Disaster Relief Routing: Integrating Research and Practice☆

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Abstract

Disaster relief presents many unique logistics challenges, with problems including damaged transportation infrastructure, limited communication, and coordination of multiple agents. Central to disaster relief logistics is the distribution of life-saving commodities to beneficiaries. Operations research models have potential to help relief agencies save lives and money, maintain standards of humanitarianism and fairness and maximize the use of limited resources amid post-disaster chaos. Through interviews with aid organizations, reviews of their publications, and a literature review of operations research models in transportation of relief goods, this paper provides an analysis of the use of such models from the perspective of both practitioners and academics. With the complexity of disaster relief distribution and the relatively small number of journal articles written on it, this is an area with potential for helping relief organizations and for tremendous growth in operations research.

Keywords: Disaster relief, vehicle routing problem, survey

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1. Introduction

Just days after the 2010 earthquake in Haiti, the United Nations (UN) called the earthquake the worst it had encountered [1]. Six months later, UN Secretary General Ban Ki-Moon said the same about devastating floods in Pakistan, and called for half a billion dollars of support just for short-term relief [2]. In addition to these catastrophes, the past decade has seen many other large disasters including the 2004 Indian Ocean earthquake and tsunami, in 2005 Hurricane Katrina, the 2005 Pakistan earthquake, in 2008 Cyclone Nargis and the 2008 Sichuan earthquake. The destruction from disasters can leave populations without shelter, food and water, and in need of urgent medical care. In these situations, it can be necessary to supplement local capacity with regional or international aid. For example, within the first 30 days of the 2001 Gujarat, India earthquake, the International Federation of the Red Cross and Red Crescent (IFRC) arranged delivery of hundreds of thousands of blankets, tents and plastic sheets. Additionally, over 300 other non-governmental organizations (NGOs) and UN agencies provided assistance [3]. The Gujarat earthquake is just one of many large disasters that have required international assistance, and is far from the largest. Appendix A contains a table of the top five (by number of lives lost) earthquakes, cyclones, and floods from 1980 to 2009. Tables are derived from data at EM-DAT, a global database of disaster information [4].

Disaster relief requires efforts on many fronts: providing rescue, health and medical assistance, water, food, shelter and long term recovery efforts. Much of successful and rapid relief relies on the logistical operations of supply delivery. In 2005, the United Nations established the Logistics Cluster as one of nine inter-agency coordination efforts in humanitarian assistance, recognizing the key importance of logistics in aid operations. The Pan American Health Organization (PAHO), a regional division of the World Health Organization (WHO), states that "countries and organizations must see [humanitarian supply logistics] as a cornerstone of emergency planning and preparedness efforts." [5].

In this paper we focus on reviewing the problems in transportation and distribution of goods within the affected region to beneficiaries and final distribution points. We analyze the representation of these problems in current operations research models for disaster relief, and identify outstanding related research questions. Mathematical models related to emergencies have a long history. In 1955, Valinsky [6] published one of the earliest papers in emergency assistance, on locating fire fighting resources. Work related to non-daily emergencies started in the 1980s, in assessing the risk of rare events such as large natural disasters (Sampson and Smith [7]) and simulations of traffic patterns to improve the flow of emergency evacuation (Sheffi et al. [8]). Disaster relief transportation also saw its start in the 1980s with a routing model developed by Knott in 1987 [9]. In order to better understand the ways in which operations research models are helping and can continue to help relief organizations, we have conducted a series of interviews with representatives from organizations involved in disaster relief. These include small and large NGOs, local and national governmental relief organizations and commercial partners of relief organizations. In addition, we discuss findings from publications of relief organizations on logistical procedures for disaster relief. We have also conducted a comprehensive literature review of operations research models in disaster relief transportation and distribution. We review findings from these studies and discuss areas where models can continue to expand and capture characteristics of relief distribution. Our literature review focuses on papers specifically in relief transportation and their modeling characteristics. For a broad overview and classification of papers in all areas of disaster operations research, see the comprehensive surveys of Altay and Green [10] and Simpson and Hancock [11].

1.1. Information Collection Methodology

To collect papers on operations research models for this review, we searched journal search engines such as ISI Web of Science, the INFORMS journal database, Transportation Research Board publication database, Science Direct, Springer Journal Database and various individual journals' search engines. These were queried using the keywords "disaster", "emergency", "catastrophe", "humanitarian", and other forms of the words such as "disastrous". The search engines' filters were used to narrow results to operations research models for disaster relief. Within these results, papers were kept that specifically address the transportation and routing of goods. Finally, the reference sections of these papers were searched to find additional relevant papers. Many papers model additional characteristics, including asset pre-positioning, facility location, infrastructure repair following a disaster, or evacuation and rescue and evacuation, but all include transportation of goods as a significant component.

