Integrating Relief Items and Resilient Strategies in Humanitarian Supply Chains: A Survey

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Abstract

The integration of relief items and resilient strategies within humanitarian supply chains (HSC) is vital for optimizing disaster management and enhancing supply chain resilience. This survey explores the significance of this integration, emphasizing advanced planning techniques such as two-stage and multi-objective planning. These methodologies provide robust frameworks for resource allocation and decision-making under uncertainty, crucial for managing the complexities of disaster scenarios. The application of the Non-dominated Sorting Genetic Algorithm II (NSGA II) further enhances decision-making by addressing multi-objective optimization challenges, enabling the balancing of conflicting objectives like cost efficiency and service level maximization. The survey highlights the role of advanced technologies and intelligent infrastructure in facilitating data-driven decision-making, which is essential for improving disaster response efficiency and effectiveness. The importance of empirical validation and stakeholder involvement is underscored, ensuring that strategies are adaptable to the dynamic nature of disaster management. By fostering interdisciplinary collaboration and leveraging innovative technologies, HSC can enhance their resilience and responsiveness, ultimately improving disaster management outcomes and the quality of life for affected communities.

1 Introduction

1.1 Significance of Integration

Integrating relief items with resilient strategies in humanitarian supply chains (HSC) is essential for improving disaster management efficiency and effectiveness. This integration optimizes resource allocation and strengthens supply chains against disruptions, as highlighted by Rodriguez [1], who underscores the need for adaptable supply networks to ensure a consistent flow of relief resources. The rising frequency and intensity of disasters necessitate innovative approaches, as noted by Mishra [2], who emphasizes enhancing the quality of life for disaster victims.

Advanced technologies are critical to this integration. Islam [3] discusses cognitive radio ad hoc networks (CRAHN) as a solution to existing disaster management inadequacies, advocating for innovative methods to improve response capabilities. The incorporation of cognitive radio technology, as further elaborated by Islam [4], enhances communication and collaboration among rescue teams, thus improving disaster management operations.

The necessity for resilient supply chains is further articulated by Aliahmadi [5], who examines the development of resilient supply chains amid growing complexity and uncertainty. This aligns with Pazoki's [6] proposal of a novel adaptive ensemble method that dynamically adjusts to data characteristics, enhancing supply chain resilience.

Digital technologies' significance in improving HSC operations is emphasized by CHAINS4 [7], which provides an overview of state-of-the-art digital technologies that enhance disaster response efficiency and effectiveness through improved coordination and resource management.

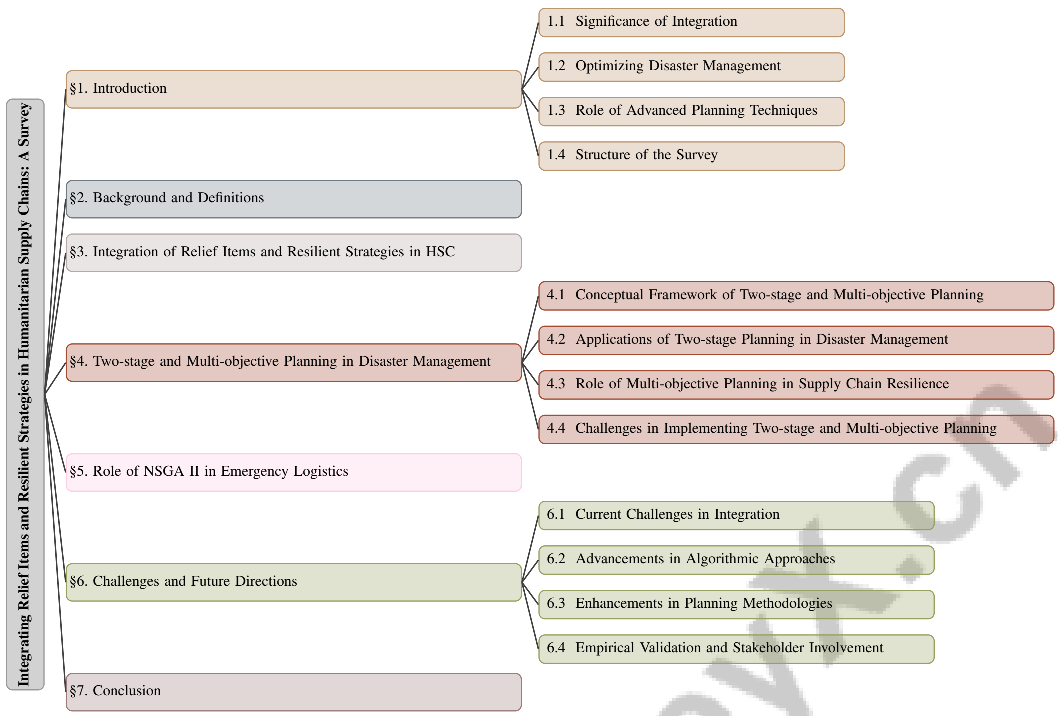

Figure 1: chapter structure

Murthy [8] highlights secure communication's importance for enhancing HSC efficiency, a point supported by Pathan [9], who discusses next-generation wireless networks' potential to improve disaster management communications and information systems (DMCIS).

Siddig [10] evaluates multi-stage stochastic programming (MSP) models for adaptive disaster relief logistics planning, emphasizing strategic planning's role in bolstering supply chain resilience.

1.2 Optimizing Disaster Management

Optimizing disaster management processes requires integrating advanced technologies and resilient strategies within humanitarian supply chains. The increasing frequency and intensity of natural disasters, exacerbated by climate change, necessitate a comprehensive approach that incorporates diverse strategies and technologies [11]. This integration is vital in contexts where traditional methods struggle to quantify complex interactions and feedback loops during catastrophes [12].

