OR/MS STUDIES ON POST-DISASTER STAGE RELIEF ITEM LOGISTICS: COMPLEMENTARY REVIEW

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ABSTRACT

This study aims to make a complementary review of recent relief item logistics researches on the post-disaster stage, trends and practical solutions on humanitarian supply chains (HSC) post-disaster stage, focusing on gaps and future research directions. The paper provides a definition of HSC and its stages; emphasizes its difference from a commercial supply chain; then continues with a presentation of a post-disaster HSC map. Then, based on an updating literature review and evaluation of ongoing studies, concludes with main findings and gaps, and suggestions about future research directions. The article serves as an update on previous literature reviews in humanitarian logistics. Our analysis shows that there are still considerable gaps in practical applications; in the incorporation of vulnerability and safety aspects of relief item distribution such as robbery and despoliation; in the effects of dynamic road availability updates; in multi-period, multi-level, and multi-objective relief item distribution; in the considerations of social costs; in the incorporation of human behavior; and in the needs of cross-services.

Keywords: Relief item distribution management; Disaster management; Humanitarian supply chain; Disaster-relief supply chain; Humanitarian logistics; Uncertainty in disaster management.

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1. INTRODUCTION

The recent natural disaster event of Typhoon Haiyan hitting the Philippines provides us with the most recent humanitarian assistance status of the world’s preparedness. Caroline Séguin, an emergency coordinator of Médecins Sans Frontières (Doctors Without Borders) in the Philippines, states that the logistical challenges became apparent soon after she arrived at the disaster scene. To provide a summary of her observations, we can give a list of obstacles: Bad weather conditions hampered the relief efforts. There were road blockages with debris. It is hard to bring staff and supplies in by plane, as the Filipino military was given priority. Evacuating people and the wounded from the disaster areas was hard. There was congestion due to the influx of aid as soon as commercial and private flights resumed. Alternative transportation modes like water transportation took 30 to 40 hours to reach the affected areas. There was a lack of infrastructure necessary for unloading and warehousing the massive amount of cargo. Also, the fuel problem and fuel supply efforts to be brought from neighborhood areas via lifeboats posed another problem. Hospitals had to perform surgery and cesareans without sterilization. They also experienced medication shortages including antibiotics. Diarrhea was on the rise due to the unhygienic conditions and lack of access to clean water. Aid concentrated on a region while there was almost no assistance in places just a few kilometers away, including a lack of medical posts. 5,800 displaced families went without shelter, water or food for survival. There was an overwhelming need for mental health services in such an apocalyptic situation, and so on. On the other hand, a growing, but unorganized volunteer service of the Filipino people did the lion’s share of the relief work [1].

We see that there are key challenges that differentiate emergency logistics planning from the business logistics planning, i.e. additional uncertainties, complex communication and coordination [2]. Mutual aid coordinator Kim Ketterhagen states that disaster logistics consists of elements such as coordinating with the staging effort, accountability, the rehabilitation section, and the resources unit [3]. It is harder to achieve efficient and timely delivery, and limited resources are often overwhelmed by the scale of the situation [4], [5]. No society is immune to the risk of disasters [6]. However, we still have the chance to decrease the adverse effects to some extent by taking adequate measures for the three stages of a disaster: pre-disaster stage, response stage, and post-disaster stage.

A mutual interest has recently emerged on disaster-related research areas. One of the approved ways to manage these stages is the use of Management of Science (MS) / Operations Research (OR) applications in the fields of humanitarian operations, humanitarian logistics or disaster management. Especially private sector logistics problems with disaster management have been widely researched in the field of OR and MS [7].

‘The most deadly killer in any humanitarian emergency is not dehydration, measles, malnutrition or the weather; it is bad management...’ John Telford, former senior emergency preparedness, and response officer, the United Nations High Commissioner for Refugees [7].

There are many research field opportunities; however, highly complicated challenges in the design of humanitarian logistics networks are faced[8]. Uncertainty may have the lion’s share. We anticipate disasters to be uncertain, low frequency and high impacted events, but also, we observe disasters which strike some regions with a high frequency, thus leaving a predictable pattern. For example, Turkey experienced earthquakes of a magnitude over 5.0 each year between 1900-2013 [9]. Serious floods were observed in Vietnam and the Philippines every year between 1999 and 2005; more than thirty hurricanes hit Central America and the Caribbean in 2005; more than 1000 tornadoes hit the United States every year [7]. It is uncertain, but still predictable to an extent. Challenges in logistics play a critical and vital role in preparedness of disaster-relief activities. Effective preparedness in a supply chain depends on a cost-efficient, optimized allocation of resources. For example, locating distribution facilities and routing vehicles may both weigh equally. Huang et al. discuss the operation research models for vehicle relief routing and distribution of resources regarding efficiency, equity and efficacy, and how these approaches influence the nature of problem modeling [10]. Zhan et al. conducts a similar study addressing a multi-supplier, multi-affected area, multi-relief, multi-vehicle, and multi-objective relief allocation problem in disaster relief logistics [11]. On the other hand, Wilson et al. show that if prediction based optimization models are used, it may be beneficial to leave the routing decisions to the responders to determine themselves, assuming that they can share knowledge and learn together. They claim that selecting routes autonomously provides higher performance despite the high uncertainty in travel time predictions [12]. Similar insights may open future research focus area to investigate routing optimization model decisions.
We can categorize the types of issues under two parts: The supply chain management and the operational issues. While funding, needs assessment, requirements planning, procurement, information management, coordination issues, transportation infrastructure, and network design and standardization of relief are under the supply chain management issues; the execution aspect of the business, like resource allocation, transportation planning, scheduling and routing under constraints can be gathered under the operational issues.

