Improving the performance of humanitarian logistics by model optimizing of chosen subsystems

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Abstract: Efficient humanitarian logistics is crucial for timely and effective response during crises. This paper investigates the enhancement of humanitarian logistics performance through model optimization of selected subsystems. The goal is to identify key subsystems within humanitarian logistics and apply optimization techniques to improve their performance metrics such as response time, resource allocation, and cost efficiency. Through a comprehensive review of existing literature and case study analysis, this study identifies critical subsystems including inventory management, transportation networks, and information systems. Each subsystem is modeled using optimization methods tailored to address specific challenges in humanitarian contexts, such as unpredictable demand and limited resources. Key findings highlight significant improvements in response times and resource utilization when subsystems are optimized individually and integrated within a holistic framework. However, the implementation of optimization models faces challenges related to data availability, accuracy, and contextual variability across different humanitarian crises. This research contributes to the field by demonstrating the potential of mathematical optimization in enhancing humanitarian logistics effectiveness. The findings underscore the importance of tailored solutions and the need for adaptive strategies that account for the dynamic and diverse nature of humanitarian operations. Future research should focus on addressing data limitations and further validating these optimization models in real-world humanitarian settings.

Keywords: humanitarian logistics, model optimization, subsystems, performance improvement, mathematical modeling.

1. Introduction

In the world, we witness a rising number of natural and manmade disasters. Humanitarian logistics plays a crucial role in dealing with the consequences of disasters. Simply put, humanitarian logistics is the process of acquiring and delivering food, water, medicine, and other essential relief supplies and services to the beneficiaries. Managing humanitarian logistics is not an easy task due to the unpredictable and sudden nature of the situations. However, technological development is changing the face of humanitarian logistics. Players are looking for novel transport means for surveillance, deploying relief items, and transporting the affected population.

Through a comprehensive review of existing literature and case study analysis, this study identifies critical subsystems including inventory management, transportation networks, and information systems. Each subsystem is modeled using optimization methods tailored to address specific challenges in humanitarian contexts, such as unpredictable demand and limited resources. The implementation of optimization models faces challenges related to data availability, accuracy, and contextual variability across different humanitarian crises. The findings underscore the importance of tailored solutions and the need for adaptive strategies that account for the dynamic and diverse nature of humanitarian operations.

The remainder of this paper is organized as follows. In Section 2, we review the related literature. In Section 3, the description of optimization models is presented. Then, examples of successful optimization utilization are provided in Section 4. Finally, Section 5 presents the conclusions.

2. Literature review

A disaster is a sudden and devastating event that affects densely populated regions in the world. The primary goal of humanitarian action is to save the lives of those affected by disasters and to fulfill their needs during and after a disaster (Heaslip & Barber, 2014). Moreover, humanitarian logistics is not always restricted to the movement of relief materials and aid workers. It may also involve activities such as helping a society reclaim its ecosystem through the planting of trees, restoration of fauna, etc (Martin et al., 2021). Some of the other activities that are undertaken by such organizations in the post-disaster period are setting up flood water barriers, hurricane shelters, etc.

The logistics of relief goods, rescue equipment, relief infrastructure, aid workers, and victims in case of a disaster are referred to as humanitarian logistics (Overstreet et al., 2011). Logistics is a critical part of disaster relief chains due to the position in the relief chain and the function it performs. Whereby all the tasks from procurement to field deployment are operated by logistics (Delkhosh, 2020). Due to unpredictability, humanitarian logistics must be capable of responding effectively. Further, logistics is the highest cost contributor in humanitarian relief operations (Hein et al., 2020). Therefore, an abundance of different optimization methods is developed to optimize resource allocation.

In the literature, four disaster phases are identified: mitigation, preparation, response, and recovery (Chong et al., 2019). Except in the mitigation phase, in all three other three phases, humanitarian logistics has a direct role.

The mitigation phase involves research, information gathering, and plan-making activities for the potential disaster. It is a proactive phase with the main goal of minimizing risks and the consequences of a disaster before they occur (Paul & Hariharan, 2012). This phase is essential to prevent or lessen the severity of damage, enhance preparedness, and protect lives and infrastructure. One of the primary functions of the mitigation phase is identifying potential risks and vulnerabilities in disaster-prone areas.