One significant challenge in disaster management is the destruction of communication infrastructure, which hampers rescue operations [3]. CRAHN deployment addresses these limitations by enhancing communication resilience during disasters [4]. Moreover, the utilization of unmanned aerial vehicles (UAVs) in disaster management underscores the importance of optimizing logistical capabilities, particularly in hard-to-reach areas [13]. UAVs facilitate efficient monitoring and delivery, with heuristic informative path planning (HIPP) algorithms improving their performance against known optimal solutions for environment remapping [14].

The integration of multi-task learning in disaster image classification, showcased by the MEDIC benchmark, enhances research in image-based disaster management by enabling model comparisons [15]. However, utilizing social media data for disaster management presents challenges regarding trustworthiness and bias due to the uncertain nature of disaster-related information [16]. Addressing these challenges is crucial for effective communication and coordination during emergencies.

Supply chain resilience, particularly in vaccine distribution, is essential for optimizing disaster management processes amid potential disruptions [17]. Resilient supply chains can withstand operational risks, allowing for recovery from unexpected disturbances while maintaining efficiency. The Holon Programming Model (HPM) integration facilitates coordinated, multi-system programs that adapt to dynamic environmental changes, optimizing disaster management processes [18].

Incorporating AI solutions with traditional disaster management practices is vital for optimizing outcomes. The use of foundation models to automate the annotation of very high-resolution (VHR) images specifically targets disaster management applications, enhancing decision-making and response efficiency [19]. These advanced methodologies are integral to addressing the complexities of modern urban environments and ensuring effective disaster management. Evacuation planning, as emphasized by Niyomubyeyi [20], is crucial for mitigating disaster impacts on urban communities, highlighting the need for comprehensive integration strategies in humanitarian logistics.

1.3 Role of Advanced Planning Techniques

Advanced planning techniques, including two-stage and multi-objective planning, are essential for enhancing the resilience and efficiency of humanitarian supply chains (HSC). These methodologies facilitate the management of complex logistics operations under uncertainty, thereby improving disaster response and recovery efforts. Chang [21] highlights a two-stage stochastic programming model that employs a rolling horizon approach to address uncertainties in logistics operations, allowing for dynamic adaptation to changing conditions and optimizing resource allocation.

Multi-objective planning is exemplified by the Non-dominated Sorting Genetic Algorithm II (NSGA-II), a prominent tool for solving multi-objective optimization problems [22]. NSGA-II enhances decision-making by evaluating trade-offs between conflicting objectives in HSC, such as cost minimization and service level maximization, thereby supporting the development of more resilient supply chains.

Intelligent infrastructure, as proposed by Dunaway [23], significantly contributes to disaster management and community resilience. The integration of real-time data analysis, machine learning, and IoT technologies enables proactive management of supply chain operations, facilitating timely disaster responses. This approach aligns with AIoT technology utilization to assess and improve resilient supply chain components, empowering them to handle disruptions more effectively [5].

Additionally, ANN-based systems for disaster detection and service discovery enhance communication and coordination during emergencies [3]. These systems improve HSC's ability to respond to disasters by providing real-time insights and facilitating efficient resource deployment.

Incorporating advanced planning techniques into humanitarian supply chains not only streamlines operations and enhances resource allocation but also significantly strengthens resilience, enabling better adaptation to and recovery from disruptions caused by disasters and emergencies. This integration of digital technologies and systematic planning allows organizations to configure a technological portfolio that addresses operational challenges across various HSC phases, ensuring a robust response to crises [24, 25, 7, 26, 27]. By leveraging innovative methodologies and technologies, HSC can better anticipate and respond to disaster challenges, ensuring a more effective and coordinated humanitarian response.

1.4 Structure of the Survey

This survey is meticulously structured to provide an in-depth analysis of how relief items integrate with resilient strategies in humanitarian supply chains (HSC), emphasizing the role of digital technologies and collaborative resource management to enhance operational effectiveness during disaster response and recovery phases [28, 7, 27, 29]. The paper begins with an **Introduction** that highlights the significance of integrating these elements to improve disaster management efficiency and resilience. It discusses advanced planning techniques, including two-stage and multi-objective planning, and the Non-dominated Sorting Genetic Algorithm II (NSGA II) in optimizing emergency logistics decision-making.

The second section, **Background and Definitions**, provides a comprehensive overview of humanitarian supply chains, their critical role in disaster management, and definitions of key terms such as relief items, resilient strategies, two-stage and multi-objective planning, and NSGA II. This section establishes the foundational understanding necessary for subsequent discussions.

In the section titled **Integration of Relief Items and Resilient Strategies in HSC**, the survey examines how these integrations enhance disaster management efficiency and effectiveness, supplemented by examples and case studies illustrating successful implementations.

The fourth section, **Two-stage and Multi-objective Planning in Disaster Management**, explores the relevance of these planning concepts in optimizing supply chain resilience. It includes a conceptual framework, real-world applications, impacts on supply chain resilience, and challenges faced during implementation.

The role of the **NSGA II in Emergency Logistics** is analyzed, detailing its application in enhancing decision-making processes and optimizing multi-objective problems within HSC. This section also provides a comparative analysis of NSGA II, discussing its advantages and applications in disaster scenarios.

Finally, the survey comprehensively addresses the in effectively integrating relief items and resilient strategies within HSC, highlighting complexities introduced by global supply chain uncertainties, increasing reliance on digital technologies, and the need for enhanced collaboration and adaptability in response to systemic risks such as natural disasters and pandemics [27, 7]. It identifies current challenges, discusses advancements in algorithmic approaches, explores potential enhancements in planning methodologies, and emphasizes the importance of empirical validation and stakeholder involvement in future research.The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Humanitarian Supply Chains in Disaster Management

Humanitarian supply chains (HSC) are essential for delivering critical goods and services during disasters, ensuring timely aid to affected populations. Their adaptability is key to mitigating disaster impacts, as conventional logistics often falter under such conditions [7]. Integrating data science with Geographic Information Systems (GIS) enhances spatial decision-making, crucial for effective disaster management [30]. Resource allocation challenges arise due to urgent demands and competing priorities, necessitating sophisticated solutions for effective distribution [31]. For instance, logistics planning for prepositioning relief items, especially for predictable events like hurricanes, is modeled as a multiperiod network flow problem to minimize costs and penalties for unmet demand [10].