2. IMPORTANCE OF THE POST-DISASTER STAGE IN A HUMANITARIAN SUPPLY CHAIN (HSC)

We deal with preparedness on the pre-disaster stage, with responsiveness on the response stage, and with recovery on the post-disaster. Those stages provide the continuity of the emergency management. Emergency logistics can be defined as the process of planning, managing and controlling the flow of resources to provide relief to affected people [4]. Among these processes, the importance of expert planning outweighs. During emergencies, many integrated logistics firms and aid organizations face challenges on relief items and personnel distribution, transportation and planning processes. These organizations have complex logistics structures in their supply chains. The USA Federal Emergency Management Agency (FEMA) has seven main components in their supply chain, each with different responsibilities and/or dynamic locations to manage. For a picture depiction and a simplified structure of FEMA, the reader can refer to Afshar and Haghani’s research [6]. As another example, the Republic of Turkey’s aid organization, Disaster & Emergency Management Presidency (AFAD) has seven main and thirty supplementary components in their supply chain [13].

If we assume that governments or assigned national authorities act as the main responsible foundations on HSCs for the post-disaster stage, a dynamic supply chain map of that foundation can be depicted as in Figure 1 and Figure 2. The reason for the term “dynamic” is that the post-disaster stage can be separated into two different periods: Immediate Post-Disaster Period and Long-Term Post-Disaster Period. Interviews have been held with national aid authorities’ planning departments such as AFAD, and according to the subject matter expert point of views, these two periods can be defined as follows:

**Immediate Post-Disaster Period** is the period when the response stage has just been completed, and demand for immediate action emerges. It may involve chaos and a unique set of problems. After an earthquake event, victims who are under debris and need first aid and vital nutrition like water, debris cleanings on road blockages are the primary demand source. Shaving priority. This period’s length may change according to the intensity of the disaster, and is highly dependent on the level of preparedness. The demand of critical needs products which are essential to the survival of the population including vaccines, medicine, food, water, should be met as nearly as possible [14]. The focus company or foundation in an HSC makes agreements with its suppliers and manages primarily the debris/disaster site, fulfilling relief-item and emergency health requisite demand at this phase [15] (Figure 1).

**Long-term Post-Disaster Period** is the period when the immediate post-disaster period comes to an end. Chaos and the first impact are settled. It lasts until the full recovery is completed. The main operations on this phase may involve debris cleaning, maintenance, restoration of network connectivity, construction and other logistics operations to recover from the effects of the disaster. This period’s length can change according to the intensity of the disaster, and may take years to a decreasing awareness level. The focus company or foundation makes agreements with its suppliers and primarily manages the construction process, network connectivity and utility services (electricity, water, gas supply) restoration at this phase. If we illustrate this period for the HSC, it can be said that in the long run, demand side tier one and two switches in each other and creates a time-dependent dynamic supply chain map (Figure 2).

The connecting lines and arrows of the above illustrated HSC maps describe the types of management and monitoring within the focus company and its tiers. The directions of arrows (← / ↔ / →) stand for the direction of the management and relations. The solid lines (—) stand for the processes that the focus company directly manages and deals with, while the dashed lines (→ - → -) show the processes which the focus company only monitors. The weight of the lines (↔ / ↔ / ↔) shows the level of management or monitoring, scaled from low to high increasing the thickness.
Figure 1. Immediate post disaster period of HSC (Source: AFAD – Istanbul, Turkey)

Figure 2. Long-term post disaster period of HSC (Source: AFAD – Istanbul, Turkey)
The HSCs consist of one focus company (foundation) and six basic tiers. The number of these tiers can increase depending on the supply chain’s size. The left-hand side of these tiers is the supply levels, and the right-hand side is the demand levels. Apart from commercial supply chains, an HSC’s main supplier is the donor, and they are different in nature [16]. While commercial supply chains deal with profit maximization, HSCs are concerned with beneficiaries’ satisfaction [17]. Governmental budgets are allocated to maintain this supply chain along with the media support, Non-Governmental Organizations (NGO), and military involvements. However, those budgets are redirected to the third-party national humanitarian agencies to be maintained. The potential roles of logistics service providers in HSCs are deeply investigated in an exploratory study [18]. If we accept ‘money and volunteer services’ as the raw material of relief supply chain, by properly allocating the raw material, the tier 2 suppliers, namely the humanitarian agencies, plan, manage, and monitor the tier 1 operational service providers who are the third-party logistics and operations firms. Although companies do not have a direct relation with the focus company, their relations with the demand tiers are strictly monitored. While having a direct effect on the end customers (demand tier 3), namely the citizens, the focus company also has an indirect connection with tier 3 demand sources by the help of that tier 1 supplier firms.

Once the disaster strikes and response stage starts, the first period of the post-disaster stage begins. At this period, the focus company concentrates on vital demands instead of demands with low and long-term priorities. Subject matter experts in emergency management state that approximately three days following the earthquake has the utmost importance regarding relief efforts, as after three days, the probability of saving a trapped person alive decreases radically [19]. Disaster/debris site, health emergency, search and rescue, and relief-item demands are the prior demand sources right after the disaster stroke; therefore, they have positioned as the tier 1 requirements in the supply chain and are handled in the first place for a limited and uncertain period. Then, the long-term post-disaster period starts by switching the first and second demand tiers. The old tier 1 demands are positioned at tier 2 instead. Demands like connectivity network restoration, utility services demand (water, electricity, gas, phone) are fulfilled in this period while tier 2 demands are also continued to be handled, but with a lower priority. This change creates a dynamic supply chain, and this dynamism is better dealt with by decision-making processes using appropriate OR/MS approaches.

Recent OR/MS researches focus on incorporating such attributes to the supply chain optimization efforts to create more robust models. In the following sections, investigations of researches, trends and future directions on relief item logistics are narrated with a complementary review based on the most recent literature reviews.

3. A NARRATIVE LITERATURE REVIEW: WHAT HAS BEEN DONE SO FAR?

In our research, we conduct a narrative literature review methodology to provide the reader a comprehensive background for understanding current knowledge and to highlight the significance of new research. Focusing mostly on quantitative researches, we scan the ABI Complete, Web of Science, EBSCOhost, Google Scholar, ScienceDirect, TRID Online, Compendex and DTIC Online databases. The keywords of our interest are relief item distribution, distribution management, disaster management, humanitarian supply chain, humanitarian logistics, disaster, disruption, uncertainty in disaster management, uncertainty in HSC, stochastic HSC, disaster-relief supply chain, time-phased supply chain, multi-period supply chain, modular supply chain, and multi-echelon supply chain.

