adaptability, and resilience. The MCDM model, in contrast, provides a structured and static evaluation of alternative digital solutions according to predefined criteria reflecting their potential contribution to preparedness, efficiency, coordination, reliability, and resilience. Thus, the CAS perspective informs the interpretation and framing of the problem, while the MCDM model provides the analytical mechanism for comparing and ranking alternatives. The study does not attempt to model the dynamic evolution of HSCs or empirically test interactions, feedback loops, or emergent behavior; rather, it uses the CAS perspective to contextualize the need for adaptive and proactive digital capabilities within humanitarian logistics. Accordingly, the study addresses the following research question: *Which digital solution is most suitable for HOs when evaluated according to its potential contribution to preparedness, efficiency, coordination, reliability, and resilience?* In this sense, the resulting ranking can be interpreted as an assessment of the potential of digital solutions to support HOs in developing capabilities associated with a "one step ahead of the crisis" approach.

2.4. Multi-Criteria Decision-Making Methods Applied in the Hybrid Model

Given that one of the objectives of this study is to develop and apply a new hybrid MCDM model that integrates the Criterion Impact Loss (CILOS) method for determining criterion weights and the Comprehensive Distance-Based Ranking (COBRA) method for comprehensive distance-based ranking, it is necessary to review previous research and the areas in which these methods have been applied. The selection of these methods is based on their complementary characteristics. The CILOS method enables the objective determination of criterion weights by analyzing the information loss resulting from changes in the values of individual criteria, whereas the COBRA method enables the evaluation and ranking of alternatives based on their distance from ideal and anti-ideal reference points. The following section provides an overview of relevant studies in which these methods have been applied to address various problems (Tables 2 and 3). The steps involved in applying both methods within the proposed hybrid MCDM model are presented in Section 3.

Table 2. Application of the CILOS method in different fields.

Application	Subject of Assessment	Role of the CILOS Method	Reference(s)
Information security	Information security risks in banks	Determination of criterion weights for business continuity, data protection, and physical security	[52]
Macroeconomics	Macroeconomic performance of countries	Determination of the weights of economic indicators	[53]
Finance	Financial performance of IT companies	Determination of financial criterion weights	[54]
Logistics	Financial resilience of companies in the logistics sector	Determination of the weights of financial indicators	[55]
Banking	Financial performance of banks	Determination of the weights of financial performance criteria	[56,57]
Environmental quality	Water quality	Determination of the weights of water quality indicators	[58]
Agriculture	Agro-technological treatments	Determination of criterion weights for treatment assessment	[59]
Urban planning	Healthy, safe, and sustainable built environment	Determination of criterion weights for assessing the health, safety, and sustainability of the built environment	[60]
Technical systems	Characteristics of rotor systems	Determination of technical criterion weights	[61]
Software solutions	Software packages for project management	Determination of criterion weights for software evaluation	[62]
Food logistics	Digital technologies in food logistics	Determination of criterion weights for technology evaluation	[63]
Road transport	Selection of a means of transport	Determination of criterion weights for the selection of a means of transport	[64]
Disaster management	Degree and impact of damage incurred	Determination of criterion weights for assessing affected areas	[65]

Table 3. Application of the COBRA method in different fields.

Application	Subject of Assessment	Role of the COBRA Method	Reference(s)
E-commerce	E-commerce development strategies	Ranking of e-commerce development strategies	[66]
E-commerce and IT procurement	E-commerce development strategies and IT suppliers	Evaluation and ranking of strategies and IT suppliers	[67]
Finance	Financial performance of companies	Ranking of companies according to financial performance	[68,69]
Finance and logistics	Financial performance of logistics companies	Evaluation and ranking of financial performance	[70]
Tourism	Resources for geotourism development	Ranking of resources for geotourism development	[71]

Table 3. *Cont.*

Application	Subject of Assessment	Role of the COBRA Method	Reference(s)
Supply chain management	Supplier ranking from a resilience perspective	Supplier evaluation	[72]
Intermodal transport	Intermodal terminal management models	Evaluation of intermodal terminal management models	[73]
Last-mile logistics	Strategies for overcoming barriers to drone implementation	Ranking of strategies for overcoming barriers	[74]
Reverse logistics	Industry 4.0 technologies and development scenarios for smart reverse logistics	Ranking of smart reverse logistics development scenarios	[75]
City logistics	Smart material handling solutions	Evaluation of transshipment technologies for city logistics	[76]
Air cargo terminals	Industry 4.0 technologies	Applicability of Industry 4.0 technologies in air cargo terminals	[77]

A review of the literature shows that the CILOS method has been applied in various fields, with its primary function being the objective determination of the relative importance, i.e., weights of criteria based on available data. Applications in logistics are particularly relevant, where the CILOS method has been used to determine criterion weights in the assessment of digital technologies in food logistics [63] and in the selection of means of transport [64]. For the subject of this study, the application of the CILOS method in disaster consequence management is particularly relevant, where the weights of criteria describing the degree and impact of the resulting damage were determined [65]. These applications provide a basis for applying the CILOS method in this study, with the aim of objectively determining criterion weights for evaluating digital solutions that can contribute to improving HL and strengthening the ability of HOs to prepare for and respond to future disruptions in a timely manner, in accordance with the "one step ahead of the crisis" approach.

A review of the literature shows that the COBRA method has been applied in various fields, including e-commerce, finance, tourism, supply chain management, and different areas of logistics, with its primary function being the evaluation and ranking of alternative solutions based on multiple criteria. In logistics, COBRA has been applied to the evaluation and ranking of resilient suppliers [72], intermodal terminal management models [73], strategies for overcoming barriers to drone implementation in last-mile logistics [74], smart reverse logistics development scenarios [75], and smart material handling solutions in city logistics [76], as well as Industry 4.0 technologies in air cargo terminals [77]. Studies applying the COBRA method to the evaluation of technological solutions in logistics environments are particularly relevant. A review of the available literature did not identify any application of the COBRA method in the context of HL, nor its use for the systematic evaluation and ranking of digital solutions. Furthermore, there is a lack of approaches that consider the selection of digital technologies based on their relevance to HOs and their potential to improve the preparedness, efficiency, coordination, reliability, and resilience of HSCs as CASs. This gap represents the research gap that this study seeks to address, with the aim of supporting the transition from a reactive to a proactive approach to action, namely, the "one step ahead of the crisis" approach.

3. Research Methodology

In accordance with the aim of this study, which focuses on evaluating digital solutions for improving HL based on insights from the existing literature and their relevance to HOs, this chapter presents the research methodology. Particular emphasis is placed on the development of an integrated model for objectively determining the importance of the defined criteria and for evaluating and ranking digital solutions, with the aim of identifying alternatives that have the greatest potential to improve the efficiency, flexibility, sustainability, and resilience of HL, as well as the ability of HOs to respond to future crisis situations in a timely manner.

The problem of evaluating digital solutions in HL is characterized by a pronounced multi-criteria nature, as their suitability for implementation depends on a number of interconnected technological, economic, organizational, operational, and other aspects. An individual solution cannot be evaluated on the basis of a single criterion; rather, different and often conflicting requirements need to be considered simultaneously. Under such conditions, Multi-Criteria Decision-Making (MCDM) methods provide a framework for objectively determining the importance of criteria and comprehensively evaluating and ranking digital solutions according to their suitability for application in HL.

The proposed methodological framework is based on the integration of two MCDM methods—the Criterion Impact Loss (CILOS) method for objectively determining the criterion weights and the Comprehensive Distance-Based Ranking (COBRA) method for comprehensive distance-based ranking of alternatives. The selection of this combination of methods is based on their complementarity, as well as on the aim of limiting certain methodological limitations characteristic of individual MCDM approaches. Unlike weighting methods, such as the Analytic Hierarchy Process (AHP) and the Best–Worst Method (BWM), which rely to a greater extent on the judgments and preferences of decision-makers, the CILOS method enables the objective determination of weights based on available data and the information loss resulting from changes in criterion values. At the same time, compared with ranking methods, such as the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and VIseKriterijumska Optimizacija I Kompromisno Rešenje (VIKOR), which predominantly rely on the distance from the ideal solution or on determining a compromise solution, respectively, the COBRA method enables comprehensive ranking of alternatives by considering them in relation to multiple reference points and different aspects of their distance.

To explicitly connect the theoretical perspective of CAS with the technological and decision-making components of the study, a conceptual and methodological framework was developed, as presented in Figure 1. The framework establishes a direct conceptual link among four central elements of the research: (i) the CAS perspective of HL, (ii) the role of digital technologies as potential enablers of adaptation and coordination, (iii) HO-relevant evaluation criteria, and (iv) the "one step ahead of the crisis" objective. From the CAS perspective, HL is characterized by multiple interacting actors, resources, information flows, and operational processes that may adapt to changing environmental and crisis conditions. Within such a system, digital technologies are viewed not as isolated technological solutions but as potential enablers of information exchange, visibility, coordination, responsiveness, resource allocation, and adaptive capacity. Their potential contribution is assessed through evaluation criteria relevant to HOs, which provide an analytical link between the theoretical characteristics of an adaptive HL system and the practical assessment of individual digital solutions based on literature-informed considerations relevant to HOs.

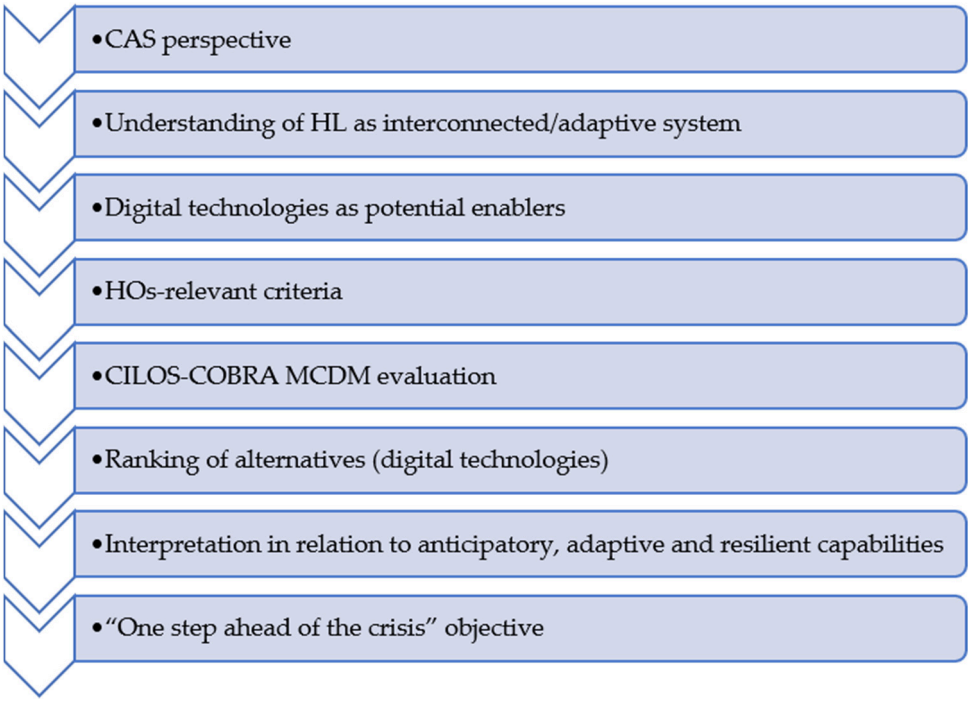


Figure 1. Conceptual and methodological framework linking CAS theory, digital technologies, evaluation criteria, and the "one step ahead of the crisis" objective.

The framework subsequently connects these elements with the "one step ahead of the crisis" objective, which emphasizes that digitalization should support not only response after a disruptive event occurs but also the anticipation of changes, early identification of potential problems, preparation of resources and logistics capacities, and timely adaptation as crisis conditions evolve. As illustrated in Figure 1, these conceptual relationships are translated into the research methodology through a logically connected sequence beginning with the research objective and the theoretical foundation derived from the literature on HL, digitalization, CAS, and MCDM. This foundation guides the selection of digital alternatives and the definition of HO-relevant evaluation criteria, which are subsequently incorporated into the hybrid CILOS-COBRA model for objective criterion weighting and ranking of the alternatives. The robustness of the obtained ranking is then examined through sensitivity analysis, while the final results are interpreted in light of the CAS perspective and in relation to the "one step ahead of the crisis" objective.

Thus, Figure 1 serves not only as a methodological flowchart but also as a conceptual framework that explains how the CAS perspective informs the formulation of the evaluation problem and the interpretation of the results. The CILOS-COBRA model does not directly model the dynamic evolution of HL as a CAS or empirically capture interactions, feedback loops, emergence, or adaptation over time. Instead, it provides a structured, static assessment of digital alternatives according to criteria reflecting capabilities that are relevant to the functioning and adaptation of HSCs. In this way, the framework uses CAS as a theoretical lens for contextualizing the decision problem, while MCDM provides the analytical mechanism for comparing digital solutions and assessing their potential contribution to the anticipatory, adaptive, and resilient capabilities of HOs.

3.1. CILOS Method

The ***CILOS method*** was developed by Zavadskas & Podvezko [78]. The method is based on analyzing changes in the significance of the remaining criteria when one of the criteria reaches its optimal value. If the relative loss of significance of a criterion is

small, its significance is considered to be more stable in relation to changes in other criteria, and, therefore, it is assigned a higher weight. In this way, the CILOS method enables the determination of objective criterion weights based on the interrelationships among criteria and changes in their significance. The CILOS procedure starts from the decision matrix $R = \left[r_{ij}\right]_{m\times n}$, which contains the values of m alternatives with respect to n criteria. Through the subsequent steps, the optimal criterion values, relative losses of significance, and final criterion weights are determined. The procedure for determining criterion weights using the CILOS method comprises the following steps [79]:

Step 1: In the first step of the CILOS method, minimization criteria are transformed into maximization criteria so that all criteria have the same orientation, i.e., a higher value represents a more favorable result. In this study, all criteria for evaluating digital solutions in HL have been defined as Max-type criteria. Therefore, in the specific case considered here, no transformation of minimization criteria is required, and the initial decision matrix R is directly used in the next step of the CILOS method.

Step 2: For each criterion in the decision matrix, its optimal, i.e., maximum, value is determined:

$$r_j = \max_i r_{ij} = rj_{k_j} \tag{1}$$

where r_{ij} is the value of the i-th alternative with respect to the j-th criterion, while k_j denotes the index of the alternative in which criterion j reaches its optimal value. In this way, for each of the n criteria, the alternative achieving its highest value is identified. The resulting values r_j represent the optimal criterion values used in the subsequent steps of the CILOS method.

Step 3: Based on the previous step, a square matrix A is constructed, where each row of the matrix corresponds to the alternative in which the optimal value is achieved for the respective criterion. The main diagonal of the matrix contains the optimal criterion values, while the remaining elements represent the values of the other criteria in the same alternative. The elements of the matrix are determined according to the following expression:

$$A = \left[a_{jk}\right]_{n\times n};\ a_{jj} = r_j;\ a_{jk} = rk_{k_j},\ j \neq k \tag{2}$$

where a_{jj} represents the optimal value of criterion j located on the main diagonal of matrix A, while a_{jk} represents the value of criterion k in alternative k_j, i.e., the alternative in which criterion j reaches its optimal value. Thus, matrix A enables the optimal value of each criterion to be compared with the values of the other criteria in the alternative that achieves that optimum.

Step 4: After matrix A has been constructed, the matrix of relative loss of significance P is determined. This indicates the extent to which the significance of criterion k decreases when criterion j reaches its optimal value. The elements of matrix P are calculated according to the following expression:

$$P = \left[p_{jk}\right]_{n\times n};\ p_{jk} = \frac{r_k - a_{jk}}{r_k} \tag{3}$$

where p_{jk} represents the relative loss of significance of criterion k when criterion j reaches its optimal value. A lower value of p_{jk} indicates a smaller relative loss of significance of criterion k. Accordingly, criteria whose significance is more stable, i.e., for which a smaller relative loss of significance is identified, are considered more important and are assigned higher weights. In other words, the CILOS method assigns greater importance to a criterion when reaching its optimal value results in a smaller relative loss of significance of the other criteria. Based on these identified interrelationships among the criteria, their objective weights are determined.

Step 5: Based on the matrix of relative loss of significance P, an homogeneous system of linear equations is constructed to determine the vector q, i.e., the initial (unnormalized) criterion weights:

$$F \times q^T = 0 \tag{4}$$

Matrix $F = \left[f_{jk}\right]_{n \times n}$ is defined as follows:

$$f_{jk} = \begin{cases} -\sum_{u=1}^{n} p_{uj} & for\ k = j \\ p_{jk} & for\ k \neq j \end{cases} \tag{5}$$

This matrix results from the following system of equations:

$$q_j \sum_{k=1}^{n} p_{kj} = \sum_{k=1}^{n} q_k p_{jk} \quad for\ j = 1,\ 2,\ \ldots,\ n \tag{6}$$

where q_j and q_k represent the initial, i.e., unnormalized, weights of criteria j and k, respectively. Since matrix P contains the mutual relative losses of significance of the n criteria, the summation in the system of equations is performed over all n criteria, while m denotes the number of alternatives in the initial decision matrix. The system of equations establishes the relationship between criterion weights and the relative losses of significance identified in matrix P. The resulting system is expressed in matrix form to facilitate its solution and determine the relationships among the criterion weights. By solving the homogeneous system, a non-zero vector $q = (q_1, q_2, \ldots, q_n)$ is obtained, whose elements represent the unnormalized criterion weights.