An integrated communications and information system is vital for managing disaster-related data and coordinating responses among organizations [9]. Advanced technologies, such as the Internet of Things (IoT) and Wireless Sensor Networks (WSNs), enhance HSC capabilities by enabling real-time data collection and monitoring, essential for informed decision-making during emergencies [7]. Recent global events underscore the importance of resilience in HSC, highlighting the need for systems that can withstand, adapt, and recover from disruptions [7]. Optimizing evacuation planning to minimize distance to shelters and reduce capacity overload is also critical for effective disaster response [20].

2.2 Key Terminologies in Humanitarian Supply Chains

Understanding key terminologies is essential for effective disaster management within humanitarian supply chains (HSC). Relief items, including food, water, medical supplies, and shelter materials, are crucial for immediate relief efforts. The resilience of supply chains, which refers to their ability to withstand and recover from disruptions, ensures operational continuity [7]. Resilience encompasses absorptive, adaptive, and restorative capacities, which are vital for maintaining supply chain functionality amid disaster challenges [7].

Modern HSCs leverage advanced technologies and data-driven approaches, such as Very-High Resolution (VHR) remote sensing imagery and automated annotation processes, significantly enhancing disaster response capabilities [19]. However, fragmented literature on technology adoption indicates a need for comprehensive evaluations and reliable solutions [7]. Key obstacles include neglecting facility disruptions in benchmarks, which can impact logistics network efficiency [32], and the reliance on computationally intensive mixed-integer linear programming, which may not guarantee optimal solutions [31]. Inadequate integration of information and communication technologies also hampers timely decision-making during disasters [9].

Contemporary data processing in HSC employs parallel processing algorithms and real-time image analysis for efficient data handling and decision-making [33]. However, benchmarks often lack comprehensive evaluations of classical metaheuristic algorithms in evacuation planning, limiting solution reliability [20]. Understanding these terminologies and concepts enhances HSC effectiveness and resilience, enabling organizations to implement digital technologies effectively and collaborate across entities, optimizing resource allocation and improving operational performance during critical disaster management phases [24, 7, 27, 29].

2.3 Supply Chain Resilience in Emergency Logistics

Supply chain resilience (SCRE) in emergency logistics ensures the continuity of essential services during disruptions by anticipating, preparing for, responding to, and recovering from such events. The complexity and interconnectivity of global supply chains demand robust strategies to address uncertainties and risks [27]. Frequent disruptions from natural disasters and market fluctuations necessitate strategies that can withstand and quickly recover from these events [25]. A systematic understanding of SCRE capabilities and performance metrics is crucial, as highlighted by Han [34], to develop structured frameworks for evaluating and implementing effective resilience strategies.

Emergency logistics is further complicated by uncertainties in demand for aid, often exacerbated by failures in telecommunications and transportation, complicating aid delivery routing [35]. Integrating multi-modal logistics service networks presents unique challenges in maintaining resilience, particularly under time uncertainty. Pang [26] discusses the limitations of existing stochastic approaches and the potential of robust optimization with budget-of-uncertainty to enhance resilience, allowing for flexible logistics planning during disruptions.

Multi-stage stochastic programming (MSP) models offer advantages over static models by minimizing costs and penalties associated with disruptions. Siddig [10] demonstrates the superior performance of MSP models, emphasizing adaptability's importance in developing resilient supply chains. These models enable dynamic adjustments to changing conditions, ensuring efficient resource allocation and delivery during emergencies.

In recent years, the importance of integrating relief items with resilient strategies in humanitarian supply chains has gained significant attention. This integration not only addresses the immediate needs during disaster management phases but also enhances the overall effectiveness of humanitarian operations. As illustrated in Figure 2, the figure highlights the critical role of integrated strategies and technologies, such as Collaborative Relief and Humanitarian Networks (CRAHN) and Unmanned Aerial Vehicles (UAVs). The visual representation underscores the benefits of such integration, including improved operational capacity, enhanced collaboration among stakeholders, and increased sustainability in disaster response efforts. By examining these elements, we can better understand the complexities involved in modern humanitarian logistics and the necessity for innovative solutions to meet the challenges posed by natural disasters.

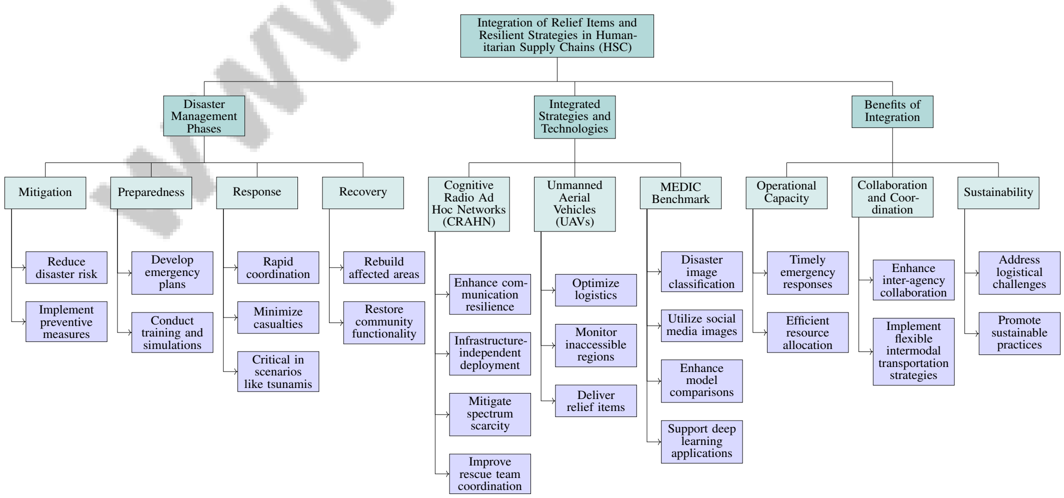

Figure 2: This figure illustrates the integration of relief items and resilient strategies in humanitarian supply chains, highlighting disaster management phases, the role of integrated strategies and technologies like CRAHN and UAVs, and the benefits of such integration in enhancing operational capacity, collaboration, and sustainability.