In the previous sections, the importance of an need for operational and practical research on HSC post-disaster stage relief item logistics is urged. Along with the exploding OR/MS researches in humanitarian logistics field in the recent years, the high rate of updating reviews in the field is preserved (Figure 3). We base our study on the existing reviews, and we try to avoid repeats of already examined papers. Instead, we conduct a complementary and updating study.

![Figure 3.OR/MS reviews related to relief item and emergency logistics](image)

From 1980 to 2006, humanitarian research focuses on social sciences, especially on disaster results, sociological and psychological effects, communication, collaboration and planning problems. Studies and the latest improvements are covered by Altay and Green [20] until 2004, and by
Kovács and Spens [21] until 2005. In 2013, the continuation of Altay and Green’s study was held by Galindo and Batta covering timeframe of 2005-2010, to evaluate how OR/MS research in disaster operations management has evolved in the last years and to what extent the pointed gaps have been covered [22]. The period after 2006 through 2015 is re-examined with either by complementary or comprehensive approach (Table 1). Nevertheless, our main focus about the post-disaster stage of HSCs is the operational and practical improvements on disaster relief distribution researches after 2006. The remarkable gap analysis on humanitarian logistics education and its derivatives are held out of scope [23]. We regret that we cannot cite all available papers due to space limitations.

Table 1. OR/MS reviews related to relief item and emergency logistics

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<tr>
<th>Reference</th>
<th>Scope</th>
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<tbody>
<tr>
<td>[24]</td>
<td>emergency evacuation</td>
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<td>[25]</td>
<td>integration in emergency operations</td>
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<tr>
<td>[7]</td>
<td>researches on disaster relief logistics challenges</td>
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<tr>
<td>[20]</td>
<td>OR/MS research in disaster operations management, and a meta-analysis</td>
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<tr>
<td>[27]</td>
<td>a systematic review of contributions on relief distribution networks</td>
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<td>[2]</td>
<td>challenges in coordinating humanitarian relief chains</td>
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<tr>
<td>[28]</td>
<td>efficacy of different asset transfer mechanisms on HSCs</td>
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<tr>
<td>[29]</td>
<td>content analysis, optimization models in emergency logistics</td>
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<tr>
<td>[30]</td>
<td>analysis of the use of OR models from the perspective of both practitioners and academics</td>
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<tr>
<td>[31]</td>
<td>challenges faced on HSCs and use of operation research tools</td>
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<tr>
<td>[22]</td>
<td>continuation of [20] with the evaluation of to what extent the gaps have been covered, and a meta-analysis</td>
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<td>[32]</td>
<td>use of social costs on the objective functions of post-disaster humanitarian logistics models</td>
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<tr>
<td>[33]</td>
<td>OR models with some stochastic component applied to Disaster Operations Management</td>
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<tr>
<td>[15]</td>
<td>findings of post-disaster waste management strategies and challenges identified in Sri Lanka</td>
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<td>[21]</td>
<td>humanitarian logistics in disaster relief operations</td>
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<tr>
<td>[23]</td>
<td>analysis on humanitarian logistics education and its derivatives</td>
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<tr>
<td>[34]</td>
<td>characteristics of the existing literature on existing humanitarian logistics</td>
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The number of papers per journal distribution of the studies investigated is also presented in Figure 4. Apparently, Transportation Research Part E: Logistics and Transportation Review, European Journal of Operational Research and Computers & Operations Research emerge as the top three journals preferred in the field of post-disaster stage relief item logistics between the years of 2006 and 2015.

Figure 4. The journal-paper distribution of the studies investigated in 2006-2015

The publications can be classified in four operational stages of disaster management: mitigation, preparedness, response and recovery [31], [42]–[45]. Among them, the majority of the research concentrates on the mitigation stage whereas the minority is gathered on the recovery stage, namely, the post-disaster period[20], [22]. Özdamar and Ertem conduct a survey which...
focuses on the models and solution methods for response and recovery planning phases of disaster lifecycle. They discuss the integration of present models and solutions into information systems [37]. Methodologies used in the research are not limited to but mainly consist of mathematical programming, probability and statistics, simulation, decision theory and multi-attribute utility theory, queuing theory, fuzzy sets, stochastic programming, expert systems and artificial intelligence, systems dynamics, constraint programming, and soft operational research techniques. Mathematical programming, including heuristics, is the most frequently used method [20], [29], [31].

Mitigation can be defined as the precautions and set of measures not to be affected, or to relieve the impacts of a sudden disaster. Preparedness consists of community activities to be able to provide a timely and adequate response to a disaster. Response phase consists of the application of planned procedures and cost-effective resource allocations to sustain the human life, the property, and the environment. Finally, recovery involves the short term and long term actions to pass through the normal life conditions and stabilization.

According to the Altay and Green study, the phase which has scarce resources regarding operational research is the disaster recovery phase with a rate of 11%. About 44% addresses mitigation; preparedness and response come with 21.1% and 23.9%, respectively [20]. Ergun et al. also describe the main characteristics of disaster supply chains; highlight particular issues associated with these; and illustrate how operations research tools can be used to make efficient decisions [31]. The analysis on how operations research models are used in the transportation of relief goods and routing of vehicles is presented by de la Torre et al. through interviews and publications of aid organizations and literature reviews [30]. This analysis is important as it provides the perspective of both practitioners and academics. They classify their review under four different titles: 1) Objective functions which involve minimizing the cost, the unsatisfied demands, the latest arrival, the total response time, or maximizing the total transportation reliability, 2) Goods involving stochastic supply and demand, or multi-commodity constraints, 3) Routing involving multiple/single/no depot and the use of heterogeneous/homogeneous vehicles, stochastic travel time, and 4) The selection of test data whether it is taken from real disasters or not. One of their findings is that multi-period routing has not been modeled in the relief routing literature, yet. Also, when planning future routes, uncertainty in the availability of vehicles, supply and demand can be a challenge as they have only been modeled in two-stage stochastic programming models for the single period of routing.