Step 6: In the final step, the initial vector q is normalized to obtain the final relative criterion weights:

$$w_j = \frac{q_j}{\sum_{v=1}^{n} q_v} \tag{7}$$

The resulting values, w_j, represent the relative weights of the criteria and are used to determine their importance in the MCDM process. Criteria for which a smaller relative loss of significance is identified, i.e., criteria whose significance is more stable in relation to changes in other criteria, receive higher weights and, consequently, have a greater influence on the final ranking of alternatives. In this way, the sum of all final criterion weights equals one, ensuring their comparability and enabling their direct application in the subsequent stages of the hybrid MCDM model.

3.2. COBRA Method

COBRA represents an MCDM method designed to evaluate and rank alternatives based on their comprehensive distance from reference solutions. Unlike some methods that base comparisons exclusively on an ideal or anti-ideal solution, COBRA simultaneously considers the positive ideal solution, negative ideal solution, and average solution, thereby providing a more balanced assessment of alternative performance. The method is characterized by a relatively simple computational procedure and the ability to be applied to various multi-criteria decision-making problems. The steps for applying this method are presented below [80]:

Step 1: Construct the decision matrix A, whose elements a_{ij} represent the performance ratings of alternative i $(i = 1, \ldots, n)$ with respect to criterion j $(j = 1, \ldots, m)$:

$$A = \left[\begin{pmatrix} a_{11} & \ldots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{n1} & \ldots & a_{nm} \end{pmatrix} \right] \tag{8}$$

where n denotes the total number of criteria, and m denotes the total number of alternatives considered.

Step 2: Construct the normalized decision matrix Δ as follows:

$$\Delta = \left[\alpha_{ij}\right]_{n\times m} \tag{9}$$

where

$$\alpha_{ij} = \frac{a_{ij}}{\max\limits_{i} a_{ij}} \tag{10}$$

Step 3: Construct the weighted normalized decision matrix Δ_w as follows:

$$\Delta_w = \left[w_j \times \alpha_{ij}\right]_{n\times m} \tag{11}$$

where w_j denotes the weight of criterion j, obtained using one of the MCDM methods.

Step 4: For each criterion, determine the positive ideal solution (PIS_j), negative ideal solution (NIS_j), and average solution (AS_j) as follows:

$$PIS_j = \max_i\left(w_j \times \alpha_{ij}\right),\ \forall j = 1,\ldots,m\ \ for\ \ j \in J^B \tag{12}$$

$$PIS_j = \min_i\left(w_j \times \alpha_{ij}\right),\ \forall j = 1,\ldots,m\ \ for\ \ j \in J^C \tag{13}$$

$$NIS_j = \min_i\left(w_j \times \alpha_{ij}\right),\ \forall j = 1,\ldots,m\ \ for\ \ j \in J^B \tag{14}$$

$$NIS_j = \max_i\left(w_j \times \alpha_{ij}\right),\ \forall j = 1,\ldots,m\ \ for\ \ j \in J^C \tag{15}$$

$$AS_j = \frac{\sum_{i=1}^{n}\left(w_j \times \alpha_{ij}\right)}{n},\ \forall j = 1,\ldots,m\ \ for\ \ j \in J^B,\ J^C \tag{16}$$

where J^B and J^C denote the sets of benefit and cost criteria, respectively.

Step 5: Determine the distances of each alternative from the positive ideal solution ($d(PIS_j)$) and the negative ideal solution ($d(NIS_j)$), as well as the positive distance ($d(AS_j^+)$) and negative distance ($d(AS_j^-)$) from the average solution as follows:

$$d\left(S_j\right) = dE\left(S_j\right) + \sigma \times dE\left(S_j\right) \times dT\left(S_j\right),\ \forall j = 1,\ldots,m \tag{17}$$

where S_j represents any of the distances PIS_j, NIS_j, AS_j^+ or AS_j^-, while σ is the correction coefficient calculated as follows:

$$\sigma = \max_i dE\left(S_j\right)_i - \min_i dE\left(S_j\right)_i \tag{18}$$

Here, $dE\left(S_j\right)_i$ and $dT\left(S_j\right)_i$ denote the Euclidean and Taxicab distances, respectively. For the positive ideal solution, these are calculated as follows:

$$dE\left(PIS_j\right)_i = \sqrt{\sum_{j=1}^{m}\left(PIS_j - w_j \times \alpha_{ij}\right)^2},\ \forall i = 1,\ldots,n,\ \forall j = 1,\ldots,m \tag{19}$$

$$dT\left(PIS_j\right)_i = \sum_{j=1}^{m}\left|PIS_j - w_j \times \alpha_{ij}\right|,\ \forall i = 1,\ldots,n,\ \forall j = 1,\ldots,m \tag{20}$$

For the negative ideal solution:

$$dE(NIS_j)_i = \sqrt{\sum_{j=1}^{m}(NIS_j - w_j \times \alpha_{ij})^2},\ \forall i = 1,\ldots,n,\ \forall j = 1,\ldots,m \tag{21}$$

$$dT(NIS_j)_i = \sum_{j=1}^{m}|NIS_j - w_j \times \alpha_{ij}|,\ \forall i = 1,\ldots,n,\ \forall j = 1,\ldots,m \tag{22}$$

For the positive distance from the average solution:

$$dE\left(AS_j^+\right)_i = \sqrt{\sum_{j=1}^{m}\tau^+(AS_j - w_j \times \alpha_{ij})^2}, \forall i = 1,\ldots,n,\ \forall j = 1,\ldots,m \tag{23}$$

$$dT\left(AS_j^+\right)_i = \sum_{j=1}^{m}\tau^+|AS_j - w_j \times \alpha_{ij}|,\ \forall i = 1,\ldots,n,\ \forall j = 1,\ldots,m \tag{24}$$

where:

$$\tau^+ = \begin{cases} 1 \ \ if \ \ AS_j < w_j \times \alpha_{ij} \\ 0 \ \ if \ \ AS_j > w_j \times \alpha_{ij} \end{cases} \tag{25}$$

and for the negative distance from the average solution:

$$dE\left(AS_j^-\right)_i = \sqrt{\sum_{j=1}^{m}\tau^-(AS_j - w_j \times \alpha_{ij})^2},\ \forall i = 1,\ldots,n,\ \forall j = 1,\ldots,m \tag{26}$$

$$dT\left(AS_j^-\right)_i = \sum_{j=1}^{m}\tau^-|AS_j - w_j \times \alpha_{ij}|,\ \forall i = 1,\ldots,n,\ \forall j = 1,\ldots,m \tag{27}$$

where:

$$\tau^- = \begin{cases} 1 \ \ if \ \ AS_j > w_j \times \alpha_{ij} \\ 0 \ \ if \ \ AS_j < w_j \times \alpha_{ij} \end{cases} \tag{28}$$

Step 6: Rank the alternatives in ascending order according to their comprehensive distance values (dC_i), which are calculated as follows:

$$dC_i = \frac{d(PIS_j)_i - d(NIS_j)_i - d\left(AS_j^+\right)_i + d\left(AS_j^-\right)_i}{4},\ \forall i = 1,\ldots,n \tag{29}$$

4. Multi-Criteria Decision-Making Application

This chapter presents an MCDM application focused on the evaluation of digital solutions for improving HL based on insights from the existing literature and their relevance to HOs, with the aim of assessing their potential to enable effective responses to crisis events. The analysis is structured into three interconnected parts: (i) presentation of the selected digital solutions and analysis of their capabilities, advantages, and limitations in the context of HL, (ii) definition of the criteria according to which these solutions will be evaluated based on literature-informed considerations relevant to HOs, and (iii) consideration of the role and importance of HOs as the entities responsible for implementing these solutions. In this way, a basis is established for their evaluation and for determining which digital solution provides the greatest value in improving HL and supporting the "one step ahead of the crisis" approach.

4.1. Digital Solutions for Optimizing Humanitarian Logistics

This section presents the digital solutions selected due to their direct applicability to key logistics activities of HOs, such as monitoring inventories and shipments, analyzing needs and available resources, coordinating logistics processes, communicating with stakeholders, and managing field activities. These four solutions were selected because, collectively, they encompass the key functions of digitalized HL—collecting data on resources and activities, processing and analyzing such data, integrating logistics processes, and facilitating communication and information exchange in the field. In this way, they enable an assessment of the different ways in which digitalization can contribute to the timely identification of needs, more efficient resource management, and improved coordination of humanitarian activities. Although these technologies may perform complementary functions and can be implemented jointly, they are considered individual alternatives in this study to enable the assessment of their relative priority for digitalization investments and implementation under resource-constrained conditions. For each solution, its capabilities, advantages, and limitations will be considered, providing a basis for its evaluation informed by the existing literature and its relevance to HOs, as well as for assessing its contribution to the improvement of HL.

4.1.1. Internet of Things in Humanitarian Logistics (A_1)

The Internet of Things (IoT) represents a set of interconnected devices and sensors that enable the continuous collection, processing, and exchange of data. In the context of humanitarian operations, IoT enables timely and reliable information to be available across different stages of operations—from planning and prevention, through emergency response, to recovery processes. In this way, IoT represents significant potential for improving the efficiency, transparency, and resilience of HSCs, as well as for the long-term improvement of humanitarian aid delivery systems [81].

The application of IoT technologies in HL is primarily reflected in continuous inventory monitoring, fleet management, and the optimization of transportation processes. Sensors, smart cameras, and wireless networks enable the collection of data on the condition and location of resources, the movement of shipments, and changes in transportation conditions. Such information is highly important for planning, coordinating, and implementing emergency interventions, particularly in situations where rapid responses to changes in demand or unforeseen events are required [82]. The IoT can contribute to the more efficient distribution of food and medical supplies, as well as to maintaining communication under conditions of disrupted infrastructure. Its application contributes to the digital transformation of HL, enabling HOs to manage resources more effectively based on real-time data and to adapt their activities to changes in the environment [83,84]. The application of IoT technologies provides numerous benefits for HSCs. First and foremost, the timely availability of data enables faster and more accurate decision-making, while continuous monitoring of inventories and transportation can reduce losses of food, medical supplies, and other resources. At the same time, optimization of transportation routes and the use of available resources contributes to increased operational efficiency. Of particular importance is the possibility of decentralized and localized distribution, which can increase the flexibility and resilience of HL systems and enable faster responses to unforeseen events [82,83]. Continuous information exchange through IoT can contribute to greater transparency and a fairer distribution of aid, thereby further strengthening HSC resilience [81].

In addition to the aforementioned advantages, the implementation of IoT systems in HL faces numerous technical, financial, and organizational challenges. Their functionality largely depends on the availability of stable electricity, communication networks, and appropriate digital infrastructure, which can represent a serious limitation in remote and

crisis-affected areas. Furthermore, high initial costs associated with the procurement, installation, and maintenance of devices, as well as the technical complexity of the systems, may hinder their implementation. Interoperability issues between different devices and information systems further complicate the integration of IoT solutions into existing HSCs [85,86]. Information security and privacy protection represent particular challenges. The large number of connected devices and continuous data collection increase the exposure of systems to cyberattacks, which is particularly important in unstable humanitarian environments. The ethical and cultural acceptability of systems, as well as the protection of users' privacy, are important prerequisites for successful IoT adoption. Therefore, it is necessary to develop standardized protocols, provide adequate staff training, and involve local communities in the implementation process, thereby increasing user trust and facilitating the long-term integration of IoT solutions into HL [87]. Overcoming these barriers requires simultaneous investment in digital infrastructure, the development of employee competencies, and the establishment of robust security protocols [85,86].

4.1.2. Big Data Processing Technologies in Humanitarian Logistics (A_2)

Big Data is a broad concept encompassing large and complex datasets that are difficult to store, process, analyze, and understand using traditional databases and conventional data-processing tools. The term "Big Data" is often used to describe enormous, complex, and real-time datasets that may be unstructured, semi-structured, or structured and that require advanced management, analysis, and processing techniques to extract meaningful information and useful insights [88]. Their importance is particularly evident in disaster management, where the integration of different data sources and the acquisition of accurate and timely information are crucial for decision-making. The expected continued growth in the volume of generated data indicates that the importance of technologies for their storage, processing, and analysis will continue to increase [89].

In HL, Big Data processing technologies enable the use of large amounts of information originating from different sources. Various technologies, such as geotagging, robotics, wearable technologies, drones, mobile devices, and applications, can be used to provide humanitarian assistance and conduct disaster-response operations. Data generated through the application of these technologies can have significant value for analyzing and gaining new insights into the functioning of HSCs. Therefore, it is important for HOs to develop Big Data processing capabilities in order to utilize the large volumes of data originating from different sources [90]. The application of Big Data processing technologies is particularly important in crisis situations, when it is necessary to rapidly collect, process, and analyze large amounts of information. Large datasets can be used to address various humanitarian challenges, including the management of blood supply chains. In addition, point-of-sale data have been analyzed to reduce logistics costs and improve the flow of inventories to stores located in areas affected by hurricanes. This technology can also contribute to more effective coordination of command and control centers, thereby facilitating the allocation of critical resources to different locations for emergency assistance [91], improving HSC resilience [92], and enhancing HL performance [93,94].

Despite these capabilities and advantages, the application of Big Data processing technologies in HL faces numerous challenges. One of the key issues concerns the digital divide, i.e., unequal access to the Internet, mobile technologies, and digital services among different social and demographic groups. The quality, reliability, and completeness of data also represent significant challenges. These include incomplete data, inconsistent data collection methods, and unreliable data from social media, as well as the difficulties associated with their verification and validation. A particular challenge concerns the processing of large datasets characterized by high volume, variety, and velocity, as well

as issues related to credibility, validation, and verification. Additional difficulties may arise due to language differences, uneven spatial distribution of data sources, and the different ways in which users generate data. Privacy, security, trust, and ethical issues are also emphasized. The use of Big Data in humanitarian operations may have political, social, and ethical consequences, particularly if the principles of humanity, neutrality, and impartiality are neglected [95]. Another challenge relates to communication with and participation of the local population. The need for appropriate volunteer training, ensuring the quality of their work, and maintaining their motivation, as well as the potential disconnect between volunteers and the local context in which the humanitarian operation takes place, represent additional factors that need to be considered when applying Big Data processing technologies.

4.1.3. Enterprise Resource Planning Systems in Humanitarian Logistics (A_3)

Enterprise Resource Planning (ERP) systems represent integrated software and information systems designed to manage and optimize organizational resources. Their primary role is to connect different business functions and processes within a unified information system. The specific characteristics of the humanitarian sector further emphasize the need for systems capable of providing timely and reliable information. However, humanitarian organizations have traditionally been slower to adopt ERP systems due to limited financial and other resources, resistance from senior management, and unstable infrastructure. Due to these specific characteristics, various ERP solutions adapted to the needs of HOs have been developed. These systems generally represent modifications of solutions originally developed for the private sector, with their functionalities adapted to the requirements of humanitarian operations [96]. The ERP implementation process enables the design and organization of HSCs using a unified reference model, while system configuration facilitates the operationalization of processes through software-embedded decision-making models that support activity execution, testing, reporting, and process improvement [97].

ERP systems provide numerous benefits for HL management. One of the most significant advantages is the ability to exchange information in real time between different organizational units and partners within HSCs. ERP systems can contribute to building more resilient supply chains, improving cooperation with suppliers, and managing available resources more efficiently. Their contribution to fleet management and the definition of HL performance is particularly important [96]. An ERP system developed for HL can contribute to increasing the efficiency of aid delivery and reducing resource waste [98]. ERP systems can also improve transparency, accountability, and reporting quality, which is particularly important in the humanitarian sector. Given that humanitarian organizations rely heavily on donor funding, the ability to track resource flows and generate reliable reports represents an important element of management. A centralized information system can enable better control over resource utilization, easier grant monitoring, and more efficient reporting in accordance with donor requirements. In emergency situations, ERP systems can also support the analysis of large volumes of data and the simulation of different humanitarian operation scenarios, thereby improving the quality of decision-making processes [99].

Despite these advantages, the application of ERP systems in HL faces numerous limitations. Unlike the stable business environments in which ERP systems are most commonly implemented, humanitarian operations often take place under conditions of inadequate telecommunications and energy infrastructure. Interruptions or the complete absence of electronic communication limit the use of standard ERP solutions and may result in reliance on paper-based documentation. Consequently, processes become slower, less reliable, and more difficult to adapt to changing conditions in crisis environments. An additional chal-

lenge is the continuous influx of new information system users, which requires ongoing training of employees and field personnel. In this regard, ERP systems should support multiple languages, online training, a user-friendly interface, and centralized installation and maintenance. Standard ERP systems are often insufficiently adapted to the reporting requirements of HOs, meaning that their implementation is frequently accompanied by the need for additional system customization, which can increase implementation complexity and costs. At the same time, the decentralized organizational structure of humanitarian organizations, characterized by a large number of offices, field units, and other organizational entities, can lead to fragmentation of data and processes [99]. Although existing ERP solutions can be relatively easy to use and may not require a high level of computer literacy, some are insufficiently integrated with the information systems of other organizations, require a high-quality internet connection, or support only certain specific functions [96]. In addition, interoperability represents one of the key prerequisites for the further development of ERP systems in the humanitarian sector, confirming the importance of common process and data models that enable the integration of different HOs [100].