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3 Integration of Relief Items and Resilient Strategies in HSC

3.1 Examples and Case Studies

Integrating relief items and resilient strategies within humanitarian supply chains (HSC) significantly enhances disaster management effectiveness. Frameworks promoting inter-agency information sharing are crucial for coordination, enabling timely responses through seamless data exchange during crises [36]. Disaster management is structured into Mitigation, Preparedness, Response, and Recovery phases, with the Response phase being critical in scenarios like tsunamis, where rapid coordination minimizes casualties and damage [37].

Case studies underscore the efficacy of integrated strategies. Cognitive radio ad hoc networks (CRAHN) are pivotal in enhancing communication resilience, enabling infrastructure-independent deployment, mitigating spectrum scarcity, and improving coordination among rescue teams. These networks support advanced disaster detection and real-time data sharing, enhancing decision-making and resource allocation [16, 3, 4, 23]. Unmanned aerial vehicles (UAVs) further optimize logistics by monitoring and delivering in inaccessible regions.

The MEDIC benchmark exemplifies advancements in disaster image classification through multi-task learning, utilizing a dataset of 71,198 social media images to enhance model comparisons and decision-making processes. This benchmark supports deep learning applications that improve memory efficiency and performance, crucial for effective disaster response [15, 38]. Despite challenges with trustworthiness and bias, social media data provides valuable insights for communication and coordination during disasters.

To illustrate the hierarchical structure of disaster management strategies, Figure 3 emphasizes key areas such as information sharing, technological integration, and data utilization. Each category within the figure highlights specific methods and innovations that enhance the effectiveness and efficiency of disaster response efforts. These case studies highlight the necessity of integrating relief items and resilient strategies within HSC. By leveraging digital technologies and innovative methodologies, HSC can improve operational capacity, enabling timely and efficient emergency responses. This integration optimizes resource allocation, enhances collaboration among organizations, and implements flexible intermodal transportation strategies, addressing logistical challenges while promoting sustainability [1, 7, 29].

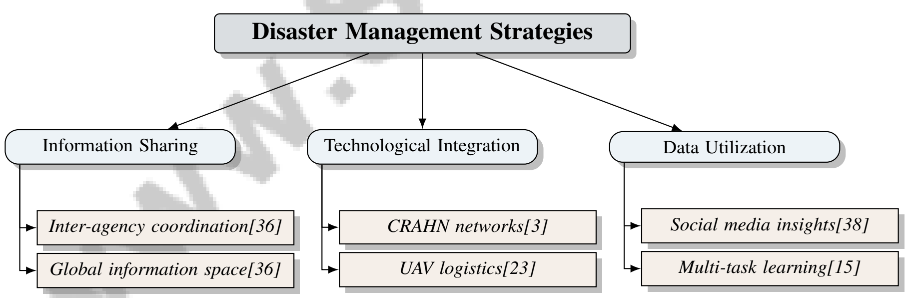

Figure 3: This figure illustrates the hierarchical structure of disaster management strategies, focusing on key areas such as information sharing, technological integration, and data utilization. Each category highlights specific methods and innovations that enhance the effectiveness and efficiency of disaster response efforts.

4 Two-stage and Multi-objective Planning in Disaster Management

4.1 Conceptual Framework of Two-stage and Multi-objective Planning

The two-stage and multi-objective planning framework is pivotal in optimizing disaster management by effectively allocating resources and adapting to evolving conditions. This approach involves an initial stage for preparatory measures and a subsequent stage for real-time adjustments. Robust optimization models, such as Mixed Integer Linear Programming (MILP), are essential in managing demand uncertainties and optimizing routing decisions, thereby enhancing the resilience of humanitarian supply chains during crises [26].

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Method Name	Optimization Techniques	Algorithmic Approaches	Forecasting and Prediction
ROB[26]	Mixed Integer Linear	-	-
CTD[39]	Circular Trajectory Design	Low Complexity Algorithms	Sequence TO Sequence
MADRL-SA[40]	Proximal Policy Optimization	Deep Reinforcement Learning	Long Short Term Memory
RADAR[41]	Graph Algorithms	Graph Algorithms	Sequence TO Sequence
CRAHN-DMS[4]	Mlp	Service Discovery Algorithm	Ann-based Approach

Table 1: Overview of optimization techniques, algorithmic approaches, and forecasting methods employed in disaster management frameworks. The table categorizes various methods by their optimization strategies, algorithmic implementations, and forecasting capabilities, highlighting their contributions to enhancing resilience and efficiency in humanitarian logistics.

As illustrated in Figure 4, the hierarchical structure of the two-stage and multi-objective planning framework highlights key optimization models, advanced algorithms, and computational techniques essential for enhancing disaster management and resource allocation. Table 1 presents a comprehensive classification of methods utilized within the two-stage and multi-objective planning framework, detailing their respective optimization techniques, algorithmic approaches, and forecasting capabilities essential for effective disaster management. In multi-objective planning, methods like Circular Trajectory Design (CTD) illustrate how low-complexity algorithms can optimize UAV trajectories and speeds, reducing mission completion times [39]. This balance between logistical efficiency and resource sustainability is crucial in disaster response. Multi-UAV deep reinforcement learning-based scheduling algorithms further minimize packet loss, emphasizing the role of advanced algorithms in enhancing mission effectiveness [40].

Advanced forecasting techniques, such as the Sequence to Sequence Forecasting Model, enhance the framework by predicting future needs using weather data and social media inputs, facilitating proactive planning and resource allocation [7]. Graph algorithms and Satisfiable-Modulo Theories (SMT) in RADAR support real-time decision-making, highlighting the integration of computational models for efficient resource distribution [41].