Cauhnye et al. break down the optimization efforts of the period after 2006 into three parts classifying them according to whether they consider disaster operations performed before or after the impact of a disaster: facility location, relief distribution and casualty transportation, and other operations [29]. They leave post-disaster evacuation out of scope as Abdelgawad and Abdulhai deeply reviewed this field of study [24].

State-of-the-art reviews show that the post-disaster and recovery period OR/MS research on logistics originate from key questions seeking an answer for practical needs of real life problems. Some of them are presented in (Table 2).

<table>
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<th>Table 2. OR/MS research question examples for the post-disaster phase</th>
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<tr>
<td>• How should be the debris cleanup prioritization operated?</td>
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<td>• What is the best allocation of individual and governmental funding on recovery operations?</td>
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<td>• What are the best locations appropriate for sheltering with the support of water, transportation, electricity, sewage utilities? How many shelters should be planned?</td>
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<tr>
<td>• What is the best location of emergency response stations for debris removal, maintenance, restoration and preposition supplies, roads, bridges and key facilities, and what should be the reliability level of those?</td>
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<td>• How vulnerable are the transportation arcs, transportation modes, and hub facilities?</td>
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<td>• What is the best location for a war room with clean control and structure? (If it is located close to the disaster area, the war room can be affected; if it is located far from the disaster area, it may lack logistics support)?</td>
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<td>• What is the best scheduling of the full restoration of lifeline services?</td>
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<tr>
<td>• If we separate the post-disaster phase into two distinct phases like ‘immediate post-disaster’ and ‘long-term post-disaster’, what should be the durations of each?</td>
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<tr>
<td>• How does uncertainty affect the locations of the HSC facilities and transportation decisions?</td>
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<tr>
<td>• Do we need additional hubs for a dynamic environment to operate temporarily in case of disasters, how many should they be, and where should they be located?</td>
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One of the significant challenges in disaster management is uncertainty. Although predictability, response capacity, coordination and accountability
in emergency and disaster management have been strengthened with ongoing international efforts like the United Nations Cluster Approach [26], [46], [47], uncertainty still differs HSCs from the commercial and military supply chains [48]. Almost every event emerges in a spontaneous pattern, and this pattern is tough to be foreseen. Therefore, literature has interests in uncertainty. For urban flood emergency type disasters, Chang et al. develop a decision-making tool for logistics preparation planning problems under uncertainty [49]. By applying data processing and network analysis functions, they present two stochastic programming models to estimate the possible locations of rescue demand points and the required amount of rescue equipment. On the optimal inventory level decision of disaster relief supplies, Lodree and Taskin propose an insurance model, incorporating classic newsvendor variants regarding demand uncertainty as well as the uncertainties brought by the event’s nature. The difference between the optimal level and newsvendor solution has been evaluated as the insurance premium, to provide decision makers a practical approach quantifying the associated risks and benefits [50]. Similar to this study, Campbell and Jones are interested in modeling the uncertainty of potential hazards to determine appropriate inventory levels of prepositioning supplies and where to locate them, assigning a probability of destruction to the supply points. They provide a sensitivity analysis on the critical ratio by changing multiple parameters on a single and multiple supply point model. They leave out incorporating the idea that risk among supply points may be dependent and the idea of backup supply points instead of one distribution center [51]. Later, Peng and Chen compare four types of inventory planning strategies by simulating the effect of static/dynamic lead time and constant/random demand in HSC and determine the differences between commercial supply chains. They find that the random demand brings more oscillations to the supply system, while the dynamic lead time changes both the trend and the vibration mode of inventory [48]. Following this study, Peng et al. develops a system dynamics model to analyze disrupted relief item supply chain by simulation of dynamic road conditions and information delay [52]. Ozgven and Ozbay propose a multi-commodity stochastic humanitarian inventory management model (MC-SHIC) to determine optimal relief item inventory levels by the use of RFID [53]. Noyan considers a risk-averse approach in a two-stage stochastic programming model; that is accounting the variability of the risk taken [54]. Dynamic optimization problem research has been observed, too. On pickup and delivery problems, which are an extension of vehicle routing problems, a multi-stage mixed integer problem has been modeled with dynamic optimization, anticipating varying travel times and unknown orders under emergency conditions [55]. Camacho-Vallejo et al. have made the latest improvements. They propose a bi-level single objective model by considering Chile 2010 earthquake case study [56].

It is apparent that there is a need for models which fully cover an HSC relief item distribution system within stochastic, dynamic, and adaptive settings together. Barbarosoğlu and Arda study a single period, scenario-based, multi-commodity, multi-modal single objective model with a minimum cost network flow formulation. It consists of random variants like demand, supply and arc capacities and bi-level decision stages [57]. Güler and Ermiş improve this bi-level stochastic problem regarding performance, and considering the uncertainty of the first stage within the problem as well[58]. Hinojosa et al. address a simpler version of Barbarosoğlu and Arda’s problem without the consideration of capacitated transportation modes and arcs as well as some uncertain figures like supply amounts [59]. Ergun et al. suggest that the proposed models should be adaptive to incorporate new information when a change occurs. They state that in a disaster framework, information is usually limited at the beginning, but as time passes, more and more accurate information becomes available [31]. For large scale natural disasters, Sheu presents a dynamic relief-demand management model for emergency logistics operations under imperfect information conditions. According to their three-step approach, initially, the relief demands in multiple areas are forecasted with data fusion. Secondly, a fuzzy clustering is used to classify those demands into groups. Finally, prioritization is applied with multi-criteria decision making. He examines less than 10% overall forecast error on the proposed model[60]. Fuzzy clustering in emergency relief item allocation is also addressed in another study in the same year, while multi-criteria optimization for an aid distribution is modeled in 2011[61], [62]. Lately, Bhattacharya et al. have presented a study on resource and infrastructure centralization analyzing the efficacy of different asset transfer mechanisms. They also provide policy recommendations for the design of HSCs [28].