4.1.4. Mobile Technologies in Humanitarian Logistics (A_4)

Mobile phones represent an accessible and relatively simple technology that can be used for communication, data collection and exchange, inventory monitoring, cash transfers, and coordination of humanitarian activities. Unlike fixed-line telephony and certain web-based systems, which may cease to function during disasters, mobile networks often remain available and enable the rapid connection of large numbers of users [101]. Mobile technologies play a significant role in HL throughout different phases of disasters—from early warning, through immediate response, to recovery. Although their application has long been predominantly focused on early-warning systems, contemporary research increasingly highlights their potential to improve logistics decision-making and resource management. Serrato-Garcia et al. [102] developed a decision-support framework that combines a multi-criteria optimization model with an information system based on mobile technologies, with the aim of increasing the efficiency of HL disaster-response operations.

In logistics processes, mobile phones are used for data collection and inventory management. The "SMS for Life" project demonstrated how healthcare workers can report medicine inventory levels via SMS messages, enabling authorities to replenish or redistribute resources in a timely manner. Following the earthquake in Haiti, SMS messages sent by people trapped under the rubble represented an important source of information for organizing assistance, while during the Ebola epidemic, mobile phones were used for health messaging, text-based surveys, and communication with the population. Mobile operator data are also particularly important, as they can provide information on population movements and behavior and can be combined with satellite, weather, demographic, and civil protection data. Mobile technologies also enable electronic cash transfers and vouchers, allowing for assistance to be distributed directly to beneficiaries without transporting large quantities of goods. In this way, mobile technology becomes a means not only of communication but also of managing the entire humanitarian aid supply chain [101]. The application of mobile technologies also extends to the coordination of different actors. Setiabudi & Widyadana [103] developed a mobile application for logistics management between the Indonesian Red Cross, reception centers, and volunteers, enabling the recording of needs and available inventories in disaster-affected areas. In addition, the Global Positioning System (GPS) integrated into mobile devices can be connected to geographic information systems, enabling the collection of geospatial data, mapping of affected areas, and visualization of disaster impacts almost in real time. The most important advantages of mobile technologies are their low cost, wide availability, ease of use, flexibility, and

ability to transmit data rapidly. They can reduce the time and costs associated with aid distribution, facilitate stakeholder coordination, and enable decision-making based on up-to-date information. They are particularly useful in remote and hard-to-reach areas, where conventional distribution methods may be costly or pose security risks [104].

Despite their numerous advantages, the application of mobile technologies faces technical, ethical, and social limitations. Mobile infrastructure is not equally available in all crisis-affected areas, which may deepen the existing digital divide and further marginalize vulnerable groups. In addition, the integration of different data sources and the processing of large amounts of information require appropriate technical infrastructure and expertise [101]. Privacy, data ownership, the legal framework, and ethical responsibility represent particular challenges. The collection of data on the location, communication, and movement of populations must be accompanied by appropriate protection measures to prevent misuse and preserve users' trust. Therefore, the successful application of mobile technologies in HL requires not only technological development but also appropriate ethical, legal, and institutional frameworks [104].

4.1.5. Complementarity of Digital Solutions, Technology Portfolio, and Implementation Prioritization

The four digital solutions considered in this study—IoT, Big Data processing technologies, ERP systems, and mobile technologies—perform different and, in many cases, complementary functions within HL. Therefore, the purpose of the MCDM analysis is not to determine which single technology should be selected to the exclusion of all others. Instead, the four solutions are treated as individual technology options within a broader digitalization portfolio, allowing for their relative contribution and priority to be assessed according to a common set of criteria. Such an approach is particularly relevant in HL because HOs operate under limited financial, technical, organizational, and human resources and may, therefore, need to determine which technologies should receive priority when planning digitalization investments.

The fact that these technologies are complementary does not prevent their comparison within an MCDM framework. The alternatives are not assumed to be mutually exclusive; rather, the ranking is intended to support prioritization among potential technology investments. Each solution can independently contribute to different dimensions of HL performance and can, therefore, be evaluated according to common criteria reflecting its potential contribution to preparedness, efficiency, adaptability, reliability, and security. The resulting ranking should, consequently, be interpreted as an indication of the relative priority of individual digital solutions within a potential technology portfolio, rather than as a recommendation to select only one technology.

This perspective also supports an implementation-sequencing approach. The ranking obtained through the MCDM model can provide an initial basis for determining which digital solutions could be considered for earlier implementation when simultaneous adoption of all solutions is not feasible. A higher-ranked alternative may, therefore, represent a potential priority for an initial investment or implementation phase, while other solutions can be introduced in subsequent phases or implemented in parallel where sufficient resources and organizational conditions exist. In this sense, the ranking provides decision support for building and sequencing a portfolio of complementary digital solutions rather than identifying a single universally applicable technology.

Accordingly, the comparison of IoT, Big Data processing technologies, ERP systems, and mobile technologies should be understood as a prioritization exercise under resource constraints. The MCDM model enables the relative value of each solution to be assessed using the same evaluation framework while recognizing that the long-term digital transformation of HL may require the coordinated adoption of multiple complementary technolo-

gies. The results, therefore, indicate potential priorities for investment and implementation and do not imply that lower-ranked alternatives lack value or should be excluded from the technology portfolio.

To operationalize these complementary technologies within a structured improvement model, a multi-layered digital system architecture for HOs is conceptualized: (i) *Data Collection Layer* (IoT sensors and mobile devices capturing real-time operational and environmental data), (ii) *Data Integration and Processing Layer* (ERP systems and Big Data platforms organizing, standardizing, and analyzing data flows), and (iii) *Decision-Support Layer* (MCDM evaluation routing priorities to decision-makers). Based on this architecture, a phased implementation plan is established: **Phase 1 (Foundational Setup):** deploying mobile technologies for rapid communication and basic data collection; **Phase 2 (Operational Visibility):** integrating IoT infrastructure for real-time tracking of critical assets; **Phase 3 (Organizational Integration):** scaling ERP systems to unify workflows; and **Phase 4 (Advanced Analytics):** embedding Big Data predictive analytics for long-term forecasting. This phased approach ensures manageable capital expenditure and capability building for resource-constrained HOs.

4.2. Defining Criteria for the Evaluation of Digital Solutions in Humanitarian Logistics

The definition of evaluation criteria represents the basis for the objective assessment of digital solutions that can contribute to the improvement of HL based on insights from the existing literature and their relevance to HOs. Given that HOs operate under conditions of uncertainty, time pressure, limited resources, and changing beneficiary needs, the evaluation of digital solutions cannot be based exclusively on their technical characteristics. For HOs, it is important that a technology contributes to better preparedness for crisis events, more efficient execution of logistics activities, integration of existing processes, rational use of available resources, and secure information management, while also being acceptable to the stakeholders who use it. In accordance with the aim of this study, the criteria were defined to enable the assessment of the overall value of digital solutions for HOs, i.e., their ability to contribute to the transition from a predominantly reactive approach to a timely and proactive approach to HL management. As a starting point for their definition, the framework proposed by Rejeb et al. [82] was used, which highlights the importance of a systematic approach to the evaluation and selection of technologies in humanitarian operations.

Contribution to Preparedness and Resilience (C_1). This criterion refers to the ability of a digital solution to improve the preparedness of HOs for crisis events and their ability to maintain and adapt their activities under disruptive conditions. A higher value of the criterion implies a greater contribution to the early identification and anticipation of changes in the environment, resource planning, preparation of logistics capacities, and rapid adaptation to changes during a crisis event. The criterion is directly related to the "one step ahead of the crisis" approach, as it considers not only the ability of HOs to respond after a crisis occurs but also their ability to use a digital solution to identify potential problems in advance and prepare an appropriate response.

Logistics Efficiency (C_2). This criterion indicates the extent to which a digital solution contributes to the improvement of specific logistics activities of HOs. It considers its impact on inventory management, procurement, warehousing, transportation, distribution of humanitarian aid, utilization of available resources, and coordination of logistics activities. A higher value of the criterion indicates that the application of a particular solution may enable HOs to execute logistics processes more quickly, reduce unnecessary activities and losses, allocate resources more effectively, and direct aid in a timely manner toward areas and beneficiaries with the greatest needs. This criterion is particularly important

because it directly links the application of digital solutions with the fundamental objective of improving HL—providing the appropriate assistance, in the appropriate quantity, at the appropriate time, and in the appropriate place.

Integration and Adaptability (C_3). For HOs, the value of a digital solution depends not only on its functionalities but also on its ability to be integrated into existing logistics and organizational processes. This criterion encompasses the possibility of integration with existing HO information systems, data exchange with other HSC actors, interoperability, scalability, and adaptation to changes in humanitarian operations. A higher value of the criterion implies that HOs can implement the solution without significantly disrupting existing processes. The ability to adapt to different conditions is particularly important, as HOs may operate simultaneously in different countries and locations and respond to crises of varying intensity.

Economic Viability (C_4). Economic viability indicates the extent to which the benefits obtained by HOs from applying a digital solution justify the resources required for its acquisition, implementation, maintenance, and use. The assessment should consider not only initial costs but also infrastructure costs, upgrades, technical support, employee training, and long-term system maintenance. This criterion is particularly important for HOs due to their limited and often earmarked financial resources, meaning that a technological solution must provide clear practical and economic value. In the broader context of responsible resource management, economic viability may also include the potential of a digital solution to reduce resource waste, unnecessary logistics activities, paper consumption, and other costs and impacts associated with the implementation of humanitarian operations.

Information Reliability and Security (C_5). This criterion refers to the quality of the information on which HOs base their logistics decisions, as well as the protection of such information. A digital solution should provide accurate, timely, complete, and accessible data on needs, resources, shipments, and other relevant elements. At the same time, the information available to HOs may contain data concerning aid beneficiaries, their location, health or social status, and other sensitive information, making data protection an important prerequisite for the responsible use of digital technologies. A higher value of the criterion implies a higher level of information reliability and a lower risk of data loss, unauthorized access, alteration, or misuse.

Social Acceptability (C_6). Social acceptability refers to the extent to which a digital solution is acceptable and accessible to the people who use it or are affected by its implementation. For HOs, this means that the solution should be sufficiently easy to use by employees and volunteers, correspond to their digital competencies, and not require disproportionately large investments in training. At the same time, the acceptance of the technology by humanitarian aid beneficiaries, local communities, and other stakeholders should be taken into account, particularly when its application involves the collection of personal data or changes in the way assistance is provided. A higher value of the criterion implies a greater willingness of relevant stakeholders to accept and use the digital solution, with a lower risk of its rejection or the creation of new forms of digital exclusion.

All the above criteria are defined as Max-type criteria, meaning that a higher value represents a more desirable characteristic of a digital solution. For C_1, C_2, C_3, C_5, and C_6, a higher value indicates, respectively, a greater potential contribution to preparedness and resilience, higher logistics efficiency, greater integration and adaptability, higher information reliability and security, and greater social acceptability. C_4 is also defined as a Max-type criterion, but it does not refer to the absolute level of costs; rather, it refers to economic viability, that is, the relationship between the expected benefits for HOs and the resources required to implement the digital solution. Therefore, a higher C_4 score indicates a more

favorable benefit-to-cost relationship. Collectively, these criteria represent capabilities and characteristics that are relevant to the functioning and adaptation of HOs within complex and changing HSCs. They should not, however, be interpreted as direct measures of CAS properties or of the dynamic evolution of HSCs. Instead, they provide a structured basis for assessing the potential of digital solutions to support organizational capabilities that are relevant from the CAS perspective. This classification of the criteria is important for the application of the proposed hybrid MCDM model, as it determines the manner in which the input criterion values will be normalized and subsequently used in calculating the final values and ranking the digital solutions.

4.3. Humanitarian Organizations: Role and Importance

HOs, such as the Red Cross and the World Health Organization, play a central role in the planning, coordination, implementation, and evaluation of humanitarian operations. Their responsibilities include managing complex humanitarian supply chains under conditions of high uncertainty and time pressure. According to Beamon & Balcik [105], these organizations face numerous challenges in organizing HSCs, while at the same time recognizing the importance of applying efficient and innovative technologies that enable the management of rapid and complex humanitarian aid distribution processes. In the contemporary humanitarian environment, the success of HOs largely depends on their ability to cooperate with local authorities, donors, and other relevant stakeholders. Schiffling & Piecyk [106] emphasize that such cooperation requires the alignment of different interests, transparent communication, and a high level of coordination among participants. In this context, HOs increasingly use digital platforms to optimize HSCs, thereby enabling more efficient information exchange and better coordination among all stakeholders [107].

Given the aforementioned role and responsibilities of HOs, it is not sufficient merely to identify digital solutions that can improve HL; it is also necessary to assess their potential value and applicability in the context of humanitarian operations. An evaluation informed by the existing literature and the identified requirements of HOs makes it possible to consider not only potential benefits but also their practical applicability and the limitations characteristic of crisis environments. Such an approach is particularly important for the "one step ahead of the crisis" approach, as the selection of appropriate digital solutions should be based on their ability to improve HO preparedness and contribute to more efficient HL management before and during a crisis event.

5. Results of Model Application and Sensitivity Analysis

Based on the defined alternatives and criteria for evaluating digital solutions in HL, this chapter presents the results of applying the proposed hybrid MCDM model. The model integrates the CILOS method, which is used to determine the objective weights of the criteria, and the COBRA method, which is used for the comprehensive evaluation and ranking of alternatives. The objective of applying the model is to identify the digital solution that, based on insights from the existing literature and its relevance to HOs, provides the greatest overall value for improving HL, i.e., the solution that can contribute most significantly to the preparedness, efficiency, adaptability, reliability, and security of logistics activities.

In accordance with the "one step ahead of the crisis" approach, the evaluation is not focused exclusively on the ability of digital solutions to support activities following the occurrence of a crisis event. Rather, particular attention is given to their potential to contribute to the timely identification of needs and risks, resource preparedness, improvement of logistics processes, and strengthening the ability of HOs to adapt to changing conditions. Therefore, the results of the model are interpreted simultaneously from the perspective of

the objective importance of individual criteria and the overall suitability of alternatives for application in humanitarian operations, based on insights from the existing literature and their relevance to HOs.

5.1. Application of the CILOS Method and Determination of Criterion Weights

In the first part of the model application, the objective weights of the criteria were determined using the CILOS method, based on a decision matrix containing the scores of four selected digital solutions according to the six defined criteria. The initial decision matrix represents the basis for all subsequent calculations within the model. As presented in Table 4, each alternative was evaluated according to all six criteria, which had previously been defined as Max-type criteria, i.e., criteria for which a higher value indicates a more favorable characteristic of the digital solution.

Table 4. Initial decision matrix.

Alternative/Criterion	C_1	C_2	C_3	C_4	C_5	C_6
A_1	10	10	8	6	8	7
A_2	9	7	7	5	6	5
A_3	8	9	10	5	9	7
A_4	9	8	8	10	7	10

The scores, expressed on a scale from 1 to 10, represent a literature-informed assessment of the suitability of the alternatives with respect to the defined criteria and their relevance to HOs. The assessment was not based on a survey or expert elicitation. Instead, the scores were derived from a structured interpretation of the evidence identified in the literature reviewed in Chapter 4. In this approach, the score assigned to each technology–criterion pair reflects the extent to which the documented capabilities and limitations of the respective technology correspond to the definition of the criterion. This approach is consistent with the purpose of the study, which is to provide a literature-informed evaluation of digital solutions relevant to humanitarian organizations rather than an expert-opinion-based assessment. By utilizing a structured literature-informed scoring system backed by evidence mapping (Table 5), the study reduces reliance on individual expert judgment and the potential cognitive and contextual biases associated with small expert panels in MCDM, while recognizing that the translation of qualitative evidence into numerical scores still involves a degree of researcher judgment. The evaluation is, thus, synthesized from documented empirical and theoretical findings across the broader humanitarian logistics literature. Table 4 presents the resulting initial decision matrix.

To improve the transparency and reproducibility of the assessment, Table 5 provides the source-to-score mapping for every technology–criterion pair. The evidence supporting each score was identified from the literature discussed in Chapter 4. The assessment considers both the documented benefits and the reported implementation limitations of each technology. Thus, a high score does not necessarily indicate that a technology is without limitations; rather, it indicates a stronger overall correspondence between the documented capabilities of the technology and the respective criterion.

The 1–10 scale was operationalized as an ordinal literature-informed assessment, where lower values indicate weak correspondence between the documented characteristics of a technology and the respective criterion, while higher values indicate strong correspondence. The assessment, therefore, does not represent a directly measured quantitative variable or a subjective probability. Instead, it provides a structured numerical representation of qualitative evidence reported in the literature. Although the scoring process was structured and evidence-based, assigning numerical scores to qualitative findings

necessarily involves a degree of researcher judgment. In assigning the scores, both positive contributions and documented barriers were considered, particularly for criteria related to economic viability, information security, integration, and social acceptability.

Table 5. Source-to-score mapping for the initial decision matrix.