To learn about current practices and challenges in disaster relief transportation and distribution, we interviewed representatives from governmental organizations, NGOs, and commercial partners of organizations. We interviewed 27 representatives over the phone or in person with follow-up questions by email. All interviewees were not asked the same set of questions. All interviews began with similar initial questions and progressed based on the responses and expertise of the interviewee. From these interviews, we share responses that have an impact on modeling disaster relief transportation and distribution problems. To protect the confidentiality of interviewees, we use the conventions from Holguin-Veras et al.'s [12] review of logistics issues during Hurricane Katrina. Government agencies are referred to only as "state", "local", or "federal" depending on their jurisdiction. Those from non-profit organizations not under the jurisdiction of a government are identified as "volunteers". Those from commercial partners are referred to as "commercial partners". In addition to interviews, we include findings from the general media, trade publications and other publications in disaster relief and humanitarian logistics.

In the next sections, we review these papers concurrently with our findings from interviews and relief organization publications. We categorize papers by problem characteristics and discuss these characteristics with related findings. Tables A.2 and A.3 provide a summary of transportation-related modeling characteristics in the papers reviewed. Table A.2 defines the terms used in Table A.3.

2. Relief Transportation in Practice and Operations Research Models

2.1. Allocation Policies

A critical and challenging component of relief distribution is the allocation of goods to beneficiaries. In many situations, the needs of beneficiaries exceed the available supply of goods and relief organizations must choose an appropriate allocation of goods. Published humanitarian guidelines do not provide standard procedures for allocation when demand exceeds supply. The Sphere Handbook is a collaborative effort between hundreds of NGOs to establish standards in humanitarian practice. It provides detailed minimum humanitarian standards to be met in relief, such as ensuring each person has 2100 daily calories of food [13]. The Sphere Handbook also states that agencies should provide aid impartially and according to need, but makes no mention of specific procedures when sufficient calories cannot be provided to all people in need. Florida and South Carolina, two U.S. states especially vulnerable to hurricanes , have detailed emergency management handbooks that describe quantities of goods to be distributed. However, they do not address how to allocate goods when these quantities cannot be met [14, 15].

In practice, organizations must make decisions on allocation of limited supply. A common trend we find is to prioritize the needs of the most vulnerable populations. In Sudan and Niger, Mèdecines Sans Frontières (MSF, or Doctors Without Borders) and the UN, respectively, restricted food aid to the most malnourished children and their families [16, 17]. Two large international NGOs interviewed make allocation decisions to beneficiaries by closely monitoring locations, targeting the people with highest needs and ensuring that people receive enough to satisfy Sphere standards. All policies described to us during interviews are egalitarian, requiring that an equal amount of need for all targeted populations are met.

In relief routing models, we find several types of egalitarian policies that maximize equality of a measure such as delivery quantity or speed. We also find examples of utilitarian policies that maximize the amount of demand satisfied without requiring equality in distribution. Campbell et al. [18], Huang et al. [19], Nolz et al. [20], Van Hentenryck et al. [21], Mete and Zabinsky [22] measure equity and efficacy of aid distribution by minimizing the time to deliver goods to beneficiaries. Campbell et al. [18] studies the properties of vehicle routing problems that minimize the average or, alternatively, the latest arrival time of goods to beneficiaries. The authors find that these objectives result in faster delivery at a higher total transportation cost than with traditional cost minimizing objectives. Huang et al. [19] extends these ideas by weighting arrival times by the amount of demand delivered. Mete and Zabinsky [22] minimizes total costs of operating delivery warehouses along with minimizing total travel time of delivery. In all of these papers, all demand must be satisfied. In Nolz et al. [20] and Van Hentenryck et al. [21], latest arrival times are minimized along with minimizing the total amount of unsatisfied demand. This combines a utilitarian measure of delivery quantity with an egalitarian measure of delivery speed.

Objectives that are egalitarian in delivery quantity are found in a number of papers. Tzeng et al. [23], Lin et al. [24] take the opposite approach to Nolz et al. [20] and Van Hentenryck et al. [21], minimizing the maximum unsatisfied demand over all beneficiaries while minimizing total travel time. These papers use an egalitarian measure for delivery quantity and a utilitarian measure for delivery speed. Balcik et al. [25] also minimizes the maximum unsatisfied demand over all beneficiaries. In all papers mentioned so far except for Campbell et al. [18], cost minimization is weighted as an objective along with other objectives. Özdamar et al. [26], Yi and Kumar [27], Yi and Özdamar [28], Shen et al. [29, 30] minimize total unsatisfied demand without considering equality of delivery. Similarly, Clark and Culkin [31] and De Angelis et al. [32] minimize total unsatisfied demand but include constraints that all beneficiaries receive a minimum amount of goods. This may not lead to equitable solutions but can be used to enforce minimum standards such as those in the Sphere Handbook. Finally, Haghani and Oh [33], Oh and Haghani [34], Barbarosoğlu et al. [35], Barbarosoğlu and Arda [36] minimize total cost of deliveries while satisfying all demands with no egalitarian or utilitarian component.