The preparation phase implies that the whole relief chain is preparing for the catastrophe, both strategically and operationally. In this phase, the emphasis is on capacity building, inventory replenishment, and preparation of transport means so it can be efficiently mobilized in times of crisis (Wagner, 2022). Many parties coordinate through lessons learned (with previous experiences) and design development. Technology, information, logistical, and other resource engagements are required for this stage to eradicate the consequences of disasters.

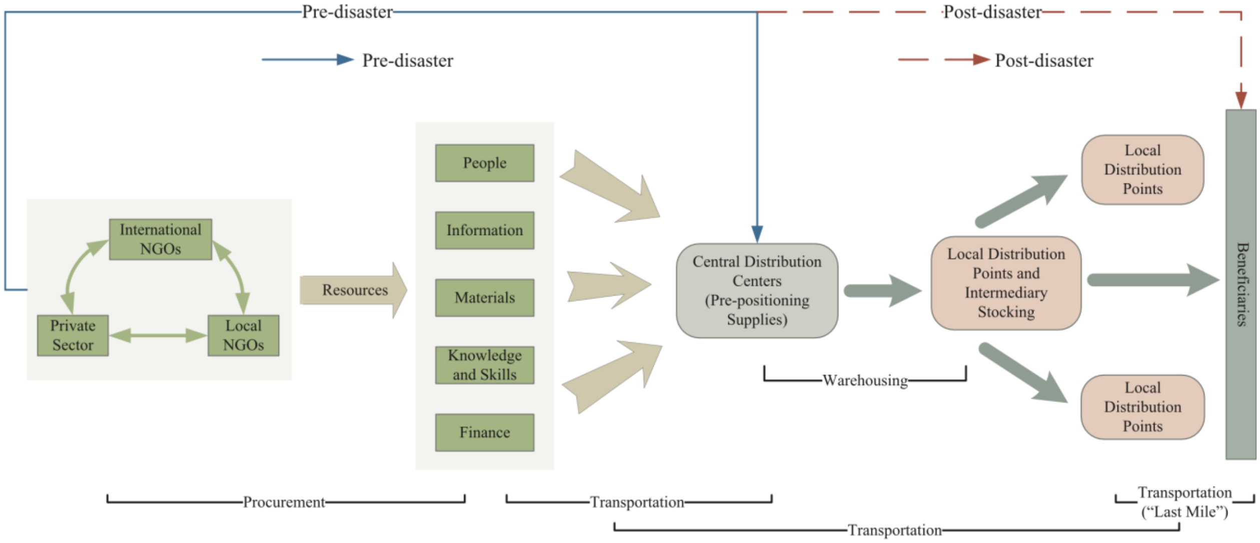
During the response phase, logistics operations are predominantly focused on meeting urgent needs and reaching the beneficiaries as fast as possible (Ehsani et al., 2023). Life is of paramount importance for humanitarian logistics when a disaster occurs. Thus, speed of actions and operations plan implementation are essential.

The recovery phase refers to the period after disaster response, where beneficiaries can still need assistance and goods like water, food, and medicine. After the response phase, this phase is a bit slower and can last longer due to the activity characteristics that require delicate work (Medel et al., 2020). The focus of this phase is long-term recovery and bringing life back to normality, restoration, and development.

In a disaster situation, multiple parties such as governments, donors, humanitarian organizations (or NGOs), aid agencies, military units, and other companies are involved. Thus, the government may support the transport of goods donated by another party. (Fathalikhani, 2020). On the other hand, the military of a country may support in terms of improving damaged infrastructure and transport of patients or medical assistance to the victims. Thus, various actors, processes, and phases make the humanitarian relief chain extremely complex (Oloruntoba & Banomyong, 2018).

Figure 1 depicts the complexity of the humanitarian relief chain structure.

Figure 1. Humanitarian relief chain structure.