Systems theory and mathematical modeling provide dynamic assessments of interaction networks, crucial for understanding complex interdependencies within disaster management systems [4]. This understanding aids in developing robust strategies to tackle the multifaceted challenges posed by disasters. The use of synthetic datasets in multi-stage stochastic programming models enhances logistics cost evaluation and decision-making processes in disaster scenarios [10].

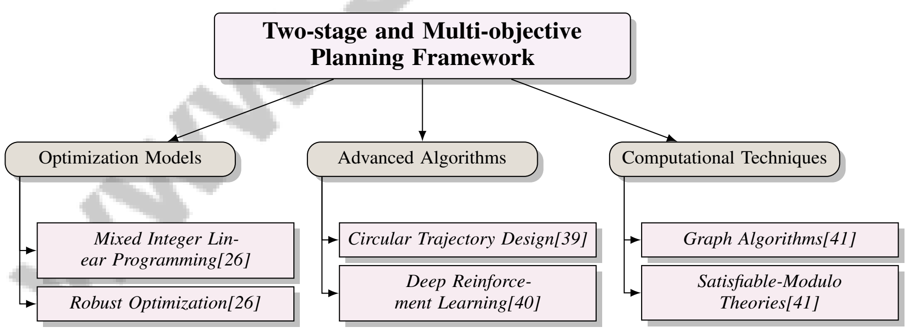

Figure 4: This figure illustrates the hierarchical structure of the two-stage and multi-objective planning framework, highlighting key optimization models, advanced algorithms, and computational techniques essential for enhancing disaster management and resource allocation.

4.2 Applications of Two-stage Planning in Disaster Management

Two-stage planning is a critical methodology in disaster management, offering a structured approach to manage uncertainties and optimize resource allocation. This framework is particularly beneficial in uncertain situations, allowing for adaptive strategies that respond dynamically to changing disaster conditions. By integrating multi-objective optimization and geographical information systems, this approach enhances collaborative decision-making among organizations involved in disaster relief, improving resource allocation, facility location, and logistics management. Such adaptability is

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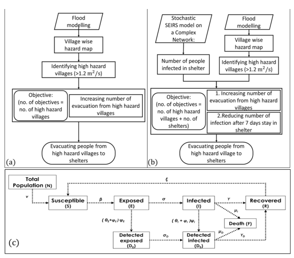
crucial for optimizing logistical costs and ensuring effective responses as disaster specifics become clearer [10, 2, 29].

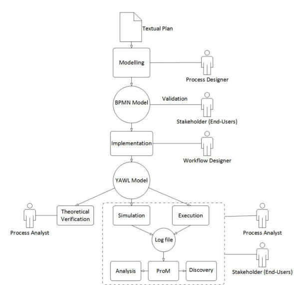
The first stage involves preparatory actions, such as prepositioning relief items and establishing logistical networks, which are vital for ensuring rapid responses once a disaster occurs. For instance, prepositioning resources in anticipation of hurricanes can significantly reduce logistics costs and penalties for unmet demand [10]. By strategically placing supplies in likely affected areas, humanitarian organizations can ensure essential goods are available when needed.

In the second stage, real-time decisions are made based on actual conditions, allowing for dynamic adjustments to initial plans, reallocation of resources, and modification of logistics strategies as new information becomes available. This flexibility is exemplified in supply chain management during pandemics, where adapting to rapidly changing demand and supply conditions is critical for maintaining the flow of essential goods [7].

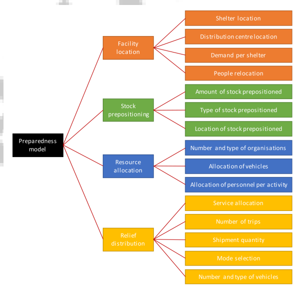
The integration of two-stage planning with advanced technologies, such as Geographic Information Systems (GIS) and data analytics, enhances its effectiveness in disaster management. These technologies provide real-time data and insights that inform decision-making processes, enabling accurate predictions and efficient resource distribution during emergencies [30]. Multi-stage stochastic programming models further support this approach by allowing evaluations of logistics costs and penalties under various scenarios, optimizing resource allocation and minimizing disruptions [10].



(a) Evacuation and Disease Control Strategies in Flood-Prone Areas: A Comparative Analysis[42]



(b) The Process Flow Diagram[37]



(c) The image represents a flowchart illustrating the components of a preparedness model.[29]

Figure 5: Examples of Applications of Two-stage Planning in Disaster Management

As illustrated in Figure 5, two-stage and multi-objective planning are crucial for effectively addressing the complex challenges posed by disasters. The first image emphasizes the importance of identifying and evacuating high-risk villages during floods, integrating flood modeling and hazard mapping to streamline efforts. The second image captures the intricate stages involved in developing and implementing a process model, focusing on the transition from textual planning to graphical modeling using Business Process Model and Notation (BPMN). Lastly, the flowchart of a preparedness model underscores strategic facility location and stock prepositioning, detailing elements like shelter and distribution center locations, as well as logistics for people relocation and demand management. Together, these examples highlight the multifaceted nature of disaster management, where two-stage planning is pivotal in optimizing responses and minimizing risks [42, 37, 29].

4.3 Role of Multi-objective Planning in Supply Chain Resilience

Multi-objective planning enhances supply chain resilience by addressing complex trade-offs between conflicting objectives, such as cost efficiency, service level maximization, and risk mitigation. Techniques like the Non-dominated Sorting Genetic Algorithm II (NSGA-II) enable decision-makers to analyze and balance these competing priorities effectively, providing a comprehensive view of potential trade-offs in supply chain management [43].

The integration of multi-objective planning frameworks is further enhanced by advanced data analytics and machine learning techniques. For instance, sentiment classification models, such as the Naïve Bayes model, offer valuable insights into public sentiment during disasters, informing supply chain strategies and improving decision-making processes [44]. Leveraging these insights allows supply chains to adapt more effectively to dynamic disaster conditions, ensuring timely delivery of essential goods and services.