Alternative	Criterion	Score	Evidence Supporting the Assessment	Sources
A_1—Internet of Things	C_1—Contribution to Preparedness and Resilience	10	IoT enables continuous collection and exchange of information, real-time monitoring of resources and transportation, faster decision-making, and adaptation to changing operational conditions. These capabilities directly support preparedness, responsiveness, and resilience in humanitarian supply chains.	[81–84]
	C_2—Logistics Efficiency	10	IoT supports continuous inventory monitoring, fleet management, transportation optimization, resource utilization, and more efficient distribution of food, medical supplies, and other humanitarian resources.	[82–84]
	C_3—Integration and Adaptability	8	IoT enables interconnected devices and continuous information exchange and can support decentralized and localized distribution. However, interoperability among heterogeneous devices and integration with existing information systems remain important implementation challenges.	[81–86]
	C_4—Economic Viability	6	IoT can reduce losses and improve transportation and resource efficiency, creating potential economic benefits. However, implementation requires investment in devices, connectivity, electricity, installation, maintenance, technical support, and digital infrastructure.	[82–86]
	C_5—Information Reliability and Security	8	Continuous sensing and data exchange improve the timeliness and availability of information for humanitarian decision-making. At the same time, connected devices and continuous data collection increase exposure to cybersecurity, privacy, and data-protection risks.	[81–87]
	C_6—Social Acceptability	7	IoT can improve transparency and support decentralized and localized humanitarian distribution. However, technical complexity, privacy concerns, staff-training requirements, and the need for local-community involvement may affect acceptance and accessibility.	[81–87]

Table 5. *Cont.*

Alternative	Criterion	Score	Evidence Supporting the Assessment	Sources
A_2—Big Data Processing Technologies	C_1—Contribution to Preparedness and Resilience	9	Big Data technologies enable the integration and analysis of large amounts of information from different sources and can support rapid decision-making, crisis analysis, resource allocation, and improvement of humanitarian supply chain resilience.	[89–94]
	C_2—Logistics Efficiency	7	Big Data applications can support inventory management, logistics-cost reduction, resource allocation, and coordination of humanitarian operations. However, their effectiveness depends on data quality, analytical capabilities, and appropriate processing infrastructure.	[90–94]
	C_3—Integration and Adaptability	7	Big Data technologies allow for information from heterogeneous sources to be integrated and analyzed, supporting coordination among humanitarian actors. However, differences in data formats, language, spatial distribution, data-generation practices, and verification requirements create integration challenges.	[90,95]
	C_4—Economic Viability	5	Big Data applications can improve resource allocation and reduce logistics costs, but implementation requires data-processing infrastructure, analytical capabilities, technical expertise, and staff training, which may impose substantial resource requirements on HOs.	[89–95]
	C_5—Information Reliability and Security	6	Big Data technologies provide access to large and diverse information sources, but the literature identifies problems related to data quality, completeness, credibility, verification, validation, privacy, security, and ethical use.	[89–95]
	C_6—Social Acceptability	5	Big Data technologies can support communication and humanitarian decision-making, but digital divides, unequal access to digital services, privacy and ethical concerns, volunteer-training requirements, and possible disconnection from local contexts may constrain social acceptability.	[95]

Table 5. *Cont.*

Alternative	Criterion	Score	Evidence Supporting the Assessment	Sources
A_3—Enterprise Resource Planning Systems	C_1—Contribution to Preparedness and Resilience	8	ERP systems provide integrated organizational information, support resource planning and management, and can contribute to more resilient supply chains and improved decision-making. Their contribution is constrained by unstable infrastructure and the specific conditions of humanitarian operations.	[96–99]
	C_2—Logistics Efficiency	9	ERP systems integrate logistics and organizational functions and support resource management, fleet management, reporting, process management, and aid delivery. They can improve logistics efficiency and reduce resource waste.	[96–99]
	C_3—Integration and Adaptability	10	Integration of organizational functions is a fundamental characteristic of ERP systems. In humanitarian applications, ERP supports unified process and information management, while interoperability and common process and data models are identified as important requirements for integrating different HOs.	[96–100]
	C_4—Economic Viability	5	ERP systems can improve resource utilization, reduce waste, and increase process efficiency. However, implementation, customization, infrastructure, maintenance, training, and system adaptation can impose considerable costs and resource requirements on HOs.	[96,99,100]
	C_5—Information Reliability and Security	9	ERP systems facilitate real-time information exchange, centralized information management, transparency, accountability, resource-flow monitoring, and reliable reporting. These capabilities support the quality and availability of information used in humanitarian decision-making.	[96–100]
	C_6—Social Acceptability	7	ERP systems can incorporate user-friendly interfaces, multilingual support, online training, and centralized installation and maintenance. Nevertheless, continuous training is required because humanitarian organizations have decentralized structures and frequently changing users.	[96,99]

Table 5. *Cont.*

Alternative	Criterion	Score	Evidence Supporting the Assessment	Sources
A_4—Mobile Technologies	C_1—Contribution to Preparedness and Resilience	9	Mobile technologies support early warning, rapid communication, data collection, population monitoring, coordination, and decision-making across different phases of disasters, from preparedness and early warning to response and recovery.	[101–104]
	C_2—Logistics Efficiency	8	Mobile technologies support inventory management, data collection, cash transfers, vouchers, logistics coordination, geospatial mapping, and resource distribution. Their broad availability and rapid data transmission can improve the efficiency and timeliness of humanitarian logistics.	[101–104]
	C_3—Integration and Adaptability	10	Mobile technologies can connect humanitarian actors, beneficiaries, volunteers, and logistics facilities and can integrate GPS, GIS, mobile communication, and other information sources. Their flexibility allows for application across different disaster contexts and operational settings.	[102–104]
	C_4—Economic Viability	10	Mobile technologies are characterized by relatively low cost, wide availability, and ease of use. Their application can reduce the time and costs associated with aid distribution and coordination, while electronic cash transfers and vouchers can reduce the need to transport large quantities of goods.	[101–104]
	C_5—Information Reliability and Security	7	Mobile technologies enable rapid collection and transmission of up-to-date information, including inventory, geospatial, population, and operational data. However, privacy, data ownership, security, legal frameworks, and ethical responsibility represent important limitations.	[101–104]
	C_6—Social Acceptability	10	Mobile phones are relatively accessible and familiar technologies characterized by wide availability, ease of use, and flexibility. They can support direct communication with affected populations and facilitate access to assistance. Nevertheless, unequal mobile infrastructure and digital exclusion remain relevant limitations.	[101–104]

Since all criteria were defined as Max-type criteria, it was not necessary to transform Min-type criteria into Max-type criteria in the first step of the CILOS method. In accordance with the procedure presented in the Methodology (Section 3. Research Methodology), the maximum, i.e., optimal, value of each criterion was determined using Equation (1). The obtained values represent the best results achieved among all considered alternatives and provide the basis for constructing the subsequent matrix in the CILOS method.

Before constructing the square matrix A, it was necessary to normalize the initial data. In accordance with the procedure defined in the Methodology, the criterion values were expressed relative to the sum of the alternative values for the respective criterion, thereby

enabling the comparison of criteria with different absolute values. The results of this step are presented in Table 6.

Table 6. Normalized decision matrix.

Alternative/Criterion	C_1	C_2	C_3	C_4	C_5	C_6
A_1	0.280	0.290	0.240	0.230	0.270	0.240
A_2	0.250	0.210	0.210	0.190	0.200	0.170
A_3	0.220	0.260	0.300	0.190	0.300	0.240
A_4	0.250	0.240	0.240	0.380	0.230	0.340

Based on the normalized values from Table 6, the square criterion matrix A presented in Table 7 was constructed in accordance with Equation (2). In this matrix, each row represents the criterion whose optimal value is being considered, while the columns represent the criteria whose values are observed in relation to that optimum. The main diagonal contains the optimal values of the corresponding criteria, whereas the off-diagonal elements represent the values of the other criteria in the alternatives that achieve those optima.

Table 7. Square matrix.

Criterion	C_1	C_2	C_3	C_4	C_5	C_6
C_1	0.280	0.290	0.240	0.230	0.270	0.240
C_2	0.280	0.290	0.240	0.230	0.270	0.240
C_3	0.220	0.260	0.300	0.190	0.300	0.240
C_4	0.250	0.240	0.240	0.380	0.230	0.340
C_5	0.220	0.260	0.300	0.190	0.300	0.240
C_6	0.250	0.240	0.240	0.380	0.230	0.340

In the next step of the CILOS method, the relative loss of criterion importance is determined based on the square matrix. Equation (3) is used to calculate the relative loss matrix, where the value of each element indicates the relative loss of one criterion when another criterion reaches its optimal value. The calculation results are presented in Table 8.

Table 8. Matrix of the relative loss of criterion importance.

Criterion	C_1	C_2	C_3	C_4	C_5	C_6
C_1	0.000	0.000	0.200	0.400	0.110	0.300
C_2	0.000	0.000	0.200	0.400	0.110	0.300
C_3	0.200	0.100	0.000	0.500	0.000	0.300
C_4	0.100	0.200	0.200	0.000	0.220	0.000
C_5	0.200	0.100	0.000	0.500	0.000	0.300
C_6	0.100	0.200	0.200	0.000	0.220	0.000

Table 8 provides the basis for constructing the system of linear equations used to determine the criterion weights. Based on the relative losses of importance and in accordance with Equation (5), the matrix of the weight-determination system, F, was constructed, while the corresponding system of linear equations was defined by Equation (6). The resulting matrix is presented in Table 9.

By solving the system of linear equations defined by Equation (6), following the procedure presented in the Methodology, a vector of unnormalized criterion weights was obtained. Subsequently, Equation (7) was applied to normalize the obtained weights so that their sum equals one. The final objective criterion weights are presented in Table 10.

Table 9. Matrix of the system for determining criterion weights.

Criterion	C_1	C_2	C_3	C_4	C_5	C_6
C_1	−0.600	0.000	0.200	0.400	0.110	0.300
C_2	0.000	−0.600	0.200	0.400	0.110	0.300
C_3	0.200	0.100	−0.800	0.500	0.000	0.300
C_4	0.100	0.200	0.200	−1.800	0.220	0.000
C_5	0.200	0.100	0.000	0.500	−0.670	0.300
C_6	0.100	0.200	0.200	0.000	0.220	−1.200

Table 10. Final criterion weights.

Criterion	C_1	C_2	C_3	C_4	C_5	C_6
W_j	0.210	0.210	0.170	0.080	0.210	0.120

The obtained weights show that the highest values were assigned to C_1—contribution to preparedness and resilience, C_2—logistics efficiency, and C_5—information reliability and security, with each criterion having a weight of 0.210. These are followed by C_3—integration and adaptability, with a weight of 0.170, and C_6—social acceptability, with a weight of 0.120, while the lowest weight was assigned to C_4—economic viability, with a value of 0.080. The structure of the weights indicates that the CILOS results assign the greatest importance to criteria directly related to the operational capacity of HOs and their ability to respond promptly to changes in the crisis environment.

It is particularly significant that C_1, C_2, and C_5 have the highest and equal weights. This indicates that, within the proposed model, the overall value of a digital solution is primarily associated with its ability to improve the preparedness and resilience of HOs, directly support logistics activities, and provide reliable and secure information. Such a result is consistent with the "one step ahead of the crisis" approach, as a proactive approach simultaneously requires timely information, adequate resource preparedness, and the ability to efficiently perform logistics activities.

The high weight of C_1 confirms that preparedness and resilience represent one of the central dimensions of the value of digital solutions for HL. Based on literature-informed considerations relevant to HOs, technology is not most valuable merely because it enables faster response after a crisis event occurs, but because it can contribute to the early detection of changes, capacity preparedness, and adaptation of the logistics system. Therefore, the result of the CILOS method can be interpreted as supporting the fundamental idea of this study that digital transformation should enable a shift from predominantly reactive toward proactive HL management.

The equally high weight of C_2 indicates that a technological solution must have clear operational value. For HOs, it is particularly important that digital technology improve inventory management, distribution, resource allocation, and activity coordination, since these processes directly determine the effectiveness of humanitarian assistance. At the same time, the high weight of C_5 indicates that the quantity of available data is insufficient if the data are not reliable, timely, and protected, which is particularly important in humanitarian operations where sensitive information about aid recipients may be processed.

The somewhat lower weight of C_3 indicates that integration and adaptability are important but have lower relative importance than C_1, C_2, and C_5. Social acceptability, represented by C_6, also has a lower weight; however, its value of 0.120 confirms that the acceptance of technology by employees, volunteers, local communities, and aid recipients remains a relevant component of its overall value. The lowest weight assigned to C_4 does

not mean that economic viability is unimportant but rather that, within the specific decision matrix, it was identified as the criterion with the lowest objective relative importance.

5.2. Application of the COBRA Method and Ranking of Digital Solutions

After determining the objective weights of the criteria using the CILOS method, the second phase of the hybrid MCDM model involved the evaluation and ranking of the alternatives using the COBRA method. In this way, the CILOS and COBRA methods have clearly differentiated but interrelated functions: CILOS determines the relative importance of each criterion in the decision-making process, while COBRA uses the obtained weights to determine the overall suitability of the alternatives.

In the first step of the COBRA method, the initial decision matrix presented in Table 4 was used as the starting point. Since all criteria are of the Max type, normalization was performed according to Equation (10), i.e., by dividing the value of each alternative under a given criterion by the maximum value of that criterion. The result of this procedure is presented in Table 11.

Table 11. Normalized decision matrix.

Alternative/Criterion	C_1	C_2	C_3	C_4	C_5	C_6
A_1	1.000	1.000	0.800	0.600	0.889	0.700
A_2	0.900	0.700	0.700	0.500	0.667	0.500
A_3	0.800	0.900	1.000	0.500	1.000	0.700
A_4	0.900	0.800	0.800	1.000	0.778	1.000

In the next step of the COBRA method, the normalized values from Table 11 were weighted using the criterion weights obtained through the CILOS method. According to Equation (11), each normalized value was multiplied by the corresponding criterion weight, resulting in the weighted normalized decision matrix. The results of this step are presented in Table 12.

Table 12. Weighted normalized decision matrix.

Alternative/Criterion	C_1	C_2	C_3	C_4	C_5	C_6
A_1	0.210	0.210	0.136	0.048	0.187	0.084
A_2	0.189	0.147	0.119	0.040	0.140	0.060
A_3	0.168	0.189	0.170	0.040	0.210	0.084
A_4	0.189	0.168	0.136	0.080	0.163	0.120

Based on the weighted normalized matrix, three reference solutions were determined in the subsequent step: the positive ideal solution (PIS), the negative ideal solution (NIS), and the average solution (AS). In accordance with Equations (12) and (13), the PIS and NIS values were determined, while Equations (14)–(16) were used to determine the values associated with the average solution. The PIS represents a reference point combining the best-achieved values for all criteria, whereas the NIS represents the opposite reference point characterized by the least favorable values. The average solution (AS) provides an additional basis for comparing alternatives with the typical performance level within the observed set. By introducing multiple reference points, the COBRA method enables an alternative to be evaluated not merely in terms of its simple distance from an ideal solution but through a broader assessment of its position within the criteria space. The obtained results are presented in Table 13.

Table 13. Positive ideal, negative ideal, and average solutions.

	C_1	C_2	C_3	C_4	C_5	C_6
PIS	0.210	0.210	0.170	0.080	0.210	0.120
NIS	0.168	0.147	0.119	0.040	0.140	0.060
AS	0.189	0.179	0.140	0.052	0.175	0.087

In the next step of the COBRA method, the distances of the alternatives from the PIS, NIS, and AS were determined. According to Equation (17), the comprehensive distance represents a combination of Euclidean and Taxicab distances, thereby capturing both the geometric and cumulative differences between an alternative and the respective reference solution. To adjust these distances, correction coefficients were determined using Equation (18). Based on the correction coefficients, the comprehensive distances of each alternative from the positive ideal, negative ideal, and average solutions were calculated using Equations (19)–(28). The obtained results are presented in Table 14. These values provide the basis for calculating the final indicator, dC_i.

Table 14. Comprehensive distances from the PIS, NIS, and AS.

Alternative	d(*PIS*)	d(*NIS*)	d(*AS*)+	d(*AS*)−
A_1	0.063	0.094	0.040	0.007
A_2	0.131	0.021	0.000	0.060
A_3	0.071	0.099	0.047	0.024
A_4	0.074	0.083	0.043	0.016

The final comprehensive dC_i values were calculated using Equation (29). In accordance with the ranking rule defined in the COBRA method, the alternatives are ranked in ascending order of their dC_i values, meaning that the alternative with the lowest value represents the most favorable solution. The results of the final ranking are presented in Table 15.

Table 15. Comprehensive distance values and ranking of alternatives.

Alternative	dC_i	Rank
A_1	−0.016	1
A_2	0.043	4
A_3	−0.013	2
A_4	−0.009	3

The results presented in Table 15 show that the Internet of Things (A_1) is the highest-ranked digital solution, with a value of −0.016. ERP systems (A_3) rank second, followed by mobile technologies (A_4), while Big Data technologies (A_2) rank fourth. Although the final values are relatively close, the order of the alternatives remains clearly determined by the ranking rule of the COBRA method, according to which a lower dC_i value indicates a more favorable alternative.