Location/allocation/distribution decision of the response phase is another challenge and is targeted in a massive amount of research. Sheu investigates efficient emergency logistics distribution of urgent relief supplies after natural disasters and presents a hybrid fuzzy clustering-optimization approach to the operation of emergency logistics co-distribution. Involving two recursive mechanisms: (1) disaster-affected area grouping, and (2) relief co-distribution determining potential advantages and disadvantages [63]. In the study presented, each
group’s time-varying relief demand is predicted using a short-term dynamic relief demand forecast model; and it is prioritized with a fuzzy-based affected-area clustering procedure for distribution scheduling. Balcik et al. propose a mixed integer programming model called last mile distribution problem; and optimize resource allocation and routing decisions on humanitarian relief supply chain [17]. Ozdamar and Demir extend the definition of this problem to include both delivery and pickups and call it the last mile delivery and pickup problem. Then, using last mile problem, Rennemo et al. propose a three-stage mixed-integer stochastic programming model for disaster response planning. With the solutions they produce, they claim that models with stochastic programming are significantly better than those of deterministic models [64]. An efficient network flow model and a parallel hierarchical optimization guided “cluster and route” procedure (HOGCR) are presented for large disaster networks with 900 nodes [65]. Some research focus only on transportation like vehicle fleet management and optimization of fleet size for disaster relief operations [39], whereas some only focus on selecting logistics center and warehouse location on humanitarian relief logistics [66], [67]. Afshar and Haghani propose a mathematical model for disaster management integrated logistics, covering vehicle routing, pick-up/delivery schedules, finding the optimal locations for several layers of temporary facilities of several capacity constraints for each facility, transportation system and equity among the victims [6]. Aman et al. also propose a resource allocation model for disaster management in the form of integer linear programming minimizing logistics demand shortage. Then they improve the model by goal programming minimizing penalty costs. They apply their formulation to the Mt. Merapi disaster [68]. To the best of our knowledge, the most up-to-date research on post-disaster network connectivity and transportation planning belongs to [69] and [70]. Nakashima et al. focus on travel demand modeling in the recovery phase for the regional communities of the metropolitan areas, whereas Tuzun, Aksu and Ozdamar present a dynamic path based mathematical model which identifies criticality of road blockages, and clears them with scarce resources for metropolitan areas. For disaster debris cleanup operations, contractor assignment is a problematic area to be addressed. Fetter and Rakes have proposed a multi-objective mixed-integer decision model for assisting decision makers in this allocation [71]. Recently, Liberatore et al. propose a planning model to put damaged elements of distribution network recovery into order to gain the maximum benefit [72].

Regarding heuristics, Yuan and Wang propose two single and multi-objective path selection models for emergency logistics management. A modified Dijkstra and ant-colony optimization algorithms are applied to solve the models [73]. Other heuristics approach developed in the field of disaster management is the genetic algorithm used by Berkoune et al. to provide faster and high-quality emergency transportation plans with near optimal solutions [74]. The same year, a two-phase heuristic approach had been given by Lin et al. to locate temporary depots and allocate disaster relief item demands by improving the same authors’ previous work, which involves longer travel distances in-between the central depot and demand nodes [75]. Barzinpour et al. work on a similar multi-objective problem considering location and allocation decisions at the same time. They solve their model using genetic and simulated annealing algorithms by providing comparison insights [76]. Recently, Wang et al. propose non-dominated sorting genetic algorithm and non-dominated sorting differential evolution algorithm to solve a model of a nonlinear integer open location-routing model for relief distribution problem [77].

A remarkable recent study has presented practical, close to real-life implementations, by Holguin-Veras et al. They address the appropriate selection of an objective function for post-disaster humanitarian models, and propose the use of social costs, which involve logistics cost and deprivation cost together to make a proper estimation of economic welfare. With numerical experiments, willingness to pay for utilities similar to water is studied as a function of constant time without regarding utility [32]. One important outcome of this study is that the single period models are not appropriate for post-disaster humanitarian logistics modeling. Nevertheless, other remarkable outcomes will be considered separately, as this study re-emphasizes that the inference of the good practice of disaster-relief item distribution is not just a matter of technical issues of planning and logistics, which is stated by Young and Jaspars in 1995 [41]. In addition to those, Hu and Sheu’s study in 2013 is in accordance with this inference, and they minimize psychological cost [78].

4. ONGOING STUDIES

Especially after 2006, studies on HSCRelief item distribution have an accelerated speed. In this section, some ongoing research efforts aiming to improve stochastic optimization methods are mentioned. As stochastic solutions consider probabilities and allow expected results rather than deterministic solutions based on strict assumptions, they are preferred in the uncertain environment of disasters.
In most disaster scenarios, the local transportation infrastructure is often heavily damaged. Alternative transportation mediums and shipping routes need to be explored. Using optimization with stochastic programming, Arslan, Hassan, Ravi, Salman and Yucel contribute to the network infrastructure strengthening investment decisions with a linear reliability order of links for the pre-disaster phase. They also incorporate their study the decisions of emergency response facility location with road network vulnerability considerations [79], [80]. Unlike most studies that assume link failure independence, they propose a novel model with dependent link failures [81]. These studies can be accepted as one step further after [57] considering investment decisions and disaster damage probabilities although their focus is not the relief item distribution.

To the best of our knowledge on conference proceedings and online open-sources, for the post-disaster emergency response phase, facility location decisions are studied by Salman and Gül. They contribute to casualty transportation along with the temporary emergency-care center location decisions. However, relief item inventory and stocking decisions, based on the newsvendor model under the assumption of lateral supply in-between emergency response agencies are studied by Salman, Karaman, and Elmaghraby. Comparisons of the current ambulance dispatching policies in case of a disaster are studied by Salman, Gel and Tanrioven [82]. Another ongoing stochastic optimization approach is on stochastic debris clearance problem, which assumes that there is limited information on debris amount on the roads. It is updated as clearance takes place, formulated by a partially observable Markov decision process model by Celik, Ergun and Keskinocak; and on debris removal during the response phase, by Kara. Finally, Kibar and Salman are working on logistics planning for restoration of network connectivity after a disaster [83].