The transition from NSGA-II to more advanced algorithms, such as NSGA-III, exemplifies the evolution of multi-objective optimization techniques. NSGA-III achieves complete coverage of the Pareto front more efficiently, particularly in complex multi-objective problems like the 3-OMM problem, encouraging its adoption for sophisticated multi-objective optimization tasks and potentially enhancing supply chain resilience through more accurate solutions [43].

4.4 Challenges in Implementing Two-stage and Multi-objective Planning

Implementing two-stage and multi-objective planning in disaster management presents several challenges that can impede the effectiveness of these strategies. One major challenge is the scalability and computational demands associated with these optimization methods. Balancing conflicting objectives in multi-objective planning can be computationally intensive, as evidenced by the NP-complete bi-objective minimum spanning tree problem, which necessitates sophisticated algorithms for efficient solutions [20]. Similarly, metaheuristic algorithms like NSGA-II can be computationally demanding in large-scale scenarios where rapid decision-making is essential [20].

The reliance on advanced technologies, such as cognitive radio networks, also poses challenges. Implementing these technologies requires robust training data and scalability to real-world conditions, as highlighted by scalability issues and the need for high-quality training data for MLP models in cognitive radio applications [4]. Additionally, the evolving nature of disruptions complicates establishing accurate probability distributions for travel times, which is vital for effective planning. Traditional methods often struggle to adapt, necessitating more dynamic and flexible approaches [26].

The integration of intermodal transportation strategies and carbon emission reduction measures into optimization models for humanitarian logistics is currently underdeveloped, hindering efforts to improve the sustainability and efficiency of relief operations during crises. This research gap is critical, as effective intermodal approaches can enhance supply chain flexibility amidst damaged infrastructure while addressing environmental impacts. Recent studies suggest that combining these elements could significantly minimize costs and shortages of relief supplies, ultimately fostering more resilient and sustainable humanitarian responses [6, 1]. Additionally, accounting for facility disruptions and logistical challenges complicates the development of effective strategies, requiring comprehensive planning to ensure resilience.

The implementation of automated annotation methods in disaster management faces significant challenges, including high computational requirements and the necessity for high-quality datasets crucial for effective decision-making. The increasing frequency and intensity of natural disasters necessitate advanced machine learning techniques; however, progress is hindered by a lack of benchmark datasets for evaluating models against established standards. Furthermore, while advancements in foundation models have enabled the automatic generation of annotations from high-resolution remote sensing imagery, ensuring data trustworthiness and minimizing bias, particularly from social media, remains critical for enhancing the reliability of real-time disaster response efforts [19, 15, 45, 16, 46]. The complexity of advanced ensemble learning methods can also lead to longer training times, which may not be feasible in time-sensitive disaster management scenarios.

These challenges underscore the urgent need for more efficient algorithms and comprehensive models that can effectively navigate the complexities and uncertainties inherent in disaster management. By integrating multi-objective optimization techniques and real-time data sources, such as social media, advancements can enhance the effectiveness of two-stage and multi-objective planning strategies, improving resource allocation and decision-making in collaborative environments while addressing data trustworthiness and bias, ultimately leading to more effective disaster response and preparedness efforts [16, 29].

5 Role of NSGA II in Emergency Logistics

The Non-dominated Sorting Genetic Algorithm II (NSGA II) is pivotal in optimizing decision-making processes within emergency logistics. Comparative analyses reveal NSGA-II's strengths in multi-objective optimization, though it encounters limitations with problems involving more than two objectives. Recent advancements, such as NSGA-III, have improved efficiency in handling multiple objectives, as evidenced by mathematical runtime analyses indicating that NSGA-III computes the complete Pareto front for three-objective problems more swiftly than NSGA-II [47, 43]. This highlights NSGA II's role in enhancing decision-making and fostering collaboration among stakeholders in disaster management.

5.1 Comparative Analysis and Advantages of NSGA II

Benchmark	Size	Domain	Task Format	Metric
3-OMM[43]	441	Multi-objective Optimization	Optimization	Iterations, Fitness Evaluations
MDSCF-SCRES[48]	191	Supply Chain Management	Survey Analysis	SCRES, MDSCF
SMIDR[44]	41,993	Natural Disaster Response	Sentiment Analysis	Accuracy, F1-score
MEDIC[15]	71,198	Disaster Response	Multi-task Image Classification	F1-score, Precision
ELOG[32]	30	Emergency Logistics	Location-Allocation	Cost, Delivery Time
HDRLP[10]	1,000	Logistics	Logistics Planning	Cost, Penalty
EMOEP[20]	1,000,000	Evacuation Planning	Location-Allocation Problem	Effectiveness, Efficiency

Table 2: This table presents a comprehensive overview of various benchmarks utilized in the evaluation of multi-objective optimization techniques, particularly in emergency logistics and disaster management scenarios. It details the size, domain, task format, and metrics employed for each benchmark, providing insights into their application and relevance to optimization studies.

NSGA II is a leading multi-objective optimization technique, adept at identifying Pareto-optimal solutions in complex emergency logistics scenarios. It effectively balances conflicting objectives like cost minimization, service level maximization, and risk mitigation, which is invaluable in disaster management [49]. NSGA II's framework enhances stakeholder communication and collaboration, crucial for disaster management, by elucidating complex interactions and improving accessibility to disaster management knowledge [49]. This aligns with Mishra's framework, emphasizing shared responsibility and cooperation to bolster disaster resilience [2].

NSGA II stands out for its computational efficiency and ability to maintain a diverse solution set, especially in bi-objective scenarios. However, its performance diminishes with more than two objectives, as mathematical analyses reveal limitations in capturing the complete Pareto front. In contrast, NSGA-III offers significant improvements in handling multi-objective challenges, achieving superior performance metrics for three or more objectives [22, 43]. NSGA II's non-dominated sorting mechanism and crowding distance approach ensure a well-distributed Pareto front, providing a comprehensive view of potential trade-offs. Table 2 provides a detailed summary of the representative benchmarks used in the comparative analysis of multi-objective optimization methods, highlighting their domains and evaluation metrics.