5.3. Sensitivity Analysis

To assess the robustness of the obtained results, a sensitivity analysis was conducted from two complementary perspectives. First, the analysis examined (i) how changes in the relative importance of the evaluation criteria affect the final ranking of digital solutions, while keeping the initial ratings of the alternatives unchanged. Second, the sensitivity of the results to (ii) changes in the initial literature-informed ratings of the digital solutions

was examined while keeping the CILOS-derived criterion weights constant. Together, these analyses provide a broader assessment of the stability of the proposed CILOS-COBRA decision framework under variations in both criterion priorities and alternative performance assessments.

5.3.1. Sensitivity Analysis—Changes in the Relative Importance of the Criteria

To verify the stability of the obtained ranking, a sensitivity analysis was conducted. The aim of the analysis is to determine whether changes in the relative importance of the criteria could lead to changes in the final ranking of the alternatives and thereby indicate the robustness of the MCDM model. For the purposes of the analysis, eight representative scenarios with different distributions of criteria weights were defined, while the sum of the weights was maintained at 1,00 in each scenario. These eight scenarios were specifically formulated to reflect a spectrum of distinct operational and strategic priorities commonly faced by HOs in real-world environments. Rather than applying arbitrary weight variations, each scenario simulates a specific strategic focus—such as prioritizing immediate operational efficiency (Scenario 1), integrating multi-functional capabilities (Scenario 2), ensuring stakeholder trust and preparedness (Scenario 3), balancing crisis readiness with economic constraints (Scenario 5), or maximizing information security and resilience (Scenarios 6–8). Testing these targeted decision configurations ensures that the model's stability is evaluated across realistic organizational profiles and operational trade-offs. As shown in Table 16, the weights of individual criteria were varied relative to the baseline scenario. The scenarios represent different plausible priorities of HOs regarding preparedness, logistics efficiency, integration and adaptability, economic viability, information reliability and security, and social acceptability of digital solutions.

Table 16. Criterion weights defined for the sensitivity-analysis scenarios.

Scenario/Criterion	C_1	C_2	C_3	C_4	C_5	C_6
Sc. 1	0.180	0.280	0.150	0.070	0.220	0.100
Sc. 2	0.190	0.240	0.190	0.070	0.200	0.110
Sc. 3	0.230	0.190	0.170	0.070	0.210	0.130
Sc. 4	0.200	0.200	0.180	0.080	0.220	0.120
Sc. 5	0.220	0.220	0.150	0.090	0.200	0.120
Sc. 6	0.210	0.200	0.180	0.060	0.220	0.130
Sc. 7	0.220	0.220	0.160	0.050	0.260	0.090
Sc. 8	0.230	0.210	0.160	0.070	0.220	0.110

Relative to the baseline scenario, which represents the weights obtained using the CILOS method, eight scenarios were developed to simulate different priorities of HOs when evaluating digital solutions. In Scenario 1, greater priority was assigned to logistics efficiency, that is, the ability of a digital solution to improve the direct execution of logistics activities, inventory management, distribution, and resource allocation. In Scenario 2, greater priority was assigned to logistics efficiency, integration, and adaptability, thereby simulating the need of HOs for a solution that simultaneously improves operational processes, enables the integration of different functions, and facilitates adaptation to changing conditions. In Scenario 3, greater priority was assigned to preparedness and resilience and social acceptability, emphasizing the ability of HOs to prepare for crisis events in a timely manner while ensuring the acceptance of the digital solution by employees, volunteers, local communities, and aid recipients. In Scenario 4, greater priority was assigned to integration and adaptability, as well as information reliability and security, thereby examining the importance of connecting different organizational and logistics functions while ensuring reliable, timely, and secure information. In Scenario 5, greater priority was assigned

to preparedness and resilience and logistics efficiency, with somewhat greater emphasis on economic viability, thereby reflecting a literature-informed assessment of the relative importance of these dimensions for humanitarian operations, particularly in relation to preparedness for crisis events, the efficiency of logistics processes, and the rational use of available resources. In Scenario 6, greater priority was assigned to preparedness and resilience, integration and adaptability, and information reliability and security, emphasizing the need of HOs for a digital solution that enables better preparedness, process integration, and reliable information management, while placing less emphasis on the economic aspect. In Scenario 7, greater priority was assigned to preparedness and resilience, logistics efficiency, and information reliability and security, simulating a strongly operationally oriented approach of HOs in which preparedness for crisis events, efficient execution of logistics activities, and information security are considered the most important factors. Finally, in Scenario 8, greater priority was assigned to preparedness and resilience while simultaneously assigning somewhat lower importance to integration and adaptability and economic viability, thereby examining a situation in which HOs place particular emphasis on the ability to anticipate and prepare for crisis events.

For each defined scenario, the evaluation procedure was repeated using the COBRA method, while the initial ratings of the alternatives remained unchanged and only the criteria weights were varied (Table 17, Figure 2). The results show that the ranking is stable in seven of the eight analyzed scenarios, whereas Scenario 5 produces a change in the relative positions of ERP systems (A_3) and mobile technologies (A_4). The Internet of Things (A_1) retained first place in all eight scenarios, while Big Data processing technologies (A_2) ranked fourth in all scenarios. ERP systems (A_3) remained in second place in seven scenarios but ranked third in Scenario 5, whereas mobile technologies (A_4) remained in third place in seven scenarios but moved to second place in Scenario 5. Thus, the sensitivity analysis indicates that the overall ranking is generally stable, although the relative positions of A_3 and A_4 are sensitive to the criterion-weight configuration represented by Scenario 5.

Table 17. Comprehensive distance values and ranking of alternatives under different criterion-weight scenarios.

Scenario	Alternative	dC_i	Rank
Sc. 1	A_1	−0.023	1
	A_2	0.046	4
	A_3	−0.017	2
	A_4	−0.003	3
Sc. 2	A_1	−0.018	1
	A_2	0.044	4
	A_3	−0.016	2
	A_4	−0.005	3
Sc. 3	A_1	−0.015	1
	A_2	0.042	4
	A_3	−0.012	2
	A_4	−0.010	3
Sc. 4	A_1	−0.015	1
	A_2	0.043	4
	A_3	−0.015	2
	A_4	−0.009	3
Sc. 5	A_1	−0.017	1
	A_2	0.042	4
	A_3	−0.009	3
	A_4	−0.011	2

Table 17. *Cont.*

Scenario	Alternative	dC_i	Rank
Sc. 6	A_1	−0.016	1
	A_2	0.043	4
	A_3	−0.015	2
	A_4	−0.008	3
Sc. 7	A_1	−0.021	1
	A_2	0.043	4
	A_3	−0.020	2
	A_4	0.001	3
Sc. 8	A_1	−0.018	1
	A_2	0.041	4
	A_3	−0.013	2
	A_4	−0.006	3

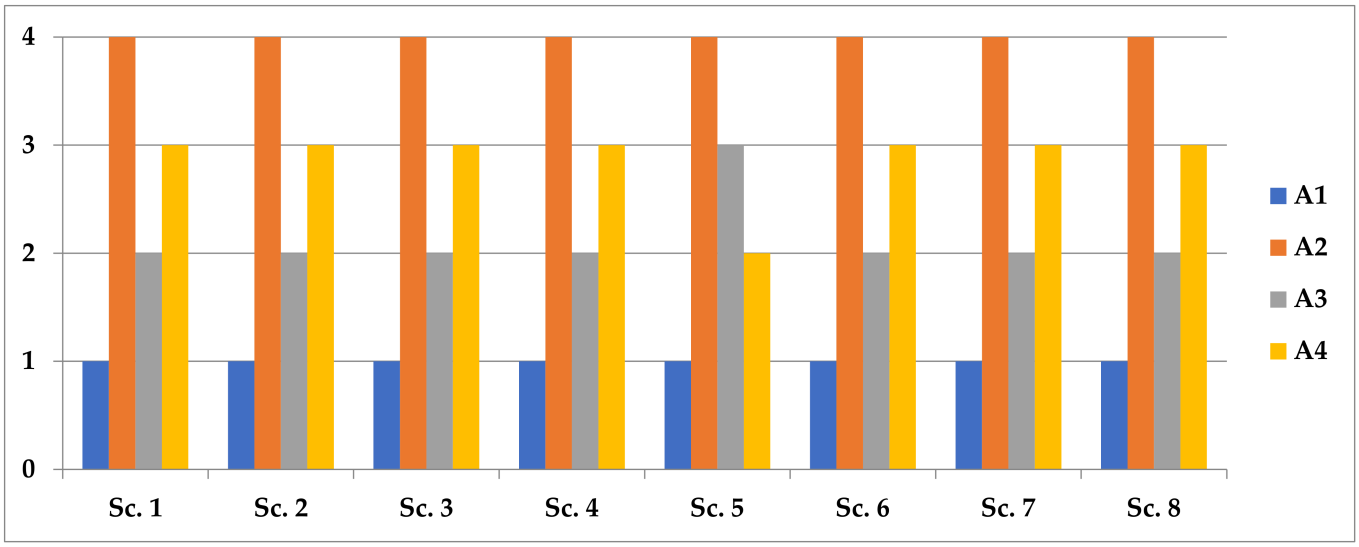


Figure 2. Ranking of alternatives under different criterion-weight scenarios.

5.3.2. Sensitivity Analysis—Changes in the Initial Ratings of the Digital Solutions

In addition to the sensitivity analysis based on variations in criterion weights, an additional sensitivity analysis was conducted to examine the robustness of the obtained ranking with respect to changes in the initial ratings of the digital solutions (Table 18). While the criterion weights obtained through the CILOS method were kept unchanged in all scenarios (C_1 = 0.210; C_2 = 0.210; C_3 = 0.170; C_4 = 0.080; C_5 = 0.210; and C_6 = 0.120), the initial ratings presented in Table 4 were systematically varied. This analysis was introduced to examine whether the relative ranking of the digital solutions remains stable when the literature-informed assessments assigned to individual technology–criterion pairs are modified within plausible ranges. In this way, the analysis complements the weight-based sensitivity analysis by testing the robustness of the results with respect to the input performance ratings themselves. The four rating-variation scenarios were specifically designed to test the robustness of the COBRA ranking algorithm against potential uncertainties, subjective variations, or contextual shifts in literature-derived assessments. By systematically introducing moderate to pronounced adjustments across operational, informational, and organizational criteria while keeping criterion weights constant, these scenarios evaluate whether the COBRA distance-based ranking mechanism maintains

stability when alternative performance profiles fluctuate under varying field conditions or technological maturity levels.

Table 18. Initial ratings of digital solutions under different sensitivity-analysis scenarios.

Scenario	Alternative	Criterion					
		C_1	C_2	C_3	C_4	C_5	C_6
Sc. 1	A_1	10	10	9	6	9	7
	A_2	9	6	7	5	6	5
	A_3	8	9	9	5	9	7
	A_4	9	8	8	9	7	10
		C_1	C_2	C_3	C_4	C_5	C_6
Sc. 2	A_1	9	10	9	6	8	8
	A_2	9	4	8	5	6	5
	A_3	8	7	10	7	9	6
	A_4	8	8	9	10	6	10
		C_1	C_2	C_3	C_4	C_5	C_6
Sc. 3	A_1	10	9	9	7	8	7
	A_2	6	7	7	6	7	5
	A_3	8	9	9	4	10	8
	A_4	9	5	8	9	7	9
		C_1	C_2	C_3	C_4	C_5	C_6
Sc. 4	A_1	9	9	8	7	9	7
	A_2	4	7	8	4	3	4
	A_3	3	10	10	6	9	5
	A_4	8	2	7	2	7	10

In Scenario 1, moderate changes were introduced across several criteria and alternatives, including an increase in the ratings of IoT for integration and adaptability and information reliability and security, a decrease in the rating of Big Data technologies for logistics efficiency, and a decrease in the rating of ERP systems for integration and adaptability. At the same time, the economic viability rating of mobile technologies was slightly reduced. This scenario, therefore, examines whether the ranking remains stable when the relative strengths of the alternatives are moderately adjusted across several dimensions. In Scenario 2, a broader set of changes was introduced to represent a situation in which the literature-informed assessment of several technologies differs more substantially from the baseline. The ratings of IoT were modified to reflect somewhat lower preparedness and resilience but higher integration and adaptability and social acceptability. Big Data technologies received a lower logistics-efficiency rating and a higher integration and adaptability rating, while ERP systems were adjusted across preparedness and resilience, logistics efficiency, economic viability, and social acceptability. Mobile technologies were also modified with respect to preparedness and resilience, integration and adaptability, information reliability and security, and social acceptability. This scenario, therefore, tests the robustness of the ranking under more extensive changes in the assessed characteristics of all four digital solutions. In Scenario 3, the initial ratings were varied with particular emphasis on logistics efficiency, economic viability, information reliability and security, and social acceptability. The IoT was assigned slightly lower logistics efficiency and higher integration and adaptability and economic viability ratings, while Big Data technologies received lower preparedness and resilience and higher information reliability and security ratings. ERP systems were modified across integration and adaptability, economic viability, information reliability and security, and social acceptability, whereas mobile technologies were adjusted across logistics efficiency, economic viability, integration and adaptability,

and social acceptability. This scenario examines whether the ranking remains robust when the relative performance profiles of the alternatives are altered across several operational, informational, and organizational dimensions. In Scenario 4, more pronounced changes in the initial ratings were introduced for all four alternatives in order to provide a stricter test of ranking stability. The ratings of IoT were moderately reduced for preparedness and resilience and logistics efficiency and increased for economic viability, while Big Data technologies were substantially adjusted across several criteria, including preparedness and resilience, integration and adaptability, economic viability, information reliability and security, and social acceptability. ERP systems were assigned a lower preparedness and resilience rating but higher logistics efficiency and integration and adaptability ratings, while mobile technologies were modified across logistics efficiency, integration and adaptability, economic viability, and information reliability and security. This scenario represents the most pronounced variation in the initial assessment and, therefore, provides an additional test of the robustness of the ranking under substantially different literature-informed input configurations.

For each defined scenario, the evaluation procedure was repeated using the COBRA method, while the criterion weights obtained through the CILOS method were kept unchanged and only the initial ratings of the alternatives were varied (Table 19, Figure 3). The results show that the ranking remained unchanged across all four analyzed scenarios. The Internet of Things (A_1) retained first place in all scenarios, ERP systems (A_3) remained in second place, mobile technologies (A_4) in third place, while Big Data processing technologies (A_2) ranked fourth in all scenarios. Although the comprehensive distance values changed across the scenarios, these changes did not affect the relative positions of the alternatives. Thus, the sensitivity analysis indicates that the obtained ranking is robust to variations in the initial literature-informed ratings of the digital solutions, while the unchanged criterion weights ensure that the observed differences are attributable exclusively to changes in the alternative ratings.

Table 19. Comprehensive distance values and ranking of alternatives under variations in initial ratings.

Scenario	Alternative	dC_i	Rank
Sc. 1	A_1	−0.033	1
	A_2	0.048	4
	A_3	−0.012	2
	A_4	−0.011	3
Sc. 2	A_1	−0.037	1
	A_2	0.054	4
	A_3	−0.010	2
	A_4	−0.009	3
Sc. 3	A_1	−0.034	1
	A_2	0.038	4
	A_3	−0.026	2
	A_4	0.012	3
Sc. 4	A_1	−0.076	1
	A_2	0.054	4
	A_3	−0.023	2
	A_4	0.019	3

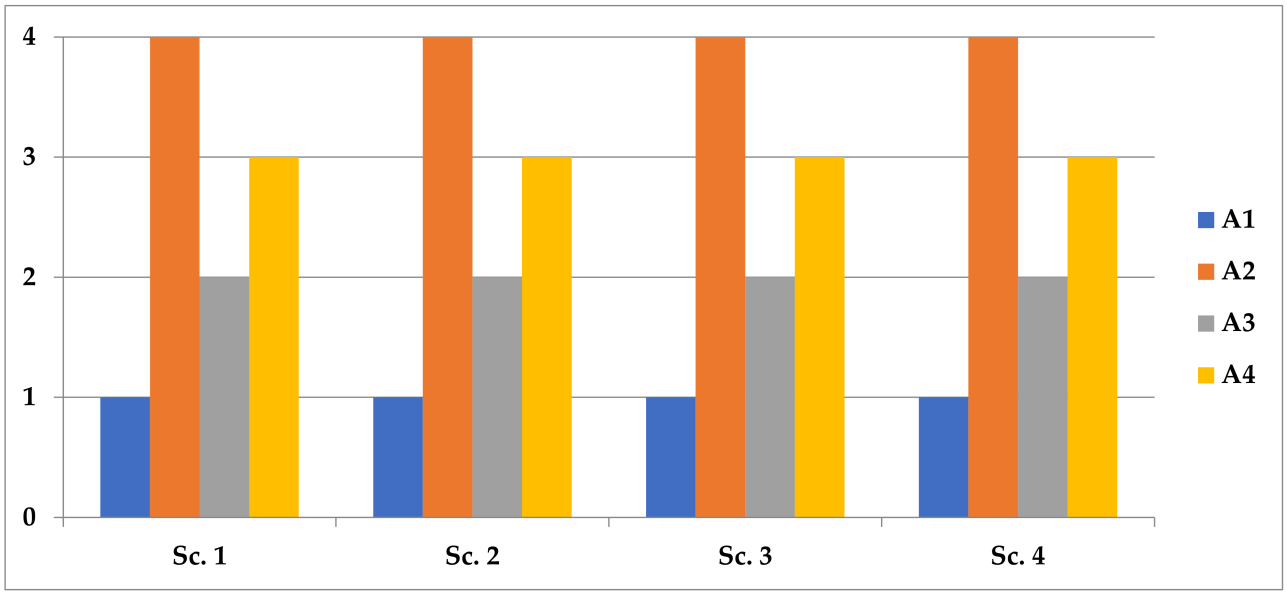


Figure 3. Ranking of alternatives with variations in the initial ratings.