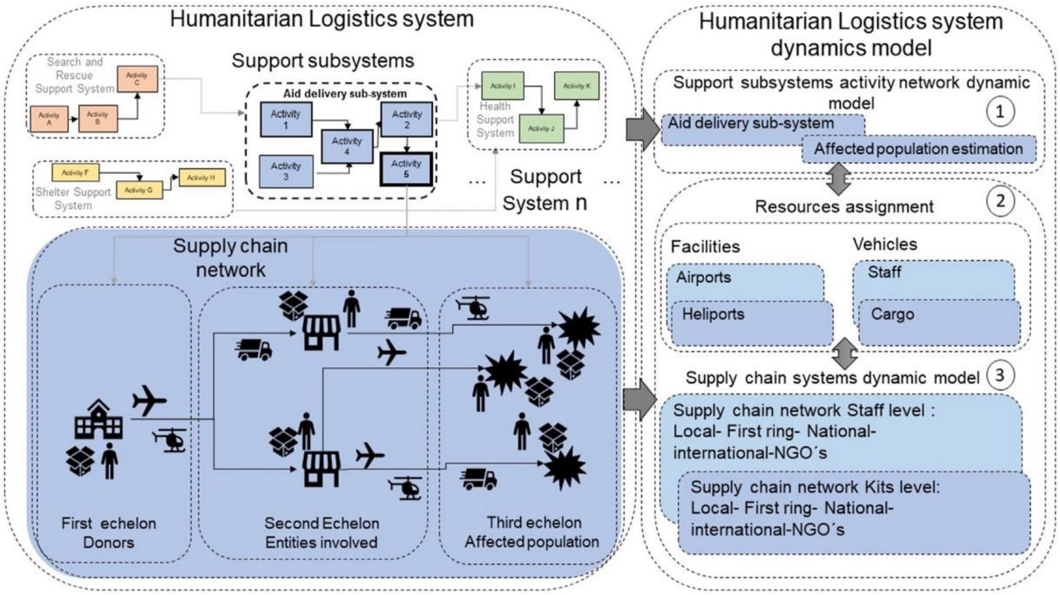
Source: Cooperative maximal covering models for humanitarian relief chain management (2018).

Humanitarian logistics can be broken down into several key subsystems, each playing an essential role in the overall supply chain and response efforts during emergencies.

The main subsystems typically include (Goor et al., 2003; Kovács & Spens, 2007; Altay, 2008):

- Transportation: Efficient movement of goods and people is crucial. This subsystem includes the selection of transportation modes (air, land, sea) and routes to deliver supplies to affected areas.
- Warehousing and Storage: Proper storage facilities are essential for managing relief supplies before they are distributed. This includes warehousing for pre-positioning materials and ensuring that items remain in good condition.
- Inventory Management: Keeping track of available stocks, forecasting needs, and managing supplies to avoid both shortages and waste is vital for effective logistical operations.
- Distribution: This subsystem focuses on the delivery of humanitarian aid to end-users or beneficiaries, ensuring that the distribution process is fair, efficient, and meets the needs of the affected population.
- Information Management: Effective communication and data management systems are critical for coordinating responses, tracking shipments, and sharing information among stakeholders.
- Coordination and Collaboration: Humanitarian logistics often involves multiple organizations and agencies (governmental, NGOs, and international organizations). Ensuring effective communication and coordination among these entities is essential for a unified response.
- Monitoring and Evaluation: Assessing the effectiveness and efficiency of logistics operations is important to improve future humanitarian responses. This includes gathering feedback and evaluating the outcome of logistics activities.

Figure 2. Humanitarian Logistics subsystems.



Source: A simulation approach for collaborative humanitarian aid distribution management: the case of Bogotá city (2022).

Humanitarian logistics subsystems are crucial because they ensure adequate organization of logistics activities. Moreover, through subsystems, the parties involved better understand processes and their roles in the whole relief chain. Also, improving the evaluation and tracking of processes is possible, making it easier to identify their shortcomings.

3. Optimization methods

Optimization methods are tools used by logistics companies or humanitarian departments to enhance aid delivery during crises. In a humanitarian context, resources are limited, demand is unpredicted, a fast response is imperative, and human lives are endangered. Therefore, the optimization methods and models target the unique challenges and help practitioners create adequate strategies and operational plans (Rodríguez-Espíndola et al., 2023). Additionally, the process of providing solutions needed for a decision is much faster.

Here are some optimization methods for relief operation challenges (Alem et al., 2016; Yang et al., 2024; Faiz et al., 2024; Xue & Xiong, 2024; Sun et al., 2022):

1. Robust and Stochastic Optimization
2. Heuristic and Metaheuristic Algorithms
3. Inventory Management Models
4. Game Theory and Collaborative Optimization

These methods can be used as a single solution or combined to create a solution through a multi-modal approach. However, the type of method to be used depends on the circumstances in the humanitarian operation area. By using those methods through computer systems, humanitarians can find the best solutions for a certain problem. Hence, the whole humanitarian logistics operates as efficiently and effectively as possible.