The above papers comprise a range of allocation policies. For each model type, there are realistic scenarios where a particular model is appropriate. Focusing on maximizing total or average speed of delivery while delivering the maximum quantity of goods possible is especially important in rapid response. With a large and urgent need, time may be better spent distributing supplies than evaluating needs. Equality in delivery is more suited to longer-term recovery and development aid where speed is less of a factor and political or social issues make equity in delivery important. While minimizing the cost of satisfying a specified level of demand is not explicitly egalitarian or utilitarian, the value of demand to be satisfied can reflect these goals. For example, the relief plans of the Federal Emergency Management Agency (FEMA) specify quantities to distribute to beneficiaries. These plans also include guides for establishing contracts with suppliers to ensure these needs can be met [37]. With these specifications and certain supply availability, a cost-minimization model for relief distribution would be appropriate.

In our interviews, a number of large volunteer organizations emphasized the amount of effort that goes into ensuring fair distribution. Monitoring of a population to understand its needs and developing relationships with local leaders to ensure orderly and fair distribution takes significant resources. Ensuring equitable distribution is a difficult task for some of the largest relief organizations. Incorporating complex allocation decisions into distribution systems is not feasible for every organization. Complex distribution system may become possible for more organizations with technology such as the UPS Trackpad used for tracking use and receipt of goods [38]. With heterogeneity in the capabilities of relief organizations, there is an opportunity to model the structures of different types of organizations.

2.2. Assessment of Needs and Uncertainty in Demand and Supply

Accurate assessment of needs is crucial for achieving accurate models and maximizing the benefit of distributing relief goods. Needs assessment methods vary between organizations and change as the disaster situation evolves. Later in the disaster, resources for needs assessment increase and more accurate and detailed information becomes available. When possible, organizations can use sources of information such as maps from the UN, World Food Programme (WFP) and WHO. Examples of available maps can be found at the website of the UN Geographic Information Working Group, which compiles maps from many organizations [39]. In addition, some volunteer organizations do not do needs assessment and instead focus on fulfilling needs identified by partner groups. One example is Mennonite Central Committee, a small organization that works internationally and relies on partner organizations for needs assessment [40].

Assessing needs is much more challenging in the earlier phases of a disaster. Some of the larger volunteer organizations we interviewed have dedicated staff that make periodic trips to affected locations to conduct assessment. Existing relief routing models can be adapted to model needs assessment rather than aid distribution. Demand at a location can represent the need to visit a location and assess need instead of demand for goods.

Wider adoption of new technology can ease data collection efforts. For example, the UPS Trackpad system [38] assigns unique identification badges to beneficiaries that are scanned when goods are distributed to them to keep track of needs. Another technology is Ushahidi [41], a website where the public can submit information through text message and email. Systems like these can help organizations perform needs assessment without sacrificing additional resources. There are potential research questions when multiple data sources are available and provide conflicting information. Of particular interest to practitioners may be whether using multiple sources of conflicting data is worth the effort to collect and combine them.

An important issue to understand is the type and quantity of data collected by relief organizations. Data collection from past relief efforts can be extremely useful for researchers to test, validate, and compare models. Much of the current literature uses either historical data or data from disaster damage scenario modeling software (Barbarosoğlu et al. [35], Özdamar et al. [26], Barbarosoğlu and Arda [36], Viswanath and Peeta [42], Clark and Culkin [31], De Angelis et al. [32], Tzeng et al. [23], Yi and Özdamar [28], Zhu et al. [43], Lin et al. [24], Vitoriano et al. [44], Mete and Zabinsky [22], Rawls and Turnquist [45], Salmerón and Apte [46], Van Hentenryck et al. [21]).

All organizations interviewed collect data for accountability to current donors and to show the impact of efforts for further fundraising. Data needed for accountability may not be at the same level of detail needed to test current models. Current relief distribution may not require the data necessary for model-based operations, and spending limited resources on data collection can impede the real goal of distributing goods. Understanding the advantage of using detailed models over methods requiring less intensive data collection is important when resources are limited. This is a challenging and important open task for the operations research community.

