Logistics for Large-Scale Disaster Response: Achievements and Challenges

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Abstract

Much research in the operations research (OR) community has focused on commercial logistics or supply chain management, but there is another kind of logistics problem, dealing with emergency response, that has not as yet received much attention. In this paper, we present a literature review of emergency logistics in the context of large-scale disasters. First, we identify key characteristics of large-scale disasters and assess their possible challenges to emergency logistics. Second, we analyze and summarize the current literature on how to deal with these challenges. Finally, we discuss existing gaps in relevant research and suggest future research directions.

Keywords: large-scale disaster; emergency response; emergency logistics

1. Introduction

In recent years, there has been a growing concern about large-scale disasters affecting the safety of our society, such as severe earthquakes, extreme tsunamis, and hurricanes [1]. Unlike daily emergencies such as fires, car accidents, and medical emergencies [2, 3], large-scale disasters have a much more significant impact on society [4]. These large-scale catastrophic disasters can conceivably cause large numbers of deaths, create chaos in human societies, and drastically impact local and regional healthcare systems.

When a large-scale catastrophic disaster happens, immediate responses and related decisions are needed to relieve and control the consequences. In this context, emergency logistics has been emphasized by more and more academic scholars from the operations research (OR) community [5]. OR is an applied science that utilizes known mathematical techniques as tools to solve specific practical problems [6].

According to a framework proposed by [7], disaster relief operations can be divided into three phrases—the preparation phrase (before disaster strikes), the immediate response phrase (instantly after a disaster) and the reconstruction phrase (recovery from a disaster). Emergency logistics is defined as the support function that ensures the timely delivery of emergency resources and rescue services into the affected regions so as to assist in rescue activities [8]. Thus, the main focus of emergency logistics in our paper is in the immediate response phase.

Many scholars in the OR community have studied emergency logistics, especially after the 9/11 2001 attack in the USA [9, 10]. We were able to find five survey papers on emergency logistics. Green and Kolesar analyzed previous OR papers focused on urban emergency services and regular emergencies, published in the INFORMS journals from 1960 to 2004 [11]. Wright et al extended the literature scope into homeland security such as traffic and cyber space safety [12]. Both of these two studies focused on OR developments in routine emergency management, but not in the context of large-scale disasters. Altay and Green III summarized the works of the OR community published from 1980 to 2006 under the broad umbrella of disaster operation management in large-scale disasters [13]. They proposed a macro level of literature classification in the field of disaster operation management, but their work does not provide a detailed analysis of the contributions made by the OR community. Simpson and Hancock discussed the previous literature on both urban emergency service systems studied in earlier periods and of large-scale disasters in the 21st century, and they also identify a detailed literature citation network among those studies [14]. But they did not investigate the research gap that exists for immediate emergency response. Most recently Caunhye et al summarized the OR literature on the pre-disaster operations phase and post-disaster operations phase [15]. They analyzed the current literature through the perspectives of OR models, decisions, objectives, and constraints. They also suggested some future research problems. Generally, all of the survey papers have summarized and classified the existing literature in emergency logistics,
but there is a lack of emphasis on the gaps between what we have studied and what we should study in emergency logistics for real world emergency response.

Our research aims to identify the current research gaps in emergency logistics research in the context of large-scale disasters. First, we identify the key characteristics of large-scale disasters and corresponding challenges posed to emergency logistics. Second, we analyze current OR efforts on how to deal with these challenges. Finally, we investigate the gaps in current research, and suggest future research directions.

2. Key characteristics of large-scale disasters and challenges of emergency logistics

In contrast with traditional routine emergencies or everyday emergencies like explosions and healthcare services, large-scale disasters can result in severe impacts on large concentrations of people, activity, and wealth and last for a longer time. Some specific characteristics of large-scale disasters differ, depending on the type of disaster and the types of relief actors involved, and they pose certain challenges for emergency logistics in the aftermath of disasters [16].

In order to clarify their internal relationships, in this section we first identify the common characteristics of large-scale disasters, and then investigate some potential challenges of practical emergency responses.

2.1. Key characteristics of large-scale disasters

Key characteristics of large-scale disasters refer to the main attributes of large-scale disasters. We elaborate the key distinct characteristics of large-scale disasters from seven viewpoints: mass scale, severe consequences, multi-agency involvement, time pressure, demand surge and resource shortage, great uncertainty, as well as infrastructure damage, as shown in Table 1.