6. Presentation of Results

The ***CILOS-COBRA model produced the ranking*** $A_1 > A_3 > A_4 > A_2$, with the Internet of Things (A_1) occupying the first position, followed by ERP systems (A_3), mobile technologies (A_4), and Big Data technologies (A_2). This ordering is a model-dependent result determined by the selected alternatives, criteria, criterion weights, and performance ratings. It, therefore, represents the relative position of the four alternatives within the decision framework developed in this study rather than a universal hierarchy of digital technologies in HL. The CILOS method assigned the highest relative importance to preparedness and resilience (C_1), logistics efficiency (C_2), and information reliability and security (C_5), whereas economic viability (C_4) received the lowest weight. These weights represent the priorities embedded in the present decision model and should not be interpreted as universally established priorities of HOs.

The COBRA procedure subsequently combined the CILOS-derived criterion weights with the performance ratings of the alternatives and generated the final ranking. Thus, the first position of A_1 is a mathematical outcome of combining the performance ratings assigned to A_1 with the criterion weights determined within the present decision framework. These ratings and weights should, therefore, not themselves be treated as independent evidence of IoT superiority. The mathematical result identifies which alternative performs most favorably within the defined decision space, whereas evidence from the literature provides the basis for assessing the technological capabilities, applications, and limitations associated with each alternative. The relatively close final values of the alternatives also indicate that the ranking represents a comparative ordering rather than a large absolute difference in technological suitability.

The obtained ranking can subsequently be interpreted from the perspective of CAS theory. HL is a complex socio-technical environment in which organizations, people, resources, information, and logistics processes interact and may adapt to changing conditions. From this perspective, digital technologies may influence the system through different but interconnected functions, including information acquisition, visibility, coordination, communication, analysis, and organizational response. The CAS perspective, therefore, informs both the formulation of the evaluation framework and the interpretation of the model results; it is not an additional component of the mathematical ranking procedure. In other words, CAS provides the theoretical lens through which the relevance of the selected

criteria and the potential contribution of the evaluated digital solutions to the adaptability and resilience of HSCs are understood, while the CILOS-COBRA model provides the quantitative mechanism for comparing the alternatives.

The first position of IoT (A_1) is a mathematical result of its aggregate performance across the selected criteria and the corresponding criterion weights. Independently of this result, IoT has functional characteristics that are relevant to HL, particularly its ability to enable continuous collection, processing, and exchange of information through interconnected devices and sensors [81]. In humanitarian operations, IoT applications can support inventory monitoring, fleet management, transportation processes, and the monitoring of the condition and location of resources [82]. These documented capabilities provide independent support for the functional relevance of IoT in HL, but they should be distinguished from the model-derived finding that A_1 received the highest overall ranking. From a CAS perspective, this functionality can be interpreted in terms of system visibility and information timeliness. The availability of timely information can support faster decision-making and enable HOs to adapt their activities to changes in the operational environment [81,83,84]. More timely information may reduce the delay between a change occurring in the operational environment and its detection by relevant decision-makers. This capability is consistent with the "one step ahead of the crisis" approach, because improved visibility can create conditions for earlier identification of deviations and earlier organizational responses. However, the present study does not empirically establish that IoT produces such improvements in humanitarian outcomes. Nor does the study directly measure how information flows generated by IoT interact with other actors, processes, or feedback mechanisms within an HSC. Rather, this interpretation connects documented technological capabilities with the theoretical requirements of an adaptive humanitarian system. The literature also indicates that the practical implementation of IoT in HL is subject to infrastructure, financial, interoperability, security, and organizational constraints. Stable electricity and communication networks, appropriate digital infrastructure, implementation and maintenance costs, interoperability between devices and information systems, and information security can affect the feasibility of IoT deployment in crisis environments [85,86]. Privacy, ethical and cultural acceptability, staff competencies, and user trust are additional considerations for successful adoption [87]. These factors are relevant when translating the model result into practice because a favorable position in the decision model does not eliminate the contextual conditions required for successful implementation.

ERP systems (A_3) ranked second and represent a different functional dimension of digitalization. Their principal role is the integration of organizational functions, information, and business processes within a common information system [96]. In HL, this functionality can support the coordination of activities and information across different organizational units and partners within humanitarian supply chains [96,97]. ERP systems can support information exchange between organizational units, resource management, cooperation with suppliers, fleet management, and humanitarian logistics performance. They may also contribute to more efficient aid delivery, improved transparency and accountability, and more systematic reporting and monitoring of resource flows [96,98,99]. These documented functions provide an independent basis for interpreting the role of ERP in HL, while the second position of A_3 remains a mathematical result of the present CILOS-COBRA model. From the CAS perspective, ERP can, therefore, be viewed as an integration and coordination mechanism. While IoT primarily contributes to the generation and availability of operational information, ERP can support the organization and processing of information across interconnected functions. The second position of A_3 in the present model reflects its aggregate performance under the selected criteria and weights. It should not be interpreted as independent evidence that ERP systems are generally less effective

than IoT or more effective than mobile or Big Data technologies. Rather, the result indicates how the alternatives compare when the dimensions included in this particular decision model are considered simultaneously. The different roles of IoT and ERP also indicate potential complementarity. The IoT can provide information about the physical state of resources and logistics activities, while ERP can incorporate and process relevant information within organizational workflows. This complementarity is a theoretical implication of their documented functional characteristics and is consistent with a CAS interpretation of HL as an interconnected system. It was not, however, directly evaluated as a technological configuration in the present MCDM model. At the same time, ERP implementation in HL is affected by infrastructure limitations, organizational decentralization, training requirements, customization needs, interoperability, and the availability of reliable communication and energy infrastructure [96,99,100]. These limitations further demonstrate why the ranking of A_3 should be interpreted as conditional on the decision framework rather than as an unconditional assessment of ERP suitability.

Mobile technologies (A_4) ranked third in the present evaluation. Their main functional advantage lies in providing relatively direct access to information and communication channels, which can be particularly relevant in humanitarian environments characterized by geographically dispersed personnel, changing operational conditions, and the need for rapid communication [101]. Mobile technologies can support data collection, inventory monitoring, coordination, early warning, cash transfers, and communication with affected populations [101,102]. The literature documents applications of mobile technologies in humanitarian logistics and disaster response, including inventory reporting, coordination among humanitarian actors, geospatial data collection, and the exchange of information during emergencies [101–103]. Their main advantages include relatively low cost, wide availability, ease of use, flexibility, and the ability to transmit information rapidly [104]. These characteristics provide independent evidence for their functional relevance, whereas their third position in the present study is determined by the combined performance of A_4 across the selected criteria and the corresponding criterion weights. The relatively favorable position of A_4 on economic viability and social acceptability contributes to its overall result under the selected weighting structure. At the same time, its performance on the other criteria limits its aggregate position relative to A_1 and A_3. This result illustrates the multi-criteria nature of the evaluation: a favorable position on individual criteria does not necessarily translate into the highest overall ranking when several dimensions are considered simultaneously. Consequently, the third position of A_4 should be understood as a result of its overall profile across the selected criteria rather than as a statement about the general value of mobile technologies in HL. From a CAS perspective, mobile technologies can be viewed as an interface connecting the technological and social components of humanitarian operations. Their contribution may arise from facilitating communication, information access, and interaction among participants [101,103,104]. Their role is, therefore, potentially complementary to technologies focused on sensing, integration, or data analysis. However, mobile technologies are also affected by infrastructure availability, the digital divide, privacy and data-protection requirements, legal and ethical considerations, and the capacity to integrate and manage information from different sources [101,104]. Consequently, their practical relevance depends on the operational and institutional context in which they are deployed.

Big Data technologies (A_2) ranked fourth. This result does not imply that their analytical capabilities are of limited value. Rather, within the present decision model, the performance ratings assigned to A_2 across the selected criteria, combined with the CILOS-derived weights, produced a less favorable overall position than those of the other three alternatives. Independent literature indicates that Big Data technologies can support the

processing and analysis of large and heterogeneous datasets relevant to disaster management and humanitarian operations [88–90]. Their application can support resource allocation, coordination, logistics cost reduction, resilience, and humanitarian logistics performance [91–94]. These documented applications demonstrate the analytical potential of Big Data technologies independently of their position in the present MCDM ranking. This distinction is important because analytical capability and overall suitability for a specific operational context are not equivalent. Big Data technologies may provide substantial value where large and sufficiently reliable datasets are available and where an organization has the capacity to process and incorporate analytical outputs into decision-making [90,95]. From a CAS perspective, their potential contribution lies in identifying patterns and relationships within complex information environments. However, analytical outputs can contribute to adaptive action only when appropriate data, organizational processes, and decision-making mechanisms are available. These considerations provide a theoretical interpretation of the position of A_2, whereas the ranking itself is determined by the mathematical structure of the MCDM model. The literature also identifies important limitations related to data quality, completeness, reliability, verification, privacy, security, ethical considerations, and unequal access to digital technologies [95]. These factors are particularly relevant in humanitarian environments and demonstrate that the analytical potential of Big Data does not automatically translate into operational value. Accordingly, the fourth position of A_2 should be interpreted within the specific criteria, weights, and performance ratings used in the present analysis.

The ***sensitivity analysis*** provides an additional assessment of the robustness of the obtained ranking from two complementary perspectives. First, the analysis examined the effect of changes in the relative importance of the criteria while keeping the initial ratings of the alternatives unchanged. The results show that the ranking was generally stable across the eight criterion-weight scenarios: the Internet of Things (A_1) remained the highest-ranked alternative and Big Data processing technologies (A_2) remained in fourth place in all scenarios. However, a change occurred in Scenario 5, in which mobile technologies (A_4) moved to second place, while ERP systems (A_3) moved to third place. Thus, the relative positions of A_3 and A_4 are sensitive to certain configurations of criterion weights, indicating that the ranking is robust overall but not completely invariant to changes in criterion priorities. Second, the sensitivity of the results to changes in the initial literature-informed ratings of the alternatives was examined while keeping the CILOS-derived criterion weights unchanged. In this analysis, the ranking $A_1 > A_3 > A_4 > A_2$ remained unchanged across all four scenarios, despite the introduction of multiple changes in the ratings of the alternatives. This indicates that the obtained ranking is robust with respect to the tested variations in the initial performance assessments and that the relative positions of the alternatives are not substantially affected by the examined changes in the input ratings. Taken together, the two sensitivity analyses indicate that the Internet of Things (A_1) demonstrates the most stable performance, retaining first place across all tested scenarios, while Big Data processing technologies (A_2) consistently occupy fourth place. The main sensitivity concerns the relative positions of ERP systems (A_3) and mobile technologies (A_4), which are affected by a particular configuration of criterion weights but remain stable when the initial alternative ratings are varied. Therefore, the findings support the robustness of the proposed CILOS-COBRA framework within the tested parameter space, while also demonstrating that the final ranking should not be interpreted as universally invariant to all possible changes in model inputs. Different performance assessments, criterion sets, weighting configurations, or decision-making contexts could potentially lead to different rankings. This limitation is particularly relevant because the priorities of HOs may vary

depending on the type and phase of a crisis, geographical context, available resources, and organizational capabilities.

The ***practical recommendations*** derived from the present analysis are conditional on the selected criteria, alternatives, criterion weights, and performance ratings. Therefore, the obtained ranking should be used to support technology–context fit rather than as a basis for recommending a universally preferred digital solution. Under the decision configuration examined in this study, IoT (A_1) obtained the highest overall ranking. Accordingly, HOs whose priorities and operating conditions are consistent with the criteria and performance ratings used in the model may consider IoT for further assessment, particularly when operational visibility, resource monitoring, and timely access to information are important objectives. This recommendation is specific to the present decision configuration and should be reassessed if the selected criteria, their relative weights, the alternatives considered, or their performance ratings change. Moreover, implementation should take into account infrastructure, interoperability, information security, privacy, staff competencies, and other contextual conditions identified in the literature [85–87].

ERP systems (A_3) may be considered in contexts where integration and coordination of organizational and logistics processes are particularly important. The literature indicates that ERP systems can support information exchange, resource management, reporting, transparency, and coordination across humanitarian supply chains [96,98,99]. However, their applicability should be assessed against infrastructure requirements, organizational structure, training needs, customization requirements, and interoperability with existing systems [96,99,100].

Mobile technologies (A_4) may be relevant where accessibility, communication, ease of use, rapid information exchange, and social acceptability receive greater emphasis. Their relatively broad accessibility and documented use in inventory monitoring, coordination, data collection, and communication can make them relevant in appropriate operational contexts [101–104]. Nevertheless, the feasibility of their application depends on network availability, digital inclusion, privacy protection, and the relevant institutional and legal conditions [101,104].

Big Data technologies (A_2) may be considered where sufficiently large and reliable datasets are available and where the organization has the analytical and managerial capacity to transform data into actionable information. Their use may be particularly relevant for contexts involving large-scale data integration, analysis, resource allocation, and decision support [90–94]. However, data quality, verification, privacy, security, ethical considerations, and the availability of appropriate technical and human capacities should be assessed before implementation [95].

Thus, the practical relevance of each alternative depends on the specific priorities and conditions of the HO rather than on its position in the ranking alone. Changes in the criteria, their relative weights, the set of alternatives, or the performance ratings should lead to a reassessment of the ranking and, consequently, of any technology-selection recommendation. The alternatives should also not necessarily be treated as mutually exclusive choices. Their different functional roles suggest that HOs may consider combining them within a broader digital architecture. For example, IoT can support the collection of operational data, ERP can integrate these data into organizational processes, mobile technologies can facilitate information access and communication, and Big Data technologies can support subsequent analysis. The literature provides evidence of these individual capabilities [81–104], but the combined configuration was not evaluated by the present MCDM model. The potential benefits of such an integrated digital architecture were not evaluated by the present MCDM model and should, therefore, be considered a direction for future research rather than a recommendation directly derived from the present results.

Regarding the expected operational impact, adopting this literature-informed evaluation model directly addresses key bottlenecks in HL. Quantifiable performance improvements are anticipated across four main dimensions: (i) *lead time reduction* through real-time asset visibility (IoT), (ii) *enhanced inventory accuracy and reduced loss* of sensitive relief items via centralized process control (ERP), (iii) *increased communication agility and field responsiveness* during initial response phases (mobile tech), and (iv) *improved demand forecasting precision* over multi-crisis horizons (Big Data). By enabling HOs to systematically evaluate and sequence technology adoption, the framework provides a measurable bridge between theoretical digitalization goals and actionable operational improvements.

7. Concluding Remarks

The efficient and effective functioning of HSCs depends on well-organized and coordinated logistics operations [108–111]. The complexity and unpredictability of crisis events further emphasize the need for timely planning, effective coordination, and the ability to adapt logistics activities to changing conditions. In this context, digitalization represents an important potential for enhancing the ability of HOs to access timely information, manage resources more efficiently, and improve the coordination of different actors within the HSC. The application of appropriate digital solutions can contribute to strengthening the preparedness and resilience of HL and creating a basis for shifting from reactive to proactive action, that is, adopting a "one step ahead of the crisis" approach. From the perspective of CAS theory, an HSC can be viewed as a socio-technical system composed of interconnected and interdependent actors, resources, processes, and information flows, whose behavior is shaped by interactions among these elements and their responses to changing conditions. Within such a system, digital technologies do not represent isolated technical tools but rather elements that can alter the way information is collected, exchanged, and used for decision-making, thereby potentially affecting the ability of the system to respond to disruptions in a timely manner.

For the purposes of the study, four digital solutions—IoT, Big Data technologies, ERP systems, and mobile technologies—and six criteria for their evaluation were analyzed: preparedness and resilience, logistics efficiency, integration and adaptability, economic viability, information reliability and security, and social acceptability. The CILOS method was applied to determine the objective weights of the criteria, while the COBRA method was used to evaluate and rank the alternatives, resulting in the development of a new hybrid CILOS-COBRA MCDM model. The robustness of the obtained results was subsequently examined through sensitivity analysis from two complementary perspectives: changes in the relative importance of the criteria and changes in the initial ratings of the digital solutions. Importantly, the study did not involve a survey of expert respondents or an empirical assessment of HOs before and after technology adoption. Instead, the initial ratings of the alternatives were derived from evidence and insights identified in the existing literature and incorporated into the proposed MCDM framework through a structured literature-informed assessment of their relevance to humanitarian logistics and humanitarian organizations. Consequently, the study should be understood as a literature-informed decision-support analysis rather than as an empirical measurement of organizational or logistics performance.