Uncertainty is also prevalent in the supply of relief goods. Supply problems are inevitable in any complex supply chain, and in relief supply issues can be an especially important to model. Every organization interviewed identified at least one level of the supply chain where supply delays and losses were a problem and many identified supply delays as a major impediment to distribution. A federal government interviewee emphasized the importance of properly prioritizing goods. In their experience, rapid delivery of goods was not delayed by lack of resources, but by using resources to deliver the wrong types of goods. Multiple volunteer organizations and commercial partners identified goods being held in customs as another significant problem. In a presentation on her volunteer medical work in Haiti, Dr. Stacey Raviv of Evanston, IL Hospital described significant time and efficiency lost because of disorganized warehouses [47]; this problem was also described by volunteer organizations interviewed. Several other volunteer organizations described the difficulty of finding transportation into a country for donated goods. A volunteer organization which stores and delivers the goods of partner organizations often had its partner organizations fail to deliver their goods in time for distribution. The overwhelming response of supply issues during our interviews highlights the potential for incorporating supply uncertainty into relief models.

Most models in the current literature incorporate uncertainty in demand and supply. Several papers use two-stage stochastic programming to model the uncertainty of the damage caused by disasters and its effect on supply or demand. In Barbarosoğlu and Arda [36], the first stage decision is to move goods between existing supply depots to preposition them. In the second stage, realization of the uncertain demand and supply are revealed and goods are transported to final beneficiaries. In Zhu et al. [43], Mete and Zabinsky [22], and Salmerón and Apte [46], demand, not supply, of goods is uncertain. In these papers, the first stage decisions, made before a disaster, are to open and stock warehouses with goods and in the second stage demand is fixed and goods must be routed from warehouses to final destinations. In Shen et al. [29], the first stage is also pre-disaster and demand is uncertain. In this paper, the first-stage decisions create routes for vehicles and the second stage allows adjustments in delivery quantities to each beneficiary after demands are revealed. In Rawls and Turnquist [45] and Van Hentenryck et al. [21], the pre-disaster first stage decisions are to locate and stock warehouses, which can be damaged by the disaster. In the second stage, demand and remaining supply after warehouses are damaged is fixed, and routes are constructed. These papers model the uncertainty in physical damage caused by the disaster and the immediate post-disaster response. There are many other potential sources of uncertainty and dynamic elements to incorporate. Uncertainty in supply can result from delays and losses of relief goods at multiple points in the relief supply chain. Demand can fluctuate unexpectedly due to many sources. These sources include people returning to greater self-sufficiency, beneficiaries moving between different areas to find greater relief, or unexpected challenges stemming from the initial disaster, such as disease epidemics resulting from the close quarters of relief shelters. Modeling this type of uncertainty could be extremely challenging. Two-stage stochastic programming models are already computationally difficult to solve and require more data than deterministic models. Computational and data challenges are only compounded by incorporating more uncertainty.

In addressing supply and demand issues in relief routing, there are many ways that current systems in both practice and models can be developed. Needs assessment in the early phases of a disaster requiring trips to beneficiaries can be integrated into models. Continued interagency collaboration, information sharing and technological improvement from practitioners can make time consuming trips less necessary. Researchers can continue to push the boundary of modeling uncertainty in supply and demand while practitioners address supply and demand problems and make the situation easier to model.

2.3. Vehicles and Routes

In this section, we discuss characteristics of vehicles and transportation networks in the current relief routing literature along with related findings from interviews and relief organizations. Models capture characteristics for a variety of relief organizations, and there are also many characteristics that can provide new areas for models to expand. Traditional vehicle routing models assume that goods are distributed by a set of vehicles on routes beginning and ending at a single depot. Relief routing models can be classified into three groups: those with a single depot (Knott [9, 48], Barbarosoğlu and Arda [36], Balcik et al. [25], Campbell et al. [18], Hsueh et al. [49], Ukkusuri and Yushimito [50], Lin et al. [24], Shen et al. [29, 30], Huang et al. [19], Nolz et al. [20], Mete and Zabinsky [22]); those where routes originate and end from multiple depots with all vehicles returning to their original depot (Barbarosoğlu et al. [35], Yi and Kumar [27], Yi and Özdamar [28], Zhu et al. [43], Vitoriano et al. [44], Horner and Downs [51], Van Hentenryck et al. [21]); and those that do not have the concept of a depot (Haghani and Oh [33], Oh and Haghani [34], Özdamar et al. [26], Viswanath and Peeta [42], Clark and Culkin [31], De Angelis et al. [32], Rawls and Turnquist [45], Salmerón and Apte [46]). In those without depots, vehicles are not required to return to their starting points. Each of these types of models makes different assumptions about the structure of the relief organizations being modeled. Models with multiple starting and ending points are more applicable to organizations with greater resources than a single depot model. Some models that do not require vehicles to return to their starting points require the ability to communicate routing decisions to vehicles throughout a region.