NSGA II's strengths in emergency logistics include enhanced decision-making capabilities, improved stakeholder collaboration, and effective handling of multi-objective optimization challenges. These attributes make NSGA II an invaluable tool for optimizing disaster management processes, crucial for enhancing the resilience of humanitarian supply chains, as demonstrated in the 2013 floods in Acapulco, where effective resource allocation and coordination were essential [28, 29].

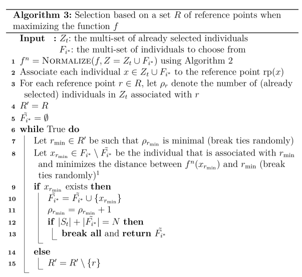
5.2 Applications of NSGA II in Disaster Scenarios

NSGA II is instrumental in optimizing the multi-objective challenges inherent in emergency logistics during disaster scenarios. It effectively balances objectives such as minimizing costs, maximizing service levels, and reducing response times, particularly in tasks like evacuation planning and resource allocation. While empirical evidence supports NSGA II's strength in bi-objective problems, challenges in multi-objective contexts have spurred research into alternatives like NSGA-III [50, 20, 22, 43].

NSGA II has been effectively applied in optimizing evacuation planning, identifying efficient routes and schedules that minimize travel time and congestion while maximizing safety and accessibility for evacuees [20]. Additionally, it optimizes supply chain networks for disaster relief, considering objectives such as cost, time, and reliability, aiding in designing resilient supply chains capable of withstanding disruptions [2].

Furthermore, NSGA II has been utilized for the allocation of emergency resources, including medical supplies and personnel, in disaster-stricken areas. It manages complex trade-offs to facilitate efficient resource distribution, ensuring critical needs are met while minimizing waste, thereby enhancing disaster response effectiveness [49].

NSGA II's implementation in disaster scenarios illustrates its adaptability and efficacy in addressing emergency logistics challenges, particularly in coordinating resource management among multiple organizations. This optimization improves the allocation of emergency facilities and resources and enhances decision-making in multi-organizational contexts, as evidenced by past disasters like the 2013 floods in Acapulco, where collaborative efforts were vital [28, 50, 32, 29]. By providing a comprehensive set of optimal solutions, NSGA II empowers decision-makers and strengthens the resilience and responsiveness of humanitarian supply chains.



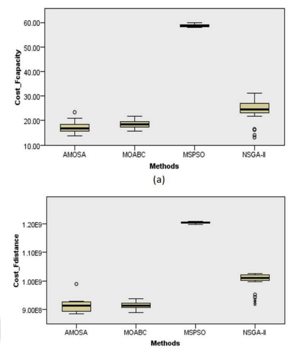
Algorithm 3: Selection based on a set R of reference points when maximizing the function f

Input : Z_t: the multi-set of already selected individuals
F_{i^*}: the multi-set of individuals to choose from

$f^n = \text{NORMALIZE}(f, Z = Z_t \cup F_{i^*})$ using Algorithm 2
Associate each individual $x \in Z_t \cup F_{i^*}$ to the reference point rp(x)
For each reference point $r \in R$, let ρ_r denote the number of (already selected) individuals in Z_t associated with r
$R' = R$
$\tilde{F}_{i^*} = \emptyset$
while True **do**
Let $r_{\min} \in R'$ be such that $\rho_{r_{\min}}$ is minimal (break ties randomly)
Let $x_{r_{\min}} \in F_{i^*} \setminus \tilde{F}_{i^*}$ be the individual that is associated with $r_{\min}$ and minimizes the distance between $f^n(x_{r_{\min}})$ and $r_{\min}$ (break ties randomly)[1]
if $x_{r_{\min}}$ exists **then**
$\tilde{F}_{i^*} = \tilde{F}_{i^*} \cup \{x_{r_{\min}}\}$
$\rho_{r_{\min}} = \rho_{r_{\min}} + 1$
if $|S_t| + |\tilde{F}_{i^*}| = N$ **then**
break all and **return** $\tilde{F}_{i^*}$
else
$R' = R' \setminus \{r\}$

(a) Algorithm 3: Selection based on a set R of reference points when maximizing the function f[43]

(b) Managing Natural Disaster Risks[51]



(c) Comparison of Cost Functions for Different Optimization Methods[20]

Figure 6: Examples of Applications of NSGA II in Disaster Scenarios

As depicted in Figure 6, NSGA II is crucial in optimizing emergency logistics during disasters, where timely decision-making is critical. The examples illustrate NSGA II's diverse applications through three visual representations. The first image, "Algorithm 3," highlights selection processes based on reference points for maximizing functions, showcasing the algorithm's adaptability. The second image presents a flowchart on "Managing Natural Disaster Risks," emphasizing the comprehensive approach necessary for effective risk monitoring, prediction, and mitigation. The final image compares cost functions across various optimization methods, including NSGA II, highlighting its effectiveness in cost minimization and operational efficiency. These examples underscore NSGA II's versatile applications in enhancing the resilience and responsiveness of emergency logistics systems during disaster scenarios [43, 51, 20].

6 Challenges and Future Directions

6.1 Current Challenges in Integration

The integration of relief items and resilient strategies within humanitarian supply chains (HSC) faces significant challenges, hindering effective disaster management. A major issue is the computational complexity of current algorithms, which struggle to optimize in irregular terrains or environments with obstacles [39]. This is compounded by the underdeveloped state of digital twins (DTs) in HSC, lacking a comprehensive integration of diverse technologies [7]. Scalability constraints in systems like the Cognitive Radio Ad Hoc Network Disaster Management System (CRAHN-DMS) further hinder practical applications due to the extensive training data required [4]. Additionally, cooperative unmanned aerial vehicle (UAV) environments may be ineffective in scenarios with limited communication capabilities [40].