The research results showed that IoT represents the highest-ranked digital solution for improving HL based on insights from the existing literature and its relevance to HOs, followed by ERP systems, mobile technologies, and Big Data technologies. The CILOS method showed that the criteria of preparedness and resilience, logistics efficiency, and information reliability and security have the greatest importance, while economic viability received the lowest relative importance. Accordingly, the research question—"*Which digital*

solution is most suitable for HOs when evaluated according to its potential contribution to preparedness, efficiency, coordination, reliability, and resilience?"—can be answered by identifying IoT as the most suitable alternative among the four digital solutions considered in this study. Its first-place position in the baseline scenario reflects its comparatively strong performance across the highly weighted criteria, particularly preparedness and resilience, logistics efficiency, and information reliability and security. These results indicate the relative position of the four digital alternatives within the specific decision framework developed in this study; they do not indicate that humanitarian logistics performance changed by a particular amount following the adoption of any of these technologies. What changes as a result of this study is not a direct empirical measurement of post-implementation field performance, but rather the strategic decision-making structure for HOs. Specifically, the framework transforms fragmented, anecdotal technology evaluation into a standardized, quantifiable prioritization matrix. It shifts organizational decision-making from a reactive, ad hoc technology adoption approach to an objective, preparedness-driven prioritization framework aligned with the "one step ahead of the crisis" principle. The results indicate that the selection of a digital solution in HL should not be based solely on its technological capabilities but rather on its potential to simultaneously contribute to operational efficiency, preparedness for crisis events, information quality, and the resilience of the logistics system.

This finding can be interpreted through the CAS perspective, which emphasizes the interconnectedness of actors, resources, information, and processes within an adaptive humanitarian system. From this perspective, the documented capabilities of IoT are particularly relevant to system visibility and information timeliness. By enabling continuous collection and exchange of data on inventories, shipments, vehicles, and other resources, IoT may reduce information delays and create conditions for earlier detection of deviations and more timely organizational responses. Such capabilities are consistent with the "one step ahead of the crisis" approach because they may support the identification of emerging operational problems before they escalate into more severe disruptions. However, these mechanisms were not directly modeled or empirically tested in the present study. The position of IoT in the ranking is, therefore, a mathematical result of its performance across the selected criteria and the corresponding criterion weights, while the CAS perspective provides a theoretical interpretation of why some of its documented capabilities may be relevant to an adaptive HSC. ERP systems, which rank second, can be viewed from the CAS perspective as an integrative element that connects different organizational and logistics subsystems and contributes to information and process coordination, while mobile technologies enable faster communication and strengthen the connection between the technological and social components of the system. Although Big Data technologies ranked fourth, they represent significant potential for processing and interpreting large volumes of data; however, their effectiveness within the proposed model depends on the ability of HOs to ensure data quality, adequate infrastructure, and integration of analytical outputs into existing decision-making processes. Thus, the obtained ranking should be interpreted as a prioritization of alternatives within the proposed decision-support framework, rather than as evidence of a causal effect of any particular technology on humanitarian logistics outcomes.

The findings provide support for all four research hypotheses formulated in the study. H_1 is supported by the successful use of literature-informed insights to identify and structure relevant characteristics of digital solutions for HL from the perspective of their relevance to HOs, demonstrating that the existing literature can provide a systematic basis for supporting HOs in the evaluation of digital solutions in the absence of primary empirical data from HOs. H_2 is supported through the translation of these literature-derived insights into six HO-relevant evaluation criteria covering preparedness and resilience,

logistics efficiency, integration and adaptability, economic viability, information reliability and security, and social acceptability. H_3 is supported by the application of the proposed CILOS-COBRA MCDM approach, which enabled the four selected digital solutions to be differentiated and comparatively ranked within a decision framework developed around the operational needs and priorities relevant to HOs. This finding is also consistent with the CAS perspective adopted in the study, as the framework translates characteristics relevant to an adaptive HSC—such as coordination, information visibility, responsiveness, adaptability, and resilience—into HO-relevant evaluation criteria that can be comparatively assessed through the MCDM model. In this sense, the CILOS-COBRA approach provides an analytical mechanism for comparing digital solutions according to their potential relevance to different dimensions of an adaptive HL system and the needs of HOs, while CAS provides the theoretical basis for interpreting why these dimensions are relevant to the functioning and adaptation of HSCs. H_4 is also supported, as the obtained results demonstrate that the relative position of the alternatives is determined through the simultaneous consideration of multiple operational, informational, organizational, economic, and social dimensions that are relevant to HOs, rather than through a single technological characteristic. These findings should, however, be interpreted as support for the hypotheses within the defined literature-informed decision framework and not as empirical proof of universal technological suitability for HOs, dynamic CAS behavior, or causal effects on HL performance.

The main strength of the study lies in the integration of the CILOS and COBRA methods into a single hybrid MCDM model. An additional strength is that digital solutions are not considered solely from a technological perspective but in terms of their relevance to HOs and the specific needs of humanitarian operations identified in the existing literature. By incorporating criteria such as preparedness and resilience, information reliability and security, and social acceptability, the model enables a broader assessment of the overall value of digital solutions. The study also has certain limitations. First, the analysis is based on four selected digital technologies and six criteria, meaning that not all technologies and dimensions that may be relevant to HL are covered. Second, the initial ratings of the alternatives represent assessments of their suitability from the perspective of HOs based on a review of the literature. Accordingly, no individual respondent or expert profile can be reported, because the study did not collect primary data through expert questionnaires or interviews. Third, the research was conducted using a relatively limited set of alternatives; therefore, the results should be interpreted within the framework of the proposed model and should not be generalized without further validation. In addition, although the CAS perspective enables a broader theoretical interpretation of the relationships between digital technologies, actors, and processes within HSC, the applied MCDM model does not explicitly model these relationships as dynamic and adaptive interactions over time, nor does it directly capture feedback loops or emergent system behavior. Therefore, the obtained results should be understood as an evaluation of alternatives within a defined set of criteria and conditions, rather than as a complete simulation of the behavior of a complex HL system.

Future research could focus on examining a broader range of digital solutions, including artificial intelligence, blockchain, digital twins, drones, and robotic solutions, while incorporating criteria, such as sustainability, interoperability, privacy, scalability, and cybersecurity. Particular value could be gained by involving a larger number of experts and representatives of different HOs, as well as by combining the CILOS-COBRA model with other MCDM methods and fuzzy approaches to verify the stability of the results and address uncertainty. Furthermore, the development of a dynamic model with time-varying criteria weights could provide a basis for extending the "one step ahead of the crisis"

approach by examining how changing conditions, interactions, and feedback mechanisms influence the evaluation of digital solutions over time. In this context, CAS theory may provide an important framework for developing such dynamic approaches, particularly by enabling the study of dynamic interactions, feedback loops, and adaptive behavior among different actors and digital technologies within HSCs. Integrating these perspectives could contribute to the development of more adaptive digitalized HSCs capable of identifying changes in a timely manner, adapting their behavior, and supporting action "one step ahead of the crisis". Future empirical studies involving experts and representatives of HOs could subsequently be used to validate, refine, or challenge the priorities identified by the present literature-informed model.

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References

1. Tadić, S.; Veljović, M.; Krstić, M.; Petrović, J. Locating a humanitarian logistics center using the fuzzy system. In Proceedings of the 51st Symposium on Operational Research (SYM-OP-IS 2024), Tara, Serbia, 16–19 September 2024; pp. 251–256. [CrossRef]
2. Gazi, K.H.; Biswas, A.; Basuri, T.; Ghosh, A.; Mondal, S.P. Finding humanitarian supply chain management challenges using uncertain MCDM methodology. *Spectr. Mech. Eng. Oper. Res.* **2025**, *2*, 248–279. [CrossRef]
3. Krstić, M.; Tadić, S.; Spajić, A. Application of a hybrid MCDM model for locating a humanitarian logistics center. *J. Oper. Strateg. Anal.* **2024**, *2*, 160–176. [CrossRef]
4. Overstreet, R.E.; Hall, D.; Hanna, J.B.; Rainer, R.K., Jr. Research in humanitarian logistics. *J. Humanit. Logist. Supply Chain Manag.* **2011**, *1*, 114–131. [CrossRef]
5. Tadić, S.; Veljović, M.; Krstić, M.; Zečević, S. Humanitarian logistics: A framework for structuring and research. *Transp. Res. Procedia* **2025**, *83*, 72–79. [CrossRef]
6. Charles, A.; Lauras, M.; Van Wassenhove, L.N.; Dupont, L. Designing an efficient humanitarian supply network. *J. Oper. Manag.* **2016**, *47–48*, 58–70. [CrossRef]
7. Jayadi, E.L. The digitalization of the humanitarian supply chain performance management literature and practice. *J. Humanit. Logist. Supply Chain Manag.* **2025**, *15*, 175–193. [CrossRef]
8. Khan, M.; Yong, L.H.; Han, B.J. Emerging techniques for enhancing the performance of humanitarian logistics. *Int. J. Supply Chain Manag.* **2019**, *8*, 450–459.
9. Nurmala, N.; de Leeuw, S.; Dullaert, W. Humanitarian-business partnerships in managing humanitarian logistics. *Supply Chain Manag. Int. J.* **2017**, *22*, 82–94. [CrossRef]
10. Negi, S. Humanitarian logistics challenges in disaster relief operations: A humanitarian organisations' perspective. *J. Transp. Supply Chain Manag.* **2022**, *16*, a691. [CrossRef]
11. Omri, A. Technological innovation and sustainable development: Does the stage of development matter? *Environ. Impact Assess. Rev.* **2020**, *83*, 106398. [CrossRef]
12. Ramirez-Villamil, A.; Jaegler, A. Transforming humanitarian supply chains through green practices: A systematic review. *Logistics* **2025**, *9*, 115. [CrossRef]
13. Lindström, J.; Smith, S.; Zeisl, Y.; Deros, E.; Birnbaum, C.; Gambade, J.; Gozio, M.; Frasca, L.; Paciarotti, C.; Ulicna, D.; et al. *Evaluation of Humanitarian Logistics in the European Commission's Civil Protection and Humanitarian Aid Operations, 2018–2022, and of the Mobility Package Within the Emergency Support Instrument Re-Activation, 2020–2022*; Publications Office of the European Union: Luxembourg, 2023.
14. Breen, L.; Schiffling, S.; Xie, Y. Healthcare and urban logistics. In *The Routledge Handbook of Urban Logistics*; Monios, J., Budd, L., Ison, S., Eds.; Routledge: London, UK, 2023; pp. 159–174. [CrossRef]

15. Khan, M.; Khan, M.; Ali, A.; Khan, M.I.; Ullah, I.; Iqbal, M. Digitalization for fast, fair, and safe humanitarian logistics. *Logistics* **2022**, *6*, 31. [CrossRef]
16. Beaulieu, M.; Roy, J.; Landry, S. Logistics outsourcing in the healthcare sector: Lessons from a Canadian experience. *Can. J. Adm. Sci.* **2018**, *35*, 635–648. [CrossRef]
17. Nikolopoulos, K.; Punia, S.; Schäfers, A.; Tsinopoulos, C.; Vasilakis, C. Forecasting and planning during a pandemic: COVID-19 growth rates, supply chain disruptions, and governmental decisions. *Eur. J. Oper. Res.* **2021**, *290*, 99–115. [CrossRef] [PubMed]
18. Zhong, R.Y.; Newman, S.T.; Huang, G.Q.; Lan, S. Big data for supply chain management in the service and manufacturing sectors: Challenges, opportunities, and future perspectives. *Comput. Ind. Eng.* **2016**, *101*, 572–591. [CrossRef]
19. Azzahra, Z.F.; Suakanto, S. A barcode-based medical asset management system with integrated monitoring in hospitals. *JUSIFO* **2025**, *11*, 21–30. [CrossRef]
20. Baldini, G.; Oliveri, F.; Seuschek, H.; Hess, E.; Braun, M. Secure RFID for humanitarian logistics. In *Designing and Deploying RFID Applications*; Turcu, C., Ed.; InTech: Vienna, Austria, 2011; pp. 41–53. [CrossRef] [PubMed]
21. Grainger, A.; Rundle, J.M.; Ahsen, S.R. Customs and humanitarian logistics. *Glob. Trade Cust. J.* **2019**, *14*, 154–168. [CrossRef]
22. Kubáňová, J.; Kubasáková, I.; Čulík, K.; Štítik, L. Implementation of barcode technology to logistics processes of a company. *Sustainability* **2022**, *14*, 790. [CrossRef]
23. Masudin, I.; Lau, E.; Safitri, N.T.; Restuputri, D.P.; Handayani, D.I. The impact of the traceability of information systems on humanitarian logistics performance: Case study of Indonesian relief logistics services. *Cogent Bus. Manag.* **2021**, *8*, 1906052. [CrossRef]
24. Mukhopadhyay, J.; Roy, S. Managing disaster supply chains with RFID for humanitarian logistics. In *Managing Humanitarian Logistics*; Sahay, B.S., Gupta, S., Menon, V.C., Eds.; Springer: Berlin/Heidelberg, Germany, 2016; pp. 115–127. [CrossRef]
25. Palasiuk, B.M.; Kichula, M.Y.; Yarema, M.V. Problems and prospects of implementing logistics management in medicine. *Bull. Soc. Hyg. Health Care Organ. Ukr.* **2024**, *4*, 66–70. [CrossRef]
26. Vhikai, R.; Mugoni, E.; Mataka, P.; Saruchera, F. Digitalisation and efficient humanitarian logistical operations in Zimbabwe. *Cogent Soc. Sci.* **2024**, *10*, 2321725. [CrossRef]
27. Wagner, S.M.; Ramkumar, M.; Kumar, G.; Schoenherr, T. Supporting disaster relief operations through RFID: Enabling visibility and coordination. *Int. J. Logist. Manag.* **2024**, *35*, 1681–1712. [CrossRef]
28. Wudhikarn, R.; Charoenkwan, P.; Malang, K. Deep learning in barcode recognition: A systematic literature review. *IEEE Access* **2022**, *10*, 8049–8072. [CrossRef]
29. Yang, H.; Yang, L.; Yang, S.-H. Hybrid Zigbee RFID sensor network for humanitarian logistics centre management. *J. Netw. Comput. Appl.* **2011**, *34*, 938–948. [CrossRef]
30. Baharmand, H.; Comes, T. Leveraging partnerships with logistics service providers in humanitarian supply chains by blockchain-based smart contracts. *IFAC-PapersOnLine* **2019**, *52*, 12–17. [CrossRef]
31. Dubey, R.; Gunasekaran, A.; Foropon, C.R.H. Improving information alignment and coordination in humanitarian supply chain through blockchain technology. *J. Enterp. Inf. Manag.* **2024**, *37*, 805–827. [CrossRef]
32. Dubey, R.; Gunasekaran, A.; Bryde, D.J.; Dwivedi, Y.K.; Papadopoulos, T. Blockchain technology for enhancing swift-trust, collaboration and resilience within a humanitarian supply chain setting. *Int. J. Prod. Res.* **2020**, *58*, 3381–3398. [CrossRef]
33. Patil, A.; Shardeo, V.; Dwivedi, A.; Madaan, J. Humanitarian logistics performance improvement model using blockchain approach. In *Proceedings of the 11th Annual International Conference on Industrial Engineering and Operations Management*; IEOM Society International: Southfield, MI, USA, 2021; pp. 1002–1013. [CrossRef]
34. Çetinkaya, C.; Özceylan, E.; Keser, İ. A GIS-based AHP approach for emergency warehouse site selection: A case close to Turkey-Syria border. *J. Eng. Res.* **2022**, *10*, 250–273. [CrossRef]
35. Jitt-Aer, K.; Wall, G.; Jones, D.; Teeuw, R. Use of GIS and dasymetric mapping for estimating tsunami-affected population to facilitate humanitarian relief logistics: A case study from Phuket, Thailand. *Nat. Hazards* **2022**, *113*, 185–211. [CrossRef]
36. Kaiser, R.; Spiegel, P.B.; Henderson, A.K.; Gerber, M.L. The application of geographic information systems and global positioning systems in humanitarian emergencies: Lessons learned, programme implications and future research. *Disasters* **2003**, *27*, 127–140. [CrossRef] [PubMed]
37. Manfré, L.A.; Hirata, E.; Silva, J.B.; Shinohara, E.J.; Giannotti, M.A.; Larocca, A.P.C.; Quintanilha, J.A. An analysis of geospatial technologies for risk and natural disaster management. *ISPRS Int. J. Geo-Inf.* **2012**, *1*, 166–185. [CrossRef]
38. Lubenets, D.; Koriashkina, L. Using GIS technologies for solving optimization problems in humanitarian logistics. In Proceedings of the I (VII) International Scientific-Practical Conference of Higher Education Students and Young Scientists "Information Technologies: Theory and Practice", Dnipro, Ukraine, 20–22 March 2024; pp. 37–40.
39. Rodríguez-Espíndola, O.; Chowdhury, S.; Beltagui, A.; Albores, P. The potential of emergent disruptive technologies for humanitarian supply chains: The integration of blockchain, artificial intelligence and 3D printing. *Int. J. Prod. Res.* **2020**, *58*, 4610–4630. [CrossRef]