5. MAIN FINDINGS AND GAPS

We determine that logistics is still underestimated in disaster operations, and researchers are criticizing that organizations are more concerned with fund-raising than planning.

Research on facility location problems mainly considers pre-disaster operations and is primarily based on mixed integer programs with binary location variables. They are formulated as maximal covering location models with multiple quantity-of-coverage and quality-of-coverage requirements. Formulations like p-median, p-center are not common. There are deterministic and stochastic models based on probability distributions or predefined scenarios, and almost all surveyed models are studied in a single period as their point of subject is the pre-disaster stage. The post-disaster stage is nearly out of scope, and multi-period research is scarce. Hoyos et al. state that an increasing trend to include multi-period analysis emerges recently, but there is still a reduced number of models which implement it [33]. This finding is also supported by Kunz and Reiner’s content analysis literature review stating that existing humanitarian logistics research shows too little interest in continuous humanitarian aid operations [34]. There is a lack of deterministic studies as well as stochastic single and multi-level multi-objective studies. The work on HSC research dominates the strategic decision level. However, there is a need to extend the research efforts to the other decision levels such as tactical and operational [35].

On facility location models with relief distribution and stock pre-positioning decisions, the lack of multi-objective models is apparent. Few models have considered optimizing both time and cost together. Görmez et al.’s study is an example having two objectives: The average distance traveled to serve a refugee and the number of new facilities to establish [84]. However, there are studies considering either time or cost incorporated into the model as hard constraints. Costs are regarded in terms of transportation, facility opening, expansion, equipment rental, penalties, shipping distance of rescue equipment, shortages, warehouse operations, acquisition (ordering), unmet demand and delay costs. Timewise, response time and transportation time are considered.

Along with facility location studies, the relief item and casualty transportation and distribution studies are considered. Although under real life conditions, relief distribution and casualty transportation affect each other considerably, the majority of research concentrate solely on relief distribution [1], [29]. We can classify the relief distribution and casualty transportation models based on the planning horizon, data type, and the number of levels and objectives. It is seen that there are limited studies on robust optimization model or research which uses binary variables with multi-period planning horizon, multi-objective approach and bi-level data type structure, in neither deterministic nor stochastic aspects. One can state that Sheu studies three-level, multi-period and multi-objective and stochastic models, but he prefers to use multi-criteria decision making and fuzzy logic [60], [63]. His work is based on more scheduling and doesn’t consider relief item distribution and/or allocation decisions. Another gap in this field of studies is on single-period, bi-level and multi-objective stochastic research, but as the post-disaster events
are not considered as a single period, this gap can make sense. It is noticeable that multi-period models are rarely stochastic. One of the rare studies which are stochastic, multi-period, single-objective with single level decision making belongs to Friedrich et al.’s ALLOCATE model[19]. Horner and Downs hold another study. In their research, they consider and evaluate scenarios to explore the effects of alternative goods distribution strategies on the provision of disaster relief[85]. Lejeune investigates multi-period service level (MSL) by formulating the stochastic service level constraints for the fill rate, ready rate, and conditional expected stock-out MSL policies [86]. Finally, Bozorgi-Amiri et.al. present a multi-objective robust stochastic programming approach for disaster relief logistics efforts under uncertainty. The multi-objectivity is studied with cost optimization figures and the penalization of infeasibility due to the uncertainty as well as maximization of customer service level. This study can be accepted as the continuation of their previous swarm-optimization effort for relief supply chain under expected values of uncertain parameters like costs, supply, demand and facility locations[87], [88].

Aside from the described fields above, there are various studies of interest incorporating both the pre/post-disaster stages like the comparison of disaster management capabilities versus pre-positioning relief item inventories [89], or scheduling short-term lifeline rehabilitation in the post-disaster stage [90], each serving new and unattended aspects of emergency management.

Our brief assessment is that the majority of the studies deal with the single objective and deterministic models since they are easier to solve. However, multi-objective studies are closer to the real life problems[91], as they consider conflicts of interests. Regarding objectives; distance, logistics and operation costs and response time are optimized.

6. HAVING APPROPRIATE OBJECTIVE FUNCTION FOR RELIEF ITEM DISTRIBUTION MODELS

This section comes out of the need for using an appropriate objective function on humanitarian research models and is used to provide details based on a recent research example in achieving this goal. Some literature focuses on using a single objective in models either regarding cost or time, and it may ignore the social effects of a disaster. However, the transitional stage between the immediate and long-term post-disaster periods is much more complex with its depressing effects coming with the time variable. The main cost aspect that emerges in this stage can be accepted as the depression costs originated from the victims, and it has better be taken into account. Relieving the suffering of the population increases welfare and service level performance.

For instance, we can take the distribution of water. The adverse effect of inexistence of water increases exponentially, especially if the waiting time is longer [32]. Alternatively, if a disaster happens in the winter season, the effect of the need for tents increases proportionally with time. While in a commercial environment, the primary objective is to minimize logistics costs, in a humanitarian case, human suffering, namely deprivation costs become more important and is better not to be eliminated.

An appropriate and realistic objective maybe realized if we consider deprivation and logistics costs together in a multi-objective function. This approach may go beyond the routine multi-objective modeling environments of the disaster management such as incorporating cost and time under multi-objectivity.

For a comprehensive literature review on objective functions, the reader can refer to Holguin-Veras et.al.’s cross-mark article defining social costs as the summation of logistics and deprivation costs [32]. In their study, they primarily address the cost characteristics regarding time-dimensionality. The limit value of the deprivation cost function, the point at which an individual dies after five days of deprivation, is assumed to be $5 million [92]. As delivery to all nodes is almost impossible, and as there will be some nodes left for the second delivery, the suffering and deprivation costs related to the undelivered nodes will show an increasing trend. Therefore, they emphasize the intertemporal externalities based on the core inference that optimization models built in a single period should be avoided.