3.1. Robust and Stochastic Optimization

Robust optimization provides logisticians with a wide range of possible future scenarios, which ensures that decision-makers choose the most suitable option. This method usually (but not always) assumes that we do not know the distribution (Wang et al., 2023). In robust optimization, because the probabilities are unknown, other measures are optimized. Common measures are to optimize the worst-case outcome (minimize the maximum cost, maximize the minimum profit), sometimes over only a subset of the possible scenarios (Ben-Tal et al., 2011). The optimization includes planning for transportation routes that can be used despite the destruction of road infrastructure or selecting warehouse facilities that can function even in affected areas. Solutions are usually derived using optimization techniques that ensure robustness, such as min-max formulations and linear programming (Sze et al., 2017).

Stochastic optimization models are used with many random variables when it is necessary to obtain optimal solutions based on the probability distributions of unstable parameters such as demand for aid, transportation times, and the availability of resources. (Bozorgi-Amiri et al., 2013). In stochastic optimization, the goal is usually to optimize the expected value of the objective function (min expected cost, max expected profit). One common method is scenario-based stochastic optimization, where different possible scenarios (varying levels of disaster impact) are generated and used to find solutions that perform well on average across these scenarios (Niknam et al., 2012).

Stochastic optimization often involves two-stage or multi-stage models (Lian et al., 2024). In a two-stage model, decisions are made in two steps:

- First Stage: Decisions are made before the uncertainty is realized.
- Second Stage: Adjustments are made after the uncertainty is realized.

Multi-stage models include more than two stages, usually if a disaster has more stages or causes another disaster, which requires many optimizations on short notice.

3.2. Heuristic and metaheuristic algorithms

Heuristic algorithms are designed to choose the options that are best in a certain step, go from one solution to another, examine it, and exclude certain solutions as inadequate. In case it is not possible to find the best solution, then it is possible to find a good solution, like Greedy Algorithms and Local Search (Bruni et al., 2018).

Metaheuristic optimization algorithms give an efficient and effective way to optimize solutions for complex relief problems. They use more variables and more advanced techniques than heuristic algorithms. Thus, they are needed in situations where traditional optimization methods are not good enough, like Genetic Algorithms and Simulated Annealing (Hosseini et al., 2014; Liu et al., 2024), where it’s possible to base a search on imitating processes from nature.

3.3. Inventory Management Models

Inventory control is the process or action taken to ensure that the inventory of relief goods is properly maintained and managed. It enables organizations to meet sudden demands without delay while lowering the cost of holding and storing items. It's very significant in ensuring that the right amount of supplies is available at the right time and in the right place. Inventory management in a humanitarian context is very complex, where demand is unstable and unpredictable, warehouse capacities are limited, and relief goods deployment is urgent.

Inventory Management Models are (Liu et al., 2020; Qi et al., 2023; Raa & Aouam, 2023):

- Pre-Positioning Models – This means to stockpile relief supplies at strategic locations, ready for deployment when a disaster occurs and the demand arises.
- Push Models – Relief supplies are positioned in local warehouses within disaster areas based on calculations and forecasts.
- Pull Models – Relief supplies are stockpiled in central warehouses and deployed to disaster zones when a disaster occurs.
- Stochastic Inventory Models – These models are used for unpredictable situations to optimize sufficient inventory and minimize costs.

It's important to efficiently utilize inventory levels, ensuring the adequate allocation of relief items. Moreover, it is also possible to constantly monitor the level of stocks and real needs in the affected zones and to implement a quick response to the emerging situation.

3.4. Game Theory

The goal of Game theory optimization is to analyze the relationship and interactivity between stakeholders, such as governments, NGOs, and private organizations, in environments characterized by limited resources and unpredictability. Game theory can provide optimal strategies for better utilization and distribution of limited resources (food and medical supplies) among organizations horizontally and vertically (Sun et al., 2022).

There are two types of Games (Diehlman et al., 2021):

- Cooperative Games: Stakeholders (players) collaborate with the same objective to complete the task. They can share warehouse or transport capacities or any other activity.
- Non-Cooperative Games: Stakeholders (players) operate independently with their separate objectives. Often, resources are limited, and there is competition among stakeholders.