Many papers present more specialized relief models. Two papers model the unique challenges of delivery by air. Barbarosoğlu et al. [35] models helicopter logistics, considering pilots with specialized skills, sensitivity of fuel efficiency to cargo weight, and refueling requirements. De Angelis et al. [32] models delivery of food by cargo plane, including landing schedules, parking capacity, and refueling schedules. Barbarosoğlu et al. [35], Yi and Kumar [27], Yi and Özdamar [28] consider the evacuation of beneficiaries while simultaneously making deliveries. With a limited number of vehicles, doing both at the same time can have an enormous potential to save costs and lives. Clark and Culkin [31], Tzeng et al. [23], Zhu et al. [43] take approaches with less operational detail than other models. In their models, commodities travel through several levels of nodes, from suppliers to beneficiaries. Nodes at each level have some quantity of supply and transportation capacity, but movement of individual vehicles is not tracked through the supply chain. As a decision variable, these models include the number of vehicles traveling between each node. The supply of vehicles available from each node is a parameter and not a function of the number of vehicles that have traveled between locations. Deliveries to recipients do not give routing information but give the number of vehicles that make deliveries and the quantity of goods delivered. These models require data at more levels of the supply chain than a last-mile distribution model, but require less detailed data at each level. These strategic-level models can be useful for finding bottlenecks in different levels of distribution and understanding the quantities of vehicles and goods needed throughout the supply chain.

Several other unique route and vehicle characteristics are modeled in the literature. Commodities in disaster relief can be many different types of goods, such as food, medications, or tents. Most papers we review consider the delivery of multiple commodities, differentiating the transportation costs and demands of different types of goods. Balcik et al. [25] explicitly models the difference between single-use perishable items and multi-use non-perishable items, with demand backlogging allowed for non-perishable items and demand lost for perishable items. Government and volunteer relief organizations interviewed identified single-use perishable and multi-use non-perishable items as two major important categories. One government organization identified between seven and ten major relief commodities within those two types. One small volunteer organization noted that the safety of a vehicle differs based on the type of goods being carried. Easily re-sold goods such as food and water can be bigger targets for robbery than specialized medicine or medical equipment. One large international volunteer organization identified delivering water by truck as a unique challenge because of the need to distribute water purification tablets and set up tap stands for filling containers. Nolz et al. [20] formulates this problem of routing and placement of water delivery systems. Rather than being transported directly to beneficiaries, potable water stations have to be delivered to central locations and cover all beneficiaries. This is modeled as a multi-vehicle covering tour problem that combines routing with the placement of tanks, constructing tours to place tanks at accessible points. The model used in Nolz et al. [20] is appropriate for distribution systems such as the one used by FEMA in the U.S., in which beneficiaries drive to distribution centers to pick up goods, to optimize the routing and placement of temporary distribution centers.

Some of the most ubiquitous assumptions of routing models are of a vehicle fleet with known capacity, known operating costs, known capabilities such as on which roads a vehicle can travel, and the ability to give these vehicles specific routing instructions. Many volunteer organizations interviewed stressed the difficulty of procuring and managing a fleet, which can affect these assumptions. A volunteer organization stated that even large organizations with a long term presence in a country do not generally own vehicle fleets. This was echoed by others who do not own their own fleets, including a large volunteer organization which works in relief, economic development and health development in over forty countries. The simplest solution may be to hire a commercial carrier to manage the details of most of the transportation, with the relief organization taking over at final destinations to distribute to beneficiaries. While PAHO recommends contracting fleets and fleet management for transportation of relief goods when possible, PAHO recognizes that fleet management companies may not be available. It is much more common to hire multiple independent local drivers and vehicles and manage them internally [5]. These local drivers are sometimes hired for their knowledge of the region. When drivers know the region but the relief organization does not, there may not be enough information to make detailed routing plans for vehicles. With limited information and limited instructions to drivers, simpler models that do not assign vehicles detailed routing plans are more appropriate. For all of the models in the current literature that assign detailed routes, this could be a useful simplification to make solving the models easier.

Another realistic assumption to consider is limited technology available in vehicles, especially when using local hired vehicles. Some of the current papers model the ability for vehicles to wait for further instructions at any stopping point in the transportation network (Özdamar et al. [26], Tzeng et al. [23], Yi and Özdamar [28], Hsueh et al. [49]). This has potential for significant cost savings as opposed to having to return to a depot, and assumes that communication with vehicles is always available. These models can help organizations to assess the value of tracking vehicles and maintaining constant communication before allocating limited funds for the technology to do so.

Many other routing related issues found during interviews and in relief organization documents point to restricted modeling of vehicles. PAHO recommends lightening the load of vehicles that have to cross rough terrain [5]. Knott [48] describes heuristics for relief routing which include rules to reduce vehicle payload by 20% if the road used is rough, and to give preference to different types of trucks on different types of roads.