This assessment rhymes with real life conditions considered in our surveys implemented in local disasters and emergency planning authorities[13]. According to the past experiences, one of the most problematic areas is the adequacy of the reliefitem supply, which is supposed to be continuously acquired as the demand emerges from lateral cities, and then from neighboring countries, respectively. It creates a time lag until all victims are satisfied.

Holguin-Veras et.al. define deprivation costs as the economic value of human suffering caused by a lack of access to goods or services, the function of deprivation time and socio-economic characteristics of the individual (e.g. age, gender, and physical condition). They expect deprivation cost to be
monotonic, nonlinear, and convex with respect to the deprivation time, and also to be hysteretic\(^1\).

Consequently, the authors focus on three key instances of penalty-based mathematical models: hard constraint, constant penalty, and variable penalty models as well as the minimization of unmet demand. Among them, they decide that variable penalty model be structurally capable of capturing required variations with some modifications. They conclude their study with some numerical examples, pointing out the practical question of empirically estimate deprivation cost functions, which is an area where further research is needed.

Similar to that objective function examination research, Campbell et al. focus on two alternative objective functions for types of TSP and VRP considering multiple vehicles and vehicle capacities [93]. Huang et al. present formulations to characterize the objective functions based on efficiency, efficacy, and equity. They provide examples to illustrate each objective's performance impact on routing solutions [10].

Therefore, it would not be right to state that one type of global objective is the right one for every case in disaster relief distribution. It all depends on the situation, and the certainty in objective may mislead the solution of research models.

7. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

We conclude that HSC relief item distribution research is fragmented; but there is no radical deviation in the path of disaster operations research direction which was pointed out by Altay and Green, 2006. There are limited studies on integrated logistics processes and cross-operations. Integration in emergency operations is a substantial need, but rather than growing organization structures, integration should be achieved by functional links within an organization [25]. As all logistics aspects are related to each other, optimization efforts, frequently result in sub-optimums. It is understandable that fragmented studies increase computational efficiency, but they ignore a comprehensive approach to the state of the problem [29].

Integrated logistics brings a multi-objective nature with it, but it is seen that the literature avoid especially multi-level multi-objective models with the view that they are difficult to solve [94]. A rare instance of multi-objective, multi-mode, multi-commodity, and multi-period stochastic model belongs to Najafi et al[95]. Moreover, if the aim is to reach a global optimum, considering multi-objectivity in terms of cost and time optimization alone is not satisfactory. Deprivation costs had better be taken into account, too.

On the other hand, coordination effectiveness in disasters, as well as the proper organization of various voluntary parties involved, can also be assessed in models. It is experienced that volunteers, survivors, and people unaffected by the disaster may join and leave relief workforces in a dynamic fashion [29]. Along with this dynamism, the practical management challenge creates another interesting objective. Najafi et al. tries to handle this challenge by proposing a dynamic model for dispatching and routing vehicles, which is capable of receiving updated information at any time and adjusting plans accordingly [96]. In summary, the lack of integrated logistics, cross-operational models, and the limited number of multi-objective models, which don’t consider inter-temporal deprivation costs, can be counted as the most attractive gaps to be focused in humanitarian studies.

Research in casualty transportation is limited. It can be expanded combining considerations such as transportation time, injury seriousness, on-field treatment, medical center service load, disruptive events, and medical center position to the disaster area effects (such as closer center, more severe injury handling).

Needs assessment is also very crucial. It is better to be realistic, and coordination is considered to be established with local disaster planning and response authorities for the robustness of the study. At the time of need assessment, volunteer organizations make periodic trips to the affected regions to conduct the assessment, but for scientific purposes, researchers are suggested to benefit from the information maps provided by the UN, the World Food Program (WFP), WHO and FEMA’s HAZUS infrastructure damage modeling software.

To cope with uncertainty, making an input analysis to find the best probability distribution to represent the old relief item supply and demand, or generating randomized event scenarios is preferred. Human behavior can also be incorporated into the models. Local authorities report that victims of disasters move between disaster areas to reach better supplies, or to run away from epidemics causing fatalities, creating a new aspect of uncertainty. To incorporate the multi-level decision-making process, conducting a two or three-stage distribution depot allocation system, considering dynamic and mobile distribution centers may add value to research and rhyme with

\(^{1}\)Hysteretic: retaining a memory of past processes
stochastic approaches. Also, truck networks can be opened to new voluntary trucking services; abandonments and fleet capacity can be changed accordingly. Time spent in the distribution points can also be incorporated into the models. Therefore, in addition to the uncertainty originating from the supply and demand, another uncertainty effect is added to the model providing a more realistic approach.

The vulnerability of the easily sold goods such as food and water despoliation can be incorporated into the models. Safety has not been modeled yet. Drivers in Haiti in 2010 drove non-stop for any reason due to such bad security conditions. Moreover, in New Orleans, after reports of violence, many drivers abandoned the disaster relief distribution task. Conveying can cause delivery delays, and the need for local drivers can create an additional constraint. Another aspect of vulnerability is the availability of roads a vehicle can travel. Many times, the vehicle drivers have to drive and discover the roads blocked by debris, or military road blocks as they do not have updated road maps. The reader can refer to a broader review of transportation infrastructure performance in disasters in [97].

The logistics optimization efforts, not considering the socio-economic shortfalls of the emergency environment, ignore the reality with conspicuous assumptions. However, these assumptions may lead to non-intuitive results. Human behavior can also affect any optimal logistics plan decided in the pre-disaster environment. For instance, evacuation plans consider guiding people to the pre-defined evacuation paths immediately, but in a disaster environment, people tend to find their families and/or beloved relatives before the evacuation, and that way, they do not follow the paths assumed beforehand. Another example can be given for the disaster relief item distributions. For practical reasons, distributions are made through the back of trucks to scrambled and crowded groups in a random manner. Especially, the distributor hands the package to the one who seems more eager and willing. That way, many times oversupplies and/or undersupplies emerge; and equity cannot be provided effectively, which increases the deprivation costs. A robust optimization can be used overcoming those ambiguities affected by human behavior. Therefore, aside from logistics costs and timely responsiveness, the robustness of relief planning can be incorporated into the objective function [29]. For a broader review of the multi-disciplinary nature of land issues covering the allocation of resources that humanitarian organizations should consider when operating in post-disaster contexts, the reader can refer to the contribution of Pantuliano [98].