40. Ackerman, E.; Koziol, M. The blood is here: Zipline's medical delivery drones are changing the game in Rwanda. *IEEE Spectr.* **2019**, *56*, 24–31. [CrossRef]
41. Damoah, I.S.; Ayakwah, A.; Tingbani, I. Artificial intelligence (AI)-enhanced medical drones in the healthcare supply chain (HSC) for sustainability development: A case study. *J. Clean. Prod.* **2021**, *328*, 129598. [CrossRef]
42. Grote, M.; Oakey, A.; Pilko, A.; Smith, A.; Cherrett, T. Drones: The scope for integration into multi-modal urban logistics services. In *The Routledge Handbook of Urban Logistics*; Monios, J., Budd, L., Ison, S., Eds.; Routledge: London, UK, 2023; pp. 72–90. [CrossRef]
43. Jeong, H.Y.; Yu, D.J.; Min, B.-C.; Lee, S. The humanitarian flying warehouse. *Transp. Res. E Logist. Transp. Rev.* **2020**, *136*, 101901. [CrossRef]
44. Choi, T.-M.; Wallace, S.W.; Wang, Y. Big data analytics in operations management. *Prod. Oper. Manag.* **2018**, *27*, 1868–1883. [CrossRef]
45. Govindan, K.; Cheng, T.C.E.; Mishra, N.; Shukla, N. Big data analytics and application for logistics and supply chain management. *Transp. Res. E Logist. Transp. Rev.* **2018**, *114*, 343–349. [CrossRef]
46. Corsini, L.; Aranda-Jan, C.B.; Moultrie, J. The impact of 3D printing on the humanitarian supply chain. *Prod. Plan. Control* **2020**, *33*, 692–704. [CrossRef]
47. Koç, M.; Khan, S.A.; Ilcan, H.; Sahmaran, M. Conceptual design of autonomous rapid printing system for emergency and humanitarian needs. *Mater. Today Proc.* **2022**, *70*, 1–5. [CrossRef]
48. Tatham, P.; Loy, J.; Peretti, U. 3D printing (3DP): A humanitarian logistic game changer? In Proceedings of the 12th ANZAM Operations, Supply Chain and Services Management Symposium, Auckland, New Zealand, 2–4 July 2014. Available online: http://hdl.handle.net/10072/62689 (accessed on 12 October 2026).
49. El Azzaoui, A.; Chen, H.; Kim, S.H.; Pan, Y.; Park, J.H. Blockchain-based distributed information hiding framework for data privacy preserving in medical supply chain systems. *Sensors* **2022**, *22*, 1371. [CrossRef] [PubMed]
50. Iqbal, T.; Ahmad, S. Transparency in humanitarian logistics and supply chain: The moderating role of digitalisation. *J. Humanit. Logist. Supply Chain Manag.* **2022**, *12*, 425–448. [CrossRef]
51. Kovacs, G.; Moshtari, M. A roadmap for higher research quality in humanitarian operations: A methodological perspective. *Eur. J. Oper. Res.* **2019**, *276*, 395–408. [CrossRef]
52. Al-Khulaidi, A.A.G.; Nasser, A.A.; Al-Ashwal, M.H.Y.; Al-Ashwal, M.M.Y.; Altayeb, A.M. Investigating information security risk management in Yemeni banks: An CILOS-TOPSIS approach. *Multidiscip. Sci. J.* **2024**, *6*, 2024175. [CrossRef]
53. Macit, N.Ş. Evaluation of the macroeconomic performance of selected European and Central Asian countries by CILOS based AROMAN method. *Eurasian Bus. Econ. J.* **2023**, *34*, 31–48. [CrossRef]
54. Alıcı, S.; Ertuğrul, İ. Evaluation of the financial performances of BIST IT sector by CILOS based CoCoSo method. *Pamukkale Univ. J. Bus. Res.* **2023**, *10*, 745–759. [CrossRef]
55. Baysal, Y.V. Comparison of financial performance of logistics companies during and before COVID-19 period via CILOS-ARAS method. *Trends Bus. Econ.* **2026**, *40*, 503–520. [CrossRef]
56. Çilek, A. Evaluation of ratio analysis results with entropy, CILOS and IDOCRIW techniques: An application in Borsa Istanbul Liquid Bank Index. *Int. J. Account. Finance Res.* **2026**, *8*, 30–54.
57. Yılmaz, N. Financial performance of the banks in Turkey soon after the World War II with integrated CILOS-DNMA model. In *Academic Studies in Social, Human and Administrative Sciences*; Iksad Publishing House: Ankara, Türkiye, 2023; pp. 169–193.
58. Das, A. Water pollution and water quality assessment and application of criterion impact loss (CILOS), geographical information system (GIS), artificial neural network (ANN) and decision-learning technique in river water quality management: An experiment on the Mahanadi catchment, Odisha, India. *Desalin. Water Treat.* **2025**, *321*, 100969. [CrossRef]
59. Rajbonshi, M.P.; Gupta, D.; Mitra, S. Seasonal comparison of the impacts of climate-smart agrotechnologies on greenhouse gas mitigation in flooded rice fields: Application of multi-criteria decision making (MCDM) technique. *Agric. Syst.* **2026**, *231*, 104550. [CrossRef]
60. Zavadskas, E.K.; Cavallaro, F.; Podvezko, V.; Ubarte, I.; Kaklauskas, A. MCDM assessment of a healthy and safe built environment according to sustainable development principles: A practical neighborhood approach in Vilnius. *Sustainability* **2017**, *9*, 702. [CrossRef]
61. Čereška, A.; Podvezko, V.; Zavadskas, E.K. Operating characteristics analysis of rotor systems using MCDM methods. *Stud. Inform. Control* **2016**, *25*, 59–68. [CrossRef]
62. Perišić, D.; Jovanović, J. Ranking of the software packages for project management using integrated MCDM methods. In Proceedings of the STED 2025: International Scientific Conference, Trebinje, Bosnia and Herzegovina, 12–15 June 2025; pp. 61–69. [CrossRef]
63. Maravić, A.; Pajić, V.; Andrejić, M. Evaluation of digital technologies in food logistics: MCDM approach from the perspective of logistics providers. *Logistics* **2026**, *10*, 6. [CrossRef]

64. Dumlu, H. CILOS ve WASPAS bütünleşik yaklaşımı ile bir lojistik firması için karayolu taşıma aracı seçimi. *Ömer Halisdemir Üniversitesi İktisadi İdari Bilim. Fakültesi Derg.* **2025**, *18*, 600–617. [CrossRef]
65. Asmiatun, S.; Pinem, A.P.R.; Hidayati, N.; Hanif, M.B. 3D visualization of post-disaster priorities using CILOS–MARCOS for decision support and mitigation. *J. Innov. Inf. Technol. Appl.* **2026**, *8*, 10–20. [CrossRef]
66. Popović, G.; Pucar, Đ.; Smarandache, F. MEREC-COBRA approach in e-commerce development strategy selection. *J. Process Manag. New Technol.* **2022**, *10*, 66–74. [CrossRef]
67. Razak, S.A.; Rodzi, Z.M.; Al-Sharqi, F.; Ramli, N. Revolutionizing decision-making in e-commerce and IT procurement: An IVPNS-COBRA linguistic variable framework for enhanced multi-criteria analysis. *Int. J. Econ. Sci.* **2025**, *14*, 1–31. [CrossRef]
68. Katrancı, A.; Kundakcı, N.; Pamučar, D. Financial performance evaluation of firms in BIST 100 index with ITARA and COBRA methods. *Financ. Innov.* **2025**, *11*, 34. [CrossRef]
69. Oğuz, A.; Satır, H. Analyzing profitability performance with the integrated MEREC-COBRA method: The case of BIST retail companies. *Bus. Econ. Res. J.* **2024**, *15*, 33–50. [CrossRef]
70. Wang, C.-N.; Truong, T.-T. Assessing financial performance disparities in the Vietnam logistics sector amidst COVID-19: A hybrid MCDM evaluation approach using MEREC-COBRA. *Humanit. Soc. Sci. Commun.* **2026**, *13*, 1601. [CrossRef]
71. Zorlu, K.; Tuncer, M.; Yılmaz, A. Assessment of resources for geotourism development: Integrated SWARA-COBRA approach under spherical fuzzy environments. *Geoheritage* **2024**, *16*, 89. [CrossRef]
72. Ulutaş, A.; Krstić, M.; Topal, A.; Agnusdei, L.; Tadić, S.; Miglietta, P.P. A novel hybrid gray MCDM model for resilient supplier selection problem. *Mathematics* **2024**, *12*, 1444. [CrossRef]
73. Krstić, M.; Tadić, S.; Agnusdei, L. Evaluating governance models in intermodal terminal operations: A hybrid grey MCDM approach. *J. Intell. Manag. Decis.* **2023**, *2*, 179–191. [CrossRef]
74. Tadić, S.; Krstić, M.; Radovanović, L. Assessing strategies to overcome barriers for drone usage in last-mile logistics: A novel hybrid fuzzy MCDM model. *Mathematics* **2024**, *12*, 367. [CrossRef]
75. Krstić, M.; Agnusdei, G.P.; Miglietta, P.P.; Tadić, S. Evaluation of the smart reverse logistics development scenarios using a novel MCDM model. *Clean. Environ. Syst.* **2022**, *7*, 100099. [CrossRef]
76. Tadić, S.; Krstić, M.; Dabić-Miletić, S.; Božić, M. Smart material handling solutions for city logistics systems. *Sustainability* **2023**, *15*, 6693. [CrossRef]
77. Tadić, S.; Krstić, M.; Savić, D.; Vasov, L. Assessing the applicability of Industry 4.0 technologies in optimizing air cargo terminal operations. *J. Organ. Technol. Entrep.* **2024**, *2*, 97–112. [CrossRef]
78. Zavadskas, E.K.; Podvezko, V. Integrated determination of objective criteria weights in MCDM. *Int. J. Inf. Technol. Decis. Mak.* **2016**, *15*, 267–283. [CrossRef]
79. Chatterjee, S.; Chakraborty, S. A study on the effects of objective weighting methods on TOPSIS-based parametric optimization of non-traditional machining processes. *Decis. Anal. J.* **2024**, *11*, 100451. [CrossRef]
80. Krstić, M.; Agnusdei, G.P.; Miglietta, P.P.; Tadić, S.; Roso, V. Applicability of Industry 4.0 technologies in the reverse logistics: A circular economy approach based on COmprehensive Distance Based RAnking (COBRA) method. *Sustainability* **2022**, *14*, 5632. [CrossRef]
81. Aretoulaki, E. An Innovative Supply Chain & Logistics Model for Tackling Humanitarian Crises with the Support of Internet of Things (IoT) Technologies and Unmanned Aerial Vehicles (Drones). Doctoral Dissertation, National Technical University of Athens, Athens, Greece, 2024. [CrossRef]
82. Rejeb, A.; Rejeb, K.; Zrelli, I. Analyzing barriers to Internet of Things (IoT) adoption in humanitarian logistics: An ISM-DEMATEL approach. *Logistics* **2024**, *8*, 38. [CrossRef]
83. Płaczek, E.; Świtalska, A. New technologies in humanitarian logistics. *J. Public Gov.* **2023**, *65*, 48–58. [CrossRef]
84. Ülkü, M.A.; Bookbinder, J.H.; Yun, N.Y. Leveraging Industry 4.0 technologies for sustainable humanitarian supply chains: Evidence from the extant literature. *Sustainability* **2024**, *16*, 1321. [CrossRef]
85. Khan, M.; Imtiaz, S.; Parvaiz, G.S.; Hussain, A.; Bae, J. Integration of Internet-of-Things with blockchain technology to enhance humanitarian logistics performance. *IEEE Access* **2021**, *9*, 25422–25436. [CrossRef]
86. Zrelli, I.; Rejeb, A. A bibliometric analysis of IoT applications in logistics and supply chain management. *Heliyon* **2024**, *10*, e36578. [CrossRef] [PubMed]
87. Parmadi, B.D.; Ramli, K. Transforming humanitarian response with IoT in conflict zones: Field insights, ethical frameworks, and deployment challenges. *Int. J. Electr. Comput. Biomed. Eng.* **2025**, *3*, 157–187. [CrossRef]
88. Dubey, R.; Luo, Z.; Gunasekaran, A.; Akter, S.; Hazen, B.T.; Douglas, M.A. Big data and predictive analytics in humanitarian supply chains: Enabling visibility and coordination in the presence of swift trust. *Int. J. Logist. Manag.* **2018**, *29*, 485–512. [CrossRef]
89. Gupta, S.; Altay, N.; Luo, Z. Big data in humanitarian supply chain management: A review and further research directions. *Ann. Oper. Res.* **2019**, *283*, 1153–1173. [CrossRef]

90. Jeble, S.; Kumari, S.; Venkatesh, V.G.; Singh, M. Influence of big data and predictive analytics and social capital on performance of humanitarian supply chain: Developing framework and future research directions. *Benchmarking Int. J.* **2020**, *27*, 606–633. [CrossRef]
91. Prasad, S.; Zakaria, R.; Altay, N. Big data in humanitarian supply chain networks: A resource dependence perspective. *Ann. Oper. Res.* **2018**, *270*, 89–117. [CrossRef]
92. Ahatsi, E.; Olanrewaju, O.A. Enhancing humanitarian supply chain resilience: Evaluating artificial intelligence and big data analytics in two nations. *Logistics* **2025**, *9*, 64. [CrossRef]
93. Bamel, U. A systematic analysis of big data-driven humanitarian supply chain management research: Implications for emerging economies. *Adm. Sci.* **2025**, *15*, 478. [CrossRef]
94. Zhang, Y. Enhancing humanitarian supply chains: The role of interpersonal skills and big data and predictive analytics. *J. Humanit. Logist. Supply Chain Manag.* **2025**, *16*, 188–204. [CrossRef]
95. Sharma, P.; Joshi, A. Challenges of using big data for humanitarian relief: Lessons from the literature. *J. Humanit. Logist. Supply Chain Manag.* **2020**, *10*, 423–446. [CrossRef]
96. Lukyanova, I.; Haddud, A.; Khare, A. Types of ERP systems and their impacts on the supply chains in the humanitarian and private sectors. *Sustainability* **2022**, *14*, 13054. [CrossRef]
97. Gavidia, J.V. A model for enterprise resource planning in emergency humanitarian logistics. *J. Humanit. Logist. Supply Chain Manag.* **2017**, *7*, 246–265. [CrossRef]
98. Koliousis, I.; He, Q.; Wu, Q.; Sarpong, D. Using an integrated humanitarian supply chain ERP system to improve refugee flow management. *Prod. Plan. Control* **2022**, *33*, 676–691. [CrossRef]
99. Falagara Sigala, I.; Kettinger, W.J.; Wakolbinger, T. Digitizing the field: Designing ERP systems for Triple-A humanitarian supply chains. *J. Humanit. Logist. Supply Chain Manag.* **2020**, *10*, 231–260. [CrossRef]
100. Saïah, F.; Vega, D.; Kovács, G. Toward a common humanitarian supply chain process model: The Frontline Humanitarian Logistics Initiative. *Int. J. Oper. Prod. Manag.* **2023**, *43*, 238–269. [CrossRef]
101. Abushaikha, I.; Schumann-Bölsche, D. Mobile phones: Established technologies for innovative humanitarian logistics concepts. *Procedia Eng.* **2016**, *159*, 191–198. [CrossRef]
102. Serrato-Garcia, M.A.; Mora-Vargas, J.; Murillo, R.T. Multi-objective optimization for humanitarian logistics operations through the use of mobile technologies. *J. Humanit. Logist. Supply Chain Manag.* **2016**, *6*, 399–418. [CrossRef]
103. Setiabudi, D.H.; Widyadana, I.G.A. Mobile technology for volunteers in the distribution of natural disaster humanitarian logistics: Case study on East Java Province Indonesian Red Cross. In Proceedings of the 9th International Workshop on Computer Science and Engineering (WCSE 2019), Hong Kong, China, 15–17 June 2019; pp. 795–800.
104. Ólafsson, G.R. The role of technology in humanitarian assistance: Opportunities and challenges. Master's Thesis, School of Social Science, Faculty of Social and Human Sciences, University of Iceland, Borgarnes, Iceland, 2024.
105. Beamon, B.M.; Balcik, B. Performance measurement in humanitarian logistics. *Int. J. Phys. Distrib. Logist. Manag.* **2008**, *38*, 419–429.
106. Schiffling, S.; Piecyk, M. Performance measurement in humanitarian logistics: A customer-oriented approach. *J. Humanit. Logist. Supply Chain Manag.* **2014**, *4*, 198–221. [CrossRef]
107. Wisetjindawat, M.; Yeo, J.; Papalambros, P. Stakeholders in humanitarian logistics: Challenges and opportunities. *J. Humanit. Logist. Supply Chain Manag.* **2018**, *8*, 2–23.
108. Ahmad, M.S.; Fei, W.; Shoaib, M.; Ali, H. Identification of key drivers for performance measurement in sustainable humanitarian relief logistics: An integrated fuzzy Delphi-DEMATEL approach. *Sustainability* **2024**, *16*, 4412. [CrossRef]
109. Apte, A. Humanitarian logistics: A new field of research and action. *Found. Trends Technol. Inf. Oper. Manag.* **2009**, *3*, 1–100. [CrossRef]
110. Hong, J.-D. Design of humanitarian supply chain system by applying the general two-stage network DEA model. *J. Humanit. Logist. Supply Chain Manag.* **2023**, *13*, 74–90. [CrossRef]
111. Kabra, G.; Ramesh, A.; Jain, V.; Akhtar, P. Barriers to information and digital technology adoption in humanitarian supply chain management: A fuzzy AHP approach. *J. Enterp. Inf. Manag.* **2023**, *36*, 505–527. [CrossRef]

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