Nearly every organization interviewed stressed the importance of awareness of cultural and political issues. In particular, these issues can affect the types of commodities that can be delivered and impact how vehicles make deliveries. One commercial shipping contractor stated that in order to maintain trust in some regions, delivery drivers needed to have an existing relationship with beneficiaries. This limits possible routes for each vehicle and makes routes driver-dependent. Limiting the region where each vehicle can travel is done in papers that model multi-modal travel (Haghani and Oh [33], Oh and Haghani [34], Özdamar et al. [26], Barbarosoğlu and Arda [36], Zhu et al. [43], Salmerón and Apte [46]), in which different vehicles have different parts of the network they can visit.

As discussed in Section 2.2, many papers model uncertainty with two-stage stochastic programming models. In addition to modeling uncertainty in supply and demand of goods, Shen et al. [29], Mete and Zabinsky [22], Rawls and Turnquist [45], Salmerón and Apte [46], Van Hentenryck et al. [21] model uncertainty in travel time. In these papers, travel times are scenario-dependent and revealed in the second stage.

In addition to modeling damage to transportation infrastructure, there are many possible sources of uncertainty to incorporate into models that we have learned about through interviews. An assumption of all current relief routing models is certainty of the size and composition of the vehicle fleet. Without this assumption, routing plans, especially multi-period routing plans, can become significantly more difficult to make. During relief efforts following Hurricane Rita, vehicles and drivers expected to distribute relief supplies abandoned New Orleans following reports of violence (Holguín-Veras et al. [12]). Several relief organizations reported problems while collaborating with organizations using volunteer drivers or vehicles. These groups may not be bound by contracts and monetary incentives and thus do not have the same incentives to uphold agreements as commercial carriers. Such a situation would likely cause uncertainty when determining the size of a fleet. Additionally, multiple volunteer organizations cited the unreliability of older local rented vehicles as a problem. These vehicles are often in need of maintenance and subject to hard use as they are driven for hours a day on rough and damaged roads. Reliability is modeled in Vitoriano et al. [44], in which vehicles have a road-dependent probability of breaking down while en route.

Even if vehicle fleets are known with certainty, unexpected events occur while on routes. A small volunteer organization that was interviewed stated that while delivering supplies in Haiti in 2010, accessibility of roads was changing constantly and unpredictably due to the movement of rubble and government and military road blocks. They had no maps with updated information and had to discover the best routes by driving and exploring. In addition to uncertain travel times, one large volunteer organization identified the time spent stopping at beneficiaries to distribute goods as a bottleneck.

Safety of drivers en route was also a concern of many organizations. Safety was such a concern for one volunteer organization in Haiti that it would sometimes not stop for any reason before reaching their destination. Other organizations agreed that safety was important and that robbery while delivering goods was a real concern. One large volunteer organization took precautions by varying the path and dispatch times of routes to avoid establishing a pattern and making themselves obvious targets. Another large volunteer organization obscures vehicles' identities when it is a potential targets and prominently displays logos identifying itself when people are sympathetic to its efforts.

Some potential strategies for safety produce additional challenges and sometimes are against a relief organization's rules. In their analysis of WFP operations in the Somali region of Ethiopia, Chander and Shear [52] note that WFP frequently used vehicle convoys for safety. Convoying would cause long delays in delivery while waiting for vehicles to group and limit travel speed significantly. Convoys and possibility of interdiction of vehicles are modeled by Vitoriano et al. [44]. In this model, vehicles have a probability of interdiction and at the expense of delivery speed they can form convoys to reduce this probability. Although it would be helpful in dangerous situations, some organizations, including IFRC, will not use armed escorts ([53]), while another large volunteer organization will not make deliveries if it believes the situation would warrant an armed escort.

In order to model the characteristics of vehicles and routes, a key issue is to understand the capabilities of relief organizations. For organizations where only simple instructions to independent drivers are possible, simpler models may be appropriate. Others may be able to make more complex decisions, especially those involving randomness or ambiguity. For organizations of many different types, addressing the reliability of vehicles and drivers can improve planning delivery schedules. Some organizations may be able to adjust to uncertainty while vehicles are on routes and improve distribution quantities or safety of drivers.

3. Conclusions

Our interviews encompassed organizations of many different sizes, capabilities, and infrastructure that work in various regions worldwide. Nevertheless, these interviews do not encompass all the possible problems of disaster or anticipate all potential issues resulting from future disasters. Continued contact and collaboration with relief organizations is key for continuing to produce models for use in practice. Most of the papers we review are the result of a collaboration with relief organizations. Researchers are collaborating with many different types of organizations: government and military organizations (Barbarosoğlu et al. [35], Özdamar et al. [26], Tzeng et al. [23], Zhu et al. [43], Salmerón and Apte [46], Van Hentenryck et al. [21]); non-governmental organizations (De Angelis et al. [32], Balcik et al. [25], Vitoriano et al. [44], Salmerón and Apte [46], Nolz et al. [20]); and experts in important related areas such as emergency medicine and seismology (Yi and Kumar [27], Yi and Özdamar [28], Mete and Zabinsky [22]). Many of those that do not describe direct collaboration with organizations use relief organization publications to construct models that follow relief in practice (Knott [9, 48], Haghani and Oh [33], Oh and Haghani [34], Clark and Culkin [31], Lin et al. [24], Rawls and Turnquist [45]). As well as improving relief distribution systems in practice, continuing to learn about unexpected challenges in disaster relief can continue to lead to innovative models and algorithms that can be of interest to the operations research community at large.