Traditional vehicle routing models make a common assumption that the goods are distributed to a deterministic set of vehicles on routes beginning and ending at a single depot [30]. However, relief routing models can be classified into four categories. These are: the single depot; the multiple depots in which vehicles start and return to their original depots; the multiple depots in which vehicles start and wait at their destination, and move ahead according to the new destination, and never come back to the original depot; and those that do not have the concept of the depot. As models with multiple starting and ending points are more realistic, it is better to stick to this assumption. Another common assumption is that communication is limited, but possible in the earliest post-disaster stage through a primitive pre-constructed truck communication network. There is limited but interesting research modeling the ability of vehicles to wait for further instructions at any stopping point in the transportation system[99].

Consequently, we realize that most of the HSC relief item distribution studies focus on pre-positioning relief items and services to make an initial distribution, and then on providing donated goods and services in a multi-period environment. We understand that single delivery is never enough; and that there is a need for multi-period and multi-objective routing and distribution research. Caunhye et al.’s literature review on optimization models in emergency logistics, and de la Torre’s literature review of disaster relief routing and distribution shed light on the gaps regarding the HSC relief item distribution classification[29], [30].

As it mostly covers the main skeleton of HSC relief item distribution classification, focusing on disaster relief item routing and distribution literature, we can build a basic summary table incorporating our up-to-date complementary review to the existing field studies (Table 3). The classification of this structural table is derived from the structural analysis of Caunhye et al. and models are examined according to their objectives, planning horizon, data type and number of levels[29].

Single period considers the pre-disaster environment, while multi-period considers the post-disaster environment in two stages that we defined as the immediate stage and the long-term stage in the introduction section of this paper. Deterministic and stochastic labels define the data type. In deterministic studies, outcomes are precisely determined through known relationships among states and events, and a given input will always produce the same output, while stochastic parameters can be probabilistically distributed, or scenario-based.
Table 3. Structure of HSC disaster relief item distribution and routing models based on objectives, planning horizon, data type and number of levels

<table>
<thead>
<tr>
<th>Reference</th>
<th>Objective</th>
<th>Horizon(Period)</th>
<th>Data Type</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>[6], [62], [65], [68], [74], [85], [99], [100], [101], [104], [106], [107], [111], [114]</td>
<td>Single</td>
<td>Multi</td>
<td>Single</td>
<td>Multi</td>
</tr>
<tr>
<td>[55], [70], [89], [102], [105], [109], [115], [118], [119], [120]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[17], [61], [67], [71], [76], [77], [90], [117]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[87], [51], [103], [72], [53], [48], [52], [80]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[49], [54], [57], [59], [64], [79], [112]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[32], [73], [78], [96], [116], [122]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[111], [88], [60], [110], [113]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[5], [56]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[19], [86]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[108], [121]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[58]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[63]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>[75]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[94]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>[95]</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Travel time, disaster location, supply, demand or both can be stochastic. Objective functions are either single or multi-objective, and there are also several allocation decisions either based on an egalitarian policy that maximizes equality of measure or a utilitarian policy that maximizes the amount of demand satisfied without equality in distribution. Single-objective models consider only one objective, while multi-objective studies combine more than one objective in one model. Minimized and maximized objective parameters used in operational HSC relief item distribution research can be found in Table 4.

Table 4. Objective functions in disaster relief routing and distribution literature

<table>
<thead>
<tr>
<th>Minimization</th>
<th>Maximization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transportation cost</td>
<td>Rescue equipment cost</td>
</tr>
<tr>
<td>Facility opening cost</td>
<td>Operations cost</td>
</tr>
<tr>
<td>Equipment rental cost</td>
<td>Shortages cost</td>
</tr>
<tr>
<td>Penalty cost</td>
<td>Acquisition cost</td>
</tr>
<tr>
<td>Delay cost</td>
<td>Inventory holding cost</td>
</tr>
<tr>
<td>Deprivation cost</td>
<td>Logistics cost</td>
</tr>
</tbody>
</table>

Based on the above structural classification, the current status of post-disaster stage disaster-relief item distribution research on HSCs can be summarized in Table 5.

Table 5. Summary of the present state of relief item distribution research on HSC

<table>
<thead>
<tr>
<th></th>
<th>Single-Period</th>
<th>Multi-Period</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Deterministic</td>
<td>Stochastic</td>
</tr>
<tr>
<td>Single-Objective</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-Level</td>
<td>✓ (15)</td>
<td>✓ (8)</td>
</tr>
<tr>
<td>Multi-Level</td>
<td>✓ (3)</td>
<td>✓ (8)</td>
</tr>
<tr>
<td>Multi-Objective</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-Level</td>
<td>✓ (9)</td>
<td>✓ (5)</td>
</tr>
<tr>
<td>Multi-Level</td>
<td>x (1)</td>
<td>x (2)</td>
</tr>
</tbody>
</table>

✓ many exist (≥5)  x no studies  ⇒ limited (<5)

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In addition to our in-text gap determinations and recommendations for future research, we can recommend focusing on multi-level models; especially on multi-objective, multi-level, and multi-period relief item distribution and routing logistics models, minimizing the social costs, which consist of the deprivation and logistics costs, in order to produce practical results and to cover the gaps. The use of variable penalty functions and tweaking the model as required can help obtain more realistic results. Although the disaster operations research society produces researches with an increasing trend to cover the gaps addressed in literature reviews, few of them find the opportunity to be turned into practice. Therefore, we can suggest implementing real world data in the computational studies, especially acquired from subject matter expert foundations like International Federation of Red Cross and Red Crescent, as much as possible.

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BIOGRAPHY

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