2.2. Challenges for emergency logistics

In the spirit of the information science (IS) literature conducted by [18], who studied the influences caused by different characteristics of disasters on coordinated emergency response systems, we investigate the potential challenge for emergency logistics according to each feature discussed in section 2.1, with the results given in Table 2.

(1) Problem scale and complexity
Large-scale disasters may affect large geographical areas and large populations, with severe damage. Emergency logistics tasks are very complicated, involving overwhelming demand assessment, resource allocation, distribution, evacuation, etc. Hence, these difficulties pose a great challenge for emergency logistics, involving substantial complexity [9].

(2) Different objective and decision criteria
Large-scale disasters may cause large numbers of casualties and property damage. Thus, the objectives and decision criteria for emergency logistics should focus on saving lives and reducing property loss rather than the traditional objective of reducing costs and increasing profit for business [5].

(3) Multiparty collaboration problem
Large-scale disasters require multiple agencies working together to carry out emergency response tasks [23]. Therefore, collaboration is needed for information exchange, resource sharing, and job dispatching among different parties, and a lack of collaboration can lead to disaster propagation and even higher numbers of casualties [24].

(4) Critical time requirement and real-time decision making
Disasters usually happen suddenly and develop

<table>
<thead>
<tr>
<th>Emergency Characteristics</th>
<th>Descriptions</th>
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<tr>
<td>Mass scale</td>
<td>May affect large geographical areas and large groups of population</td>
<td>[17]</td>
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<tr>
<td>Severe consequences</td>
<td>May cause large number of casualties and property damage</td>
<td>[18]</td>
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<tr>
<td>Multi-agency involvement</td>
<td>May involve multiple parties such as rescue teams, volunteers, and international support teams</td>
<td>[19]</td>
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<td>Time pressure</td>
<td>Time is critical for life saving, and there is time pressure for quick decision making and action</td>
<td>[5]</td>
</tr>
<tr>
<td>Demand surge and resource shortage</td>
<td>Huge demand surge with severe resource shortages</td>
<td>[20]</td>
</tr>
<tr>
<td>Great uncertainty</td>
<td>Great uncertainty caused by the nature of the disaster which is often unpredicted and unprecedented</td>
<td>[21]</td>
</tr>
<tr>
<td>Infrastructure damage</td>
<td>Infrastructure is often damaged, becoming inaccessible or unusable</td>
<td>[22]</td>
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rapidly. Any delay of relief efforts may cause severe consequences and many failures. Hence, there is time pressure to make quick decisions and to provide quick responses [25]. Sometimes it is best to look for a quick feasible solution rather than sophisticated optimization, because timeliness is a critical factor in the effectiveness and success of emergency logistics.

(5) Allocation of scarce resources

Large-scale disasters may create a huge demand for emergency resources which greatly exceeds resource availability [20]. It becomes imperative to allocate these scarce resources for different demand areas and ensure their availability to those that need resources the most.

(6) Stochastic and scenario based modeling

Due to the great uncertainty in large-scale disasters, it is difficult to assess disaster consequences, damage scenarios, and resource requirements exactly. To cope with these uncertainties, it is necessary to establish stochastic or scenario-based models.

(7) Logistics with damaged infrastructure

Large-scale disasters may cause severe damage to communications, power supplies, and transportation infrastructure, and make them unavailable for emergency relief operations. These additional constraints need to be taken into consideration for emergency logistics operations.

3. Research gaps in current studies and future research directions

Based on the challenges to emergency logistics discussed in section 2.2, we further review the achievements and the gaps of the current literature in responding to these challenges, and identify future research directions. The findings are summarized in table 3, followed by a detailed discussion in each subsection.

3.1. Problem scale and complexity

Emergency logistics can be viewed as very complex dynamic systems which contain many complex constraints and involve different interdependent tasks. For example, after an occurrence of a large-scale disaster, the primary task is collecting and distributing emergency resources to the affected areas. However, several interdependent tasks emerge, such as who holds the emergency resource, where can one get the emergency resource, who delivers the emergency resource to the affected areas, when are transport vehicles available, etc. Hence, emergency logistics is a complicated problem since various decision problems must be considered simultaneously.

Currently, emergency logistics problems have been studied in the field of assessing demand requirements [10, 26], allocating emergency resources [27, 28, 29, 30, 31], distributing emergency resources [10, 32, 33, 34, 35, 36, 37, 38], as well as evacuating casualties from dangerous areas to safe places [39, 40, 41, 42, 43] (readers can refer to the recent survey paper [44]). Moreover, some studies integrate different specific decision problems into one decision model, such as [45, 46, 47, 48].