Many benchmark models neglect real-world complexities, such as infrastructure limitations and human factors, reducing their generalizability across different disaster contexts [10, 20]. Data accuracy and reliability also pose challenges, particularly with sensor failures or misinterpretations

AI-generated, for reference only.

in disaster management systems [9]. Resource dependency, especially in scenarios with limited computational power, can impede systems like PISA [33]. The intricacies of products, processes, and partnerships further obstruct collaboration within supply chains [6], and systems like RADAR remain in proof-of-concept stages, requiring further development for larger scenarios [41].

Addressing these challenges necessitates innovative solutions and advanced digital technologies (DTs) to integrate relief items and resilient strategies effectively. A strategic technological portfolio can enhance operational efficiency across all phases of disaster management—Mitigation, Preparedness, Response, and Recovery—by optimizing resource allocation and improving multi-organizational collaboration [28, 7, 29].

6.2 Advancements in Algorithmic Approaches

Recent advancements in algorithmic approaches have significantly enhanced the integration and resilience of humanitarian supply chains (HSC). The Hybrid Non-dominated Sorting Genetic Algorithm (HNSGA) employs multiple search operators to bolster optimization robustness and efficiency, crucial for navigating dynamic emergency logistics [47]. The Holon Programming Model (HPM) offers a coordinated multi-system framework adaptable to environmental changes, with future research focusing on refining its security features [18]. This adaptability is vital for maintaining operational continuity amid disruptions.

Incorporating capacity constraints into relief center location problems and extending results to p-median problems are identified as future research directions, aiming to optimize resource allocation and logistics planning during emergencies [31]. Integrating advanced technologies into supply chain practices is crucial for enhancing decision-making and operational efficiency in global supply chain networks [27]. This integration is essential for anticipating and responding to disruptions, ensuring a seamless flow of goods and services during crises.

Developing models that account for international supply chains and diverse disaster scenarios can improve integration through a comprehensive understanding of global supply chain dynamics [1]. Refining models via numerical experiments and real-life case studies can enhance logistics networks' resilience, providing practical insights into effective disaster management strategies [26].

6.3 Enhancements in Planning Methodologies

Enhancements in planning methodologies for humanitarian supply chains (HSC) are crucial for integrating relief items and resilient strategies effectively. Future research identifies the refinement of disaster preparedness system models to incorporate dynamic response elements, enhancing applicability across various contexts [29]. This fosters adaptable and effective planning strategies tailored to unique disaster challenges.

Automated annotation techniques like FMARS can improve data availability and decision-making by facilitating rapid processing of large datasets, enabling timely emergency responses [19]. Exploring dynamic location-allocation strategies and factors like material collection points can further optimize resource distribution during disasters [32].

Future research could also focus on model compression techniques and continual learning setups to enhance Visual Question Answering (VQA) systems' deployment in disaster scenarios, improving planning methodologies' efficiency [52]. Deploying CRAHN-DMS in real-world settings and refining machine learning models are crucial for enhancing communication resilience and operational efficiency during disasters [4]. Ensuring data security in wireless sensor networks and integrating technologies within the Disaster Management Communication and Information Systems (DMCIS) framework are vital for robust data management in HSC [9].

Applying HNSGA to complex combinatorial optimization problems and integrating multiple ensemble local search operators can enhance planning methodologies' performance [47]. Future work should also focus on refining algorithms for challenging terrains and incorporating additional communication technologies to improve performance in difficult disaster environments [39].

6.4 Empirical Validation and Stakeholder Involvement

Empirical validation and stakeholder involvement are critical for advancing the integration of relief items and resilient strategies within humanitarian supply chains (HSC). Empirical validation ensures disaster management models' reliability and applicability, allowing adaptation to dynamic and complex scenarios. Integrating statistical methods is essential for assessing real-time application performance, enhancing model accuracy and robustness to address disaster challenges effectively [33].

Future research should prioritize the empirical validation of integrated digital twins (DTs) in HSC, incorporating stakeholder perspectives to enhance technology effectiveness [7]. Engaging stakeholders to refine resource distribution criteria, as highlighted by Johnson [41], and utilizing probabilistic modeling of resource availability can improve decision-making processes.

Exploring emerging technologies such as AI and IoT is vital for addressing global disaster management challenges [30]. These technologies can enhance supply chain adaptability and resilience, facilitating more efficient emergency responses. Furthermore, enhancing algorithmic robustness in dynamic environments and integrating factors like energy consumption and real-time environmental changes are critical areas for future exploration [40].

Stakeholder involvement is integral to refining evacuation planning algorithms, allowing real-time data incorporation and additional factors that enhance model robustness [20]. Engaging with stakeholders and leveraging their insights enables disaster management strategies to be more effectively tailored to the specific needs and conditions of affected communities.

7 Conclusion

The integration of relief items with resilient strategies in humanitarian supply chains (HSC) is essential for optimizing disaster management and strengthening supply chain resilience. This approach enhances the efficiency and effectiveness of disaster response, ensuring the timely delivery of essential resources to affected areas. Advanced planning techniques, such as two-stage and multi-objective planning, are pivotal in addressing the complexities and uncertainties inherent in disaster scenarios, providing structured frameworks for efficient resource allocation and decision-making.

The application of the Non-dominated Sorting Genetic Algorithm II (NSGA II) plays a crucial role in resolving multi-objective optimization challenges, effectively balancing competing objectives like cost efficiency and service level enhancement. This algorithm, combined with advancements in intelligent infrastructure, forms a robust foundation for data-driven decision-making, which is vital for saving lives, improving disaster resilience, and elevating the quality of life for impacted communities.

Furthermore, the importance of empirical validation and active stakeholder engagement is underscored in refining and implementing these strategies, ensuring their adaptability to the dynamic and complex nature of disaster management. Through interdisciplinary collaboration and the adoption of cutting-edge technologies, humanitarian supply chains can significantly enhance their resilience and responsiveness, ultimately leading to more successful disaster management outcomes.

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