Throughout this paper, we have identified several areas where modeling can be furthered to capture characteristics of relief distribution. We have learned of uncertainty in supply of relief goods; uncertainty in availability of vehicles and drivers, inconsistency in their characteristics such as capacity, mobility, and available technology; the challenges of assessing needs; limited knowledge of routes and travel costs on those routes; limited decision-making abilities in assigning routes to vehicles; and the necessity of considering strategies that emphasize safety and reliability of drivers and vehicles.

There are many relief distribution models that incorporate uncertainty in demand, supply, and travel time. The majority of these papers model disaster scenarios. In these models, there are many possible ways that a disaster could strike, causing different amounts of supply loss, transportation network damage, and demand for relief goods. This uncertain physical damage is important to model. We have also found that there are many sources of uncertainty beyond the initial damage. It is likely that this uncertainty has not been modeled in relief routing because of the difficulty of making such a model practical. Incorporating multiple layers of uncertainty and additional cost considerations into relief models can quickly lead to intractably complex models. Adding to this challenge is the need to use these models in a field situation with limited time and computing power. There is a large potential to build models that balance the complexity of the uncertainty in relief routing with tractability and usability. Some characteristics, such as limited instructions to drivers and technology such as tracking of and consistent communication with vehicles call for simpler models.

The unique characteristics of different disasters and relief organizations will continue to provide opportunities and challenges for researchers. One of the most emphasized points in our interviews is that every disaster is unique and every relief organization has its own set of practices and policies. Over the course of a post-disaster response, the situation can evolve from chaos with limited information into a more orderly situation more amenable to models. Even the same type of disaster in the same region can present different challenges in two different years. The rain season is a threat to Haiti every year, but after the damage caused by the 2010 Earthquake, damages from the rain season present a much greater challenge [54]. In delivering solutions to relief organizations, limitations during a disaster situation such as data availability, computing power, and the form of the output expected by an organization can dictate the scope and form of a model. Practitioners can benefit from complex models outside the current capabilities of relief organizations. This type of model can give insight into the benefit of operational procedures without the expense of implementation. In addition, researchers can also explore the value of different levels of data collection and detailed knowledge of the situation by exploring models with different levels of complexity. A multi-stage stochastic model can be a better approximation of reality than a deterministic model, but requires significant effort to use in practice and may not provide significant improvement over a simpler model.

Disaster relief distribution models have existed in the operations research literature for only a little over two decades, and there are many years of potential future work. We need to continue to understand the real problems faced by practitioners, especially as their practices evolve. Improved technology such as UPS Trackpad, disaster management software, and GIS mapping can alleviate some of the chaos and provide better data sources for OR-based decision support systems. Along with technology, organizational and collaborative structures are improving with interagency collaboration like the Logistics Cluster and the increased emphasis on logistics in relief efforts. Advancing work in this area means advancing the ability to model highly chaotic and unpredictable distribution systems regardless of the modeling context. If models are to be flexible enough to address the high uncertainty of disasters, the framework can also be carried over into other areas with similar challenges.

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Appendix A. Major Disasters in the Last 30 Years

The Centre for Research on the Epidemiology of Disasters (CRED) maintains EM-DAT, a comprehensive database of disasters from 1900 to 2009. They define a disaster as an event in which at least one the following criteria are satisfied ([4]):

- Ten (10) or more people reported killed
- Hundred (100) or more people reported affected
- Declaration of a state of emergency.
- Call for international assistance.

They define a person as being affected as “requiring immediate assistance during a period of emergency, i.e., requiring basic survival needs such as food, water, shelter, sanitation and immediate medical assistance”, and total number of people affected includes all people injured, left homeless, or affected. The costs and scale of disasters are illustrated in Table A.1. Table A.1 shows the top five disasters in terms of lives lost from 1980 to 2009, along with the 2010 Haiti earthquake. More recent disasters in 2010, including estimates for the Pakistan 2010 floods are not yet available on EM-DAT. Estimated damage is defined in EM-DAT as follows: [4]

> The economic impact of a disaster usually consists of direct (e.g. damage to infrastructure, crops, housing) and indirect (e.g. loss of revenues, unemployment, market destabilisation) consequences on the local economy...For each disaster, the registered figure corresponds to the damage value at the moment of the event, i.e. the figures are shown true to the year of the event.