Notably, there has also been research on humanitarian logistics and humanitarian supply chains, but these efforts have focused on responding to extreme disasters through inventory scheduling [49, 50] or regarding the emergency response as a supply chain management problem [51]. Since these problem domains are studied from the perspective of supply chain or inventory management and are different from real-time emergency responses, we have not included these studies in our review. However, readers who want to know more detail about other problem domains in disaster management can refer to review papers [11, 12, 13, 14].

In general, previous studies have mainly focused on decomposition-oriented methods, which deal with emergency logistics problems by simplifying the problems or decomposing large problems into multiple smaller problems. Although the idea of an integration-oriented method in the context of large-scale disasters has been raised recently, there is still a lack of research into integrated models that address the entire emergency logistics process for large scale problems.
3.2. Different objective and decision criteria

The objectives and decision criteria not only reflect the attitudes and principles of decision-makers towards
decision problems, but also act as measurements to assess various schemes or schedules.

According to a summarization of current literature, objectives commonly used in emergency logistics can be classified into three groups: improvement of distribution performance, assessment of demand fulfillment, and reduction in human deaths. The criteria for improving distribution performance include: minimizing distribution time [32, 38, 40, 47], minimizing the maximal completion time [30], minimizing evacuation time [42], minimizing distribution cost [10, 32, 34, 35, 36, 37, 48], maximizing vehicle tour duration [36], as well as selection of the shortest path [33]. The criteria to assess demand fulfillment include minimizing unsatisfied demand [41, 45, 46], and maximizing demand fill rate [10, 32]. For criteria related to reducing human deaths, there decision objectives such as minimizing the total number of fatalities [27] and minimizing the loss benefit of human death [31].

Generally, most current research focuses on traditional logistics objectives (minimization of distribution time and distribution cost, and selection of shortest path). Typically, cost-based and time-based objective functions are often representative of current research efforts. Few studies have considered emergency related decision criteria such as minimizing the number of fatalities or maximizing demand fulfillment. However, the primary principle in emergency logistics is saving human lives and reducing property damage through various emergency relief activities. Thus, the decision objectives and criteria of future studies should be more directly linked to end results such as life saving and damage reduction.

3.3. Multiparty collaboration problem

Multiparty collaboration problems arise from the interdependent nature of the implementation of emergency response tasks in a highly unpredictable, dynamic and complex environment, in which multiple groups of emergency response agencies need to collaborate [24].

Current studies that investigated this topic have mainly focused on the coordination of multiple decision problems, such as Yi and Ozdamar [45] and Yi and Kumar [46] who investigated the decision coordination problem between emergency distribution and emergency evacuation; Yan and Shih [47] combined road damage repair with an emergency distribution to analyze the integrated schedules. A similar work by Balci et al., considered the integration of resource allocation and emergency distribution [48].

On the whole, the multiparty collaboration problem still remains at the top of the research agenda [24]. Most current literature investigates this topic from a single authority’s perspective, i.e. assume a single authority to deal with emergency response. In fact, emergency logistics almost always needs to simultaneously implement different sequential response tasks [52]. Future studies in this field should focus on the investigation of the interdependency of tasks, resources, and workflows across and among different decision authorities.

3.4. Critical time requirement and real-time decision making

Timeliness and real-time decision-making are required for emergency management agencies, because time means life in the phase of immediate emergency response. This means that the highest objective for emergency logistics is to save lives as soon as possible, whereas the cost factor is not a major consideration.

For the critical time requirement problem, current studies mainly focus on making the minimum distribution time the decision objective, or setting a time window as a constraint in the mathematical model. Those studies related to minimizing distribution time have been analyzed in section 3.2. A prominent study was conducted by Gong and Batta, who propose a continuous function to depict the growth in the number of casualties after a disaster strikes [30]. They also discuss methods to calculate critical time measure. For studies of the time-window setting, Haghani and Oh incorporate a time-window constraint into a time-space-based distribution network [37]. Some papers have investigated the problem of real-time decision making through continuously updating information used in decision models. This includes Sheu who used data fusion methods to forecast relief demand in multiple areas, so as to support the emergency distribution [26], and Jotshi et al. who estimates the number of fatalities and road conditions in a post-disaster environment by using the data fusion method [38]. This information was then used to dispatch and route emergency vehicles to rescue casualties. In addition, combine efficient optimization technology with real-time decision support system is another interesting area of research to assist emergency response [29].