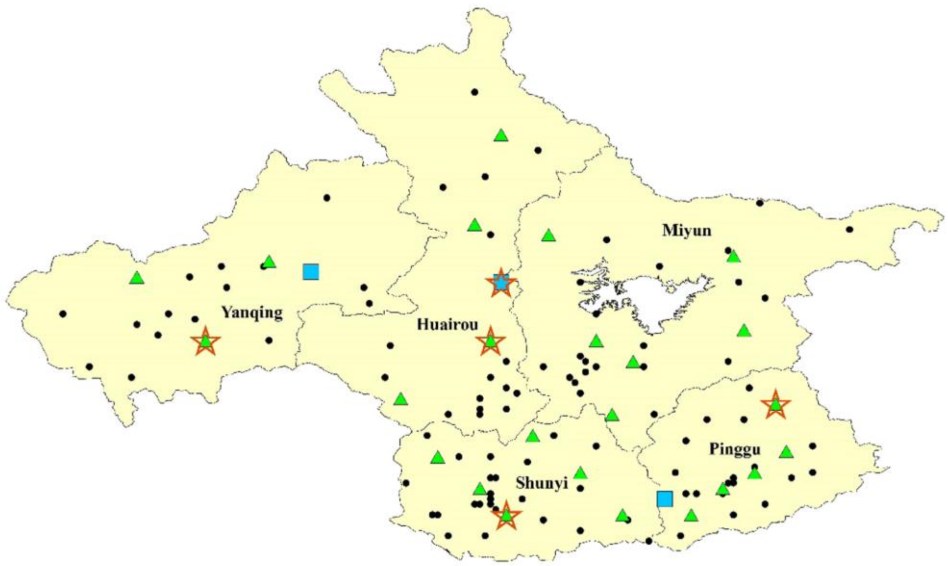
Game theory shows the potential for cooperation by quantitatively showing the effects of cooperation in humanitarian operations. When applied to humanitarian supply chain coordination, game theory can significantly improve efficiency, reduce costs, and optimize outcomes.

4. Optimization methods implementation

In this part of the work, examples of the use of optimization methods from the existing literature will be listed. The most optimal solutions for given problems will be seen through examples. By using software, many alternatives that are available to decision-makers are created, which shortens the time necessary for decision-making. All subsystems can be optimized individually or together.

In Figure 3, we see an example of using the software to optimize the location of warehouses in the territory of northern Beijing in case of flooding. Also, the position of potential locations where warehouses of several categories, from regional to local, can be located. The circles represent the demand nodes, the triangles represent the second-level warehouses, and the squares represent the first-level warehouses (Chen et al., 2016). Stars represent the optimal solution made by the software, which means there is only one first-level warehouse and four second-level warehouses.

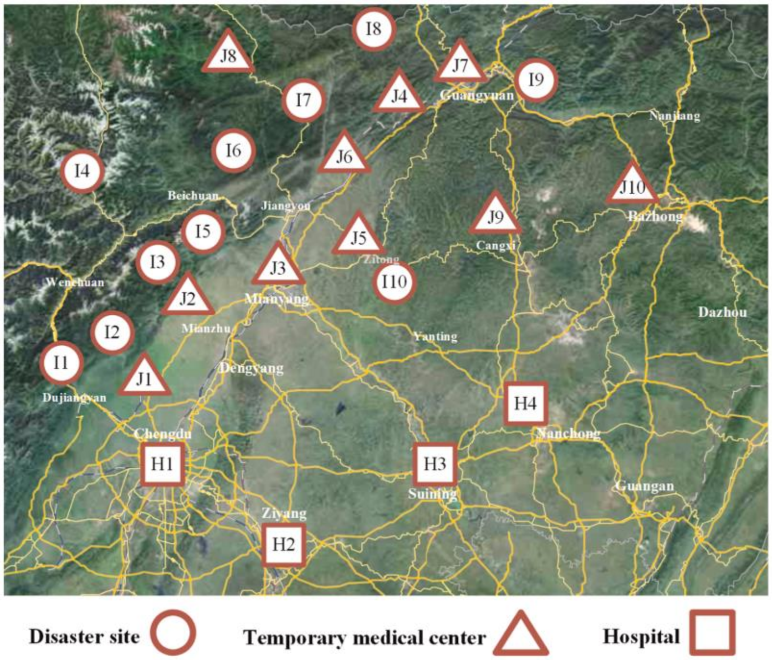
Figure 3. Optimal emergency supply warehouse locations for the Northern Beijing example.