Table A.1: Top Five Disasters by Number of Lives Lost From 1980-2009 (plus 2010 Haiti Earthquake) and Number of Disasters 1980-2009 (source: [4])

Type	No. of Disasters, 1980-2009	Year	Country	Lives Lost	No. People Affected	Damage (Millions $)
Earthquake	756	2010	Haiti	222570	3,700,000	8000
		2004	Indonesia	165708	532898	4451.6
		2008	China P Rep	87476	45976596	85000
		2005	Pakistan	73338	5128000	5200
		1990	Iran Islam Rep	40000	710000	8000
Cyclone	2516	1991	Bangladesh	138866	15438849	1780
		2008	Myanmar	138366	2420000	4000
		1985	Bangladesh	15000	1810000	50
		1998	Honduras	14600	2112000	3793.6
		1999	India	9843	12628312	2500
Flood	3120	1999	Venezuela	30000	483635	3160
		1980	China P Rep	6200	67000	160
		1998	China P Rep	3656	238973000	30000
		1996	China P Rep	2775	154634000	12600
		2004	Haiti	2665	31283	

Table A.2: Terms Used in Table A.3 To Categorize Relief Routing Papers

- Objective function
  - Minimize cost: the objective minimizes costs, which may be travel, inventory costs, or a combination.
  - Minimize unsatisfied demand: the objective minimizes unsatisfied demand at beneficiaries. This may be the sum of unsatisfied demands over time, or minimization of the maximum unsatisfied demand.
  - Minimize latest arrival: the objective minimizes the latest arrival of goods to a group of beneficiaries.
  - Minimize total response time: the objective minimizes the total arrival time to all beneficiaries.
  - Maximize travel reliability: the objective maximizes the reliability of vehicles, such as the probability of vehicles arriving to their intended destinations.
- Goods
  - Stochastic supply: the quantity of goods available for distribution is uncertain.
  - Stochastic demand: the amount of need at final destinations is uncertain.
  - Multicommodity: multiple types of goods are transported, each having different quantities of demand and weight or volume taken up on vehicles.
- Routing
  - Multiple depot: vehicles routes begin and end at one of many designed depots.
  - Single depot: vehicle routes begin and end at a single depot.
  - No depot: vehicles do not have specific routes beginning and ending at depots.
  - Heterogeneous vehicles: vehicles can differ in transportation capacity, speed, fuel consumption, or roads and beneficiaries that are accessible to them.
  - Stochastic travel time: vehicle travel time can be uncertain.
- Test data
  - Data from real disasters: paper uses test cases with data from past disasters or using disaster scenario simulations.

Table A.3: Summary of Characteristics in Disaster Relief Distribution Models

	Min cost	Min unsatisfied demand	Min latest arrival time	Min total response time	Max travel reliability	Stochastic supply	Stochastic demand	Multicommodity	Multiple depot	Single depot	No depot	Heterogeneous vehicles	Stochastic travel time	Data from real disasters
Knott 1987 [9]		x								x		x		
Knott 1988 [48]								x		x		x		
Oh and Haghani 1996, 1997 [33, 34]	x			x				x			x	x		
Barbarosoğlu et al. 2002 [35]	x			x				x	x			x		x
Özdamar et al. 2004[26]		x						x			x	x		x
Barbarosoğlu and Arda 2004 [36]	x					x	x	x		x		x		x
Viswanath and Peeta 2006 [42]				x							x			x
Clark and Culkin 2007 [31]	x	x						x			x	x		x
De Angelis et al. 2007 [32]		x									x	x		x
Tzeng et al. 2007 [23]	x	x		x				x	x			x		x
Yi and Kumar 2007 [27]		x						x	x			x		
Yi and Özdamar 2007 [28]		x						x	x			x		x
Balcik et al. 2008 [25]	x	x						x		x		x		
Campbell et al. 2008[18]	x		x	x						x				
Hsueh et al. 2008 [49]			x	x						x				
Ukkusuri and Yushimoto 2008 [50]					x					x				
Zhu et al. 2008 [43]	x						x	x	x			x		x
Shen et al. 2009 [29, 30]		x		x			x			x		x	x	
Vitoriano et al. 2009 [44]					x				x			x		x
Huang et al. 2010 [19]	x		x	x						x				
Lin et al. 2010 [24]		x		x						x		x		x
Nolz et al. 2010 [20]			x	x						x		x		
Mete and Zabinsky 2010 [22]	x	x					x	x		x		x	x	x
Rawls and Turnquist 2010 [45]	x	x				x	x	x			x		x	x
Salmerón and Apte 2010 [46]		x									x	x	x	x
Van Hentenryck et al. 2010 [21]	x	x		x		x	x		x				x	x

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