Generally speaking, present studies are simple, only reflecting the critical time requirement factor, and studies that explore the time-varying process between disaster scenarios and time critical are rare. Future research in this topic should address two aspects: on one hand, investigate the measurement of critical time;
on the other hand, make more of an effort to address decision support user interface issues for real-time applications of decision models.

3.5. Allocation of scarce resources

Resource allocation decision problems arise from the shortage of available resources. A general issue in this problem domain is how to allocate emergency resources so as to relieve the consequences caused by a natural disaster [28]. In the context of insufficient emergency resources, different criteria can result in different resource allocation schemes. Usually, priority setting is a key determining factor to allocate scarce emergency [31].

The criteria for allocation decisions in the current literature can be based on minimum expected number of fatalities [27], cost-effectiveness analysis [53], cost-benefit-based methods [31], and minimizing maximal completion time [30]. There is another kind of study which incorporates resource allocation into other emergency response activities. In this literature, the allocation decision is determined via a given deterministic priority [40, 45, 46], or via severity assessment for different disaster areas [26].

In fact, the resource allocation decision usually involves many different types of resources, where some resources may have different properties to meet demand requirements, such as periodical requirements or one-time requirements. But current research about resource allocation seldom considers this difference. On the other hand, although current studies have considered prioritization in resource allocation decisions, how to set priorities is still an open problem for emergency relief actors. However, real emergency response should consider both resource shortages and human life equality; thus, future research needs to combine priority setting and demand fulfillment as the criteria for resource allocation, achieving a balance between priority and equality.

3.6. Stochastic and scenario-based modeling

Stochastic challenges come from high uncertainty, complexity and unpredictibility in the context of large-scale disasters. And the randomness arises from the uncertainty of available supply, demand requirements, traffic capacity, etc. This can be solved by introducing stochastic methods or scenario-based analysis. The difficulty in modeling this problem lies in the unavailability of suitable probability distributions for the uncertainty factors.

The majority of current research emphasizes deterministic optimization models with the assumption of known data for given situations, such as integer programming (IP), mixed integer programming (MIP), linear programming (LP), multi-objective programming (MOP), and hierarchical planning (HP). Very few works have investigated stochastic models. For example, Barbarosoglu and Arda propose a two-stage stochastic programming model for scheduling emergency transportation schemes[35]; Tan et al. investigate the evacuation problem under uncertainty by using fuzzy programming [42]; in a related work about emergency preparation by Chang et al. [54] investigate emergency preparations for floods in uncertain environments by introducing scenario planning. Another useful method for dealing with uncertainty is simulation, which was introduced in the emergency evacuation [38, 39] and resource allocation [29].

There is a significant lack of research into models of uncertainty for emergency logistics. The reasons may be the result of either the complexity of stochastic models or the meaningless results obtained by assuming a probability distribution for the uncertain variable. Further research on this problem can address two aspects: either combine disaster scenario generation with an optimization model, or deal with the difficulties in uncertainty in an emergency situation, even if a suitable probability distribution is unavailable.

3.7. Logistics with damaged infrastructure

There can be many constraints imposed on emergency logistics by damaged infrastructure. Possible issues that need to be considered in emergency logistics decisions involve the inaccessibility of transportation networks, constrained capacity of traffic routes, disruption of lifelines, reliability of communication channels, etc.

Current literature related to this problem can be summarized as analyzing infrastructure vulnerability [55], incorporating the repair of damaged roads into the distribution model [47], considering route congestion [38, 39], route complexity caused by disaster damage [33], and adding traffic capacity constraints into the distribution network [37, 42].

In summary, considering capacity constraint is the most common way used in emergency logistics models to cope with the impact of damaged infrastructure, which is usually regarded as a lower bound or an upper bound with given disaster scenario. However, how to determine the lower and upper limit is still a difficult issue, since the condition of infrastructure damage is dynamic and varied with the change of large-scale disaster. Further research on this problem can be focused on alternative solutions, such as investigating
the combinatorial choice of multi-mode transportation routing to cope with infrastructure damage/availability.

4. Conclusions

In this paper, we have identified the key characteristics of large-scale disasters and assessed their possible challenges to emergency logistics. We have analyzed and summarized the current literature that deals with these challenges. Finally we have discussed existing gaps in the current research and indicated future research directions. The main contribution of our work has been to facilitate the tracing of published works on emergency logistics for large-scale disaster response, as well as identifying gaps in knowledge and indicating which problems should be subject to future research.

References