Source: The regional cooperation-based warehouse location problem for relief supplies (2016).

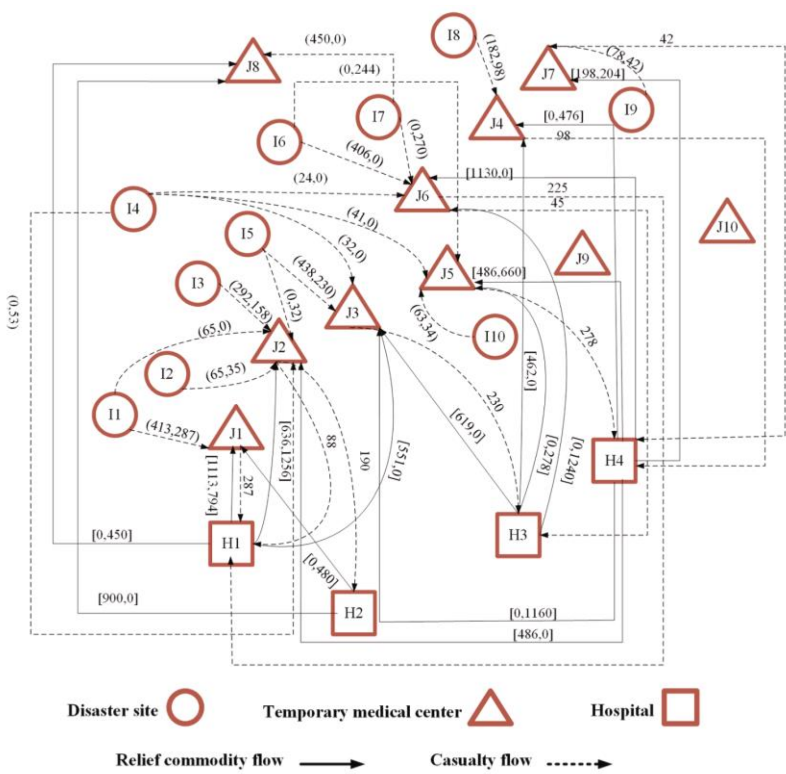
In the following example, it shows an earthquake-hit region with many aftershocks and secondary disasters. Within Figure 4a, I1-I10 represent the disaster sites, J1-J10 indicate the candidate temporary medical centers, and H1-H4 denote the candidate hospitals (Sun et al., 2022). Through optimization, it is necessary to determine where medical equipment, medicine, and casualties will be transported. Temporary medical centers are shown in usable condition, without major damage, as well as hospitals that are outside the epicenter.

Figure 4a. Map of disaster sites, candidate temporary medical centers, and candidate hospitals.



Source: A novel scenario-based robust bi-objective optimization model for humanitarian logistics network under risk of disruptions (2022).

Figure 4b. Decision results under nominal values.



Source: A novel scenario-based robust bi-objective optimization model for humanitarian logistics network under risk of disruptions (2022).

Figure 4b shows the result of the movement optimization of necessary humanitarian goods and disaster victims. In this scenario, eight temporary medical centers and four hospitals are opened with given resources and capacities. The lines visualize the flow of relief supplies and casualties between key points or locations in a disaster scenario.

5. Conclusion

The success of any humanitarian logistics operation depends upon how short the gap is between its preparedness and response in meeting challenges of food and medical insecurities and other humanitarian issues faced by the displaced population. The success, speed, effectiveness, or failure of each completed or ongoing operation is to be taken as a learning curve that should help humanitarian logistics organizations perform better and faster in the future.

Generally, the processes unfolding when a disaster occurs depend a lot on the current situation in the disaster area. However, possible outcomes should be anticipated and forecasted in the preparation phase through optimization methods and algorithms. Therefore, optimization methods play a crucial role in improving the planning, execution, and adaptability of humanitarian logistics, leading to more effective and timely aid delivery in crises. Hence, through humanitarian logistics practices like demand forecasting, flexibility, and risk management, humanitarian organizations can optimize their operations and make a lasting impact on the beneficiaries’ lives.

6. Literature

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