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Review

A literature review on inventory management in humanitarian supply chains

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A B S T R A C T

In this paper, we present a review and analysis of studies that focus on humanitarian inventory planning and management. Specifically, we focus on papers which develop policies and models to determine how much to stock, where to stock, and when to stock throughout the humanitarian supply chain. We categorize papers according to the disaster management cycle addressed; specifically, we focus on pre-disaster and post-disaster inventory management. We evaluate existing literature in terms of problem aspects addressed such as decision makers, stakeholders, disaster types, commodities, facility types, performance measures as well as methodological aspects (i.e., types of policies, models, and solution approaches). We identify current gaps in the literature and propose directions for future research.

Contents

1. Introduction

Every year, disasters affect millions of people. According to [1] database, 6873 natural disasters occurred in the world between 1994 and 2013, resulting in 1.35 million deaths and affecting 218 million people on average per year [2]. Moreover, the world has witnessed the deadliest disasters of the century over the last decade; the total death toll from the 2004 Asian tsunami, the 2008 Cyclone Nargis, and the 2010 Haiti earthquake was more than 500,000. The number of climate-related disasters such as floods, droughts, storms and heat waves are also on the rise, and the intensity of such events is not expected to decrease in the future [3]. Furthermore, man-made disasters (such as conflicts, nuclear accidents, terrorist attacks) threaten the lives of people; for instance, the Syrian conflict, which started in 2011, has triggered the world's largest humanitarian crisis since World War II, killing more than 200,000 people to date and causing millions of people to be displaced [4].

Amid all the difficulty, people affected by disasters rely on life-saving assistance (such as food, shelter, water) from humanitarian organizations. Depending on location, timing, type and intensity of disasters, there may be significant differences in needs of victims and scale and scope of disaster responses. Nevertheless, a common objective for all relief operations is to access people in need and deliver aid on time. In other words, similar to the traditional supply chains, humanitarian supply chains must be designed to provide "the right supplies with the right quality at the right time in the right place to the ultimate customer" [5]. Effective logistics management is essential to achieve this objective. Humanitarian logis-

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tics involves procurement, warehousing, inventory management, transportation, and distribution functions, and is the most expensive part of disaster relief operations [6].

The importance of effective logistics management has been increasingly acknowledged in the humanitarian sector over the last years, and this increased attention has also found its counterpart in academia. The unique and challenging humanitarian environment (see e.g., [5,7–9]) have attracted many researchers to this field. As a result, the number of articles in Operations Research (OR) and Management Science (MS) focusing on humanitarian logistics has tremendously increased in the last decade. Several literature survey articles are also published, which examine the existing disaster management/humanitarian logistics (DM/HL) studies and evaluate the state-of-the-art from different perspectives (see Section 2). In this paper, we present a survey of OR/MS studies that focus on *humanitarian inventory management*, which highly affects the efficiency and responsiveness of humanitarian supply chains. Although some of the existing literature survey papers include discussions on inventory management, to the best of our knowledge, there is no study that particularly examines the policies and models developed for managing humanitarian inventories.

The fundamental questions of inventory management are the same for commercial and humanitarian supply chains, which are (i) *how much to order*, (ii) *when to order*, and (iii) *where to store* [10]. There is a well-established inventory management literature, which focuses on answering these questions for commercial supply chains. However, due to the unique characteristics of humanitarian settings, the policies and models developed for commercial supply chains may not be directly applied to manage humanitarian inventories [10]. Below, we summarize the distinct features of humanitarian inventories:

- *Objectives*. Improving customer service and decreasing inventory costs are important for both humanitarian organizations and business enterprises. However, efficiency is usually the most important objective in commercial inventory management, while satisfying beneficiary needs is always the utmost priority for humanitarian organizations. Whybark [10] considers humanitarian relief inventories as one form of "social" inventories, which "*serve broad social objectives as opposed to being used for the benefit of an individual*" [10]. Whybark [10] stresses the need for further research that investigates the criteria to use while making inventory decisions in disaster relief settings. While the benefits from keeping inventory can be usually converted to monetary measures in the commercial sector (e.g., lost profits), it is challenging for humanitarian organizations to quantify the benefits associated with serving people affected by disasters [10,11]. A critical criterion to consider in managing disaster inventories can be deprivation cost, which associates an economic value for human suffering due to lack of access to relief supplies [12].
- *Ownership*. Humanitarian relief inventories might have multiple owners such as governments and non-governmental/private organizations. Therefore, it is often difficult to have accurate information about the aggregate amount of stocks on-hand [10].
- *Demand*. There is a high level of uncertainty associated with timing, location, type and amount of demand in most humanitarian settings, which bring significant challenges in developing effective inventory policies [10]. Demand-related parameters are usually more predictable in commercial settings. Moreover, demand can be forecasted using historical sales data in commercial settings, whereas historical information for relief demand may not be available. Furthermore, since victims in a disaster area has no choice over the aid supplies, true demand for commodities may never become known [7]. Finally, when a disaster occurs, demand must be immediately satisfied implying zero lead time requirements, while customers may be willing to wait for a reasonable amount of time in commercial settings.
- *Infrastructure*. The network infrastructure is generally reliable in commercial settings, whereas post-disaster network may be damaged and involve uncertainties. Furthermore, disasters may affect the power infrastructure in the affected regions, which may also prevent relief organizations from using advanced technologies to track and manage inventories. Business enterprises usually use technologies that support their decisions and operations with minimal or no interruption, and hence they usually have full inventory visibility.
- *Financial resources*. Humanitarian organizations collect most of the donations after disaster occurrences. Therefore, humanitarian organizations may not have financial resources necessary to keep and manage inventory. Moreover, some donations may be earmarked for certain operations and needs. Commercial organizations usually have less constraints in allocating budgets for inventory-related expenses.
- *Sourcing*. Humanitarian organizations may need to consider several issues while making sourcing decisions. For instance, purchasing supplies from local suppliers is usually preferred to support long-term economical development of the affected region. Giving equal opportunity to different suppliers might be an important concern, as well. Therefore, humanitarian organizations may not necessarily look for the most economical way to acquire relief supplies, which may affect ordering decisions and inventory management. Commercial organizations usually do not have such constraints preventing them from making the lowest cost acquisitions [11].

The OR/MS studies that address humanitarian inventory management develop new approaches (or adopt existing ones) to capture the unique aspects of the humanitarian environment. In this paper, we provide a systematic review of articles that present mathematical models for inventory management in humanitarian networks. In particular, we examine the papers which involve one or more of the following inventory management decisions: *where to stock*, *when to stock*, and *how much to stock*. These decisions may be of concern in different disaster management phases. We find that the existing studies that focus on pre-disaster inventory management generally address *long term pre-positioning decisions* (i.e., determining location and amount of stocks), while the studies on post-disaster (or post-warning) inventory management consider *short-term pre-positioning and inventory ordering* decisions. That is, according to our classification in this paper, pre-positioning decisions in the pre-disaster stage are generally made with no advance information or by only using historical data, while pre-positioning and ordering decisions in the post-disaster/warning stage are made once some information about a disaster become available. In this study, we review characteristics of the models developed to manage inventory in pre- and post-disaster/warning phases. The papers, which purely focus on facility location or routing/distribution decisions while assuming a fixed amount of inventory at the facilities, are not within the scope of this survey; interested readers are referred to other survey papers, which exclusively focus on distribution network design (e.g., [13]) and routing models (e.g., [14]) in humanitarian relief.

In Section 2, we provide a review of literature surveys on HL/DM and position our study. Section 3 presents our survey methodology. In Section 4, we present an in-depth analysis on characteristics of the studies that focus on pre-disaster and post-disaster/warning inventory management. Finally, we identify future research directions and present concluding remarks in Section 5.

Table 1
Survey citation statistics. (+ denotes the survey article in the corresponding column cites the article in that row.)

List of cited articles	Literature surveys																		
	Altay and Green [15]	Anaya-Arenas et al. [13]	Apte [9]	Caunhye et al. [16]	Çelik et al. [8]	De la Torre et al. [14]	Galindo and Batta [17]	Habib et al. [18]	Hoyas et al. [19]	Johnson and Smilowitz [20]	Kunz and Reiner [21]	Leiras et al. [22]	Liberatore et al. [23]	Natarajarathinam et al. [24]	Ortuño et al. [25]	Overstreet et al. [26]	Özdamar and Ertem [27]	Simpson and Hancock [28]	White et al. [29]
Balcik and Beamon [30]		+	+	+	+			+	+			+	+		+	+	+		
Beamon and Kotleba [31]			+	+	+		+			+		+		+	+	+			
Beamon and Kotleba [32]			+		+							+			+	+			
Bozkurt and Duran [33]																			
Bozorgi-Amiri et al. [34]		+						+				+							
Campbell and Jones [35]		+										+							
Chakravarty [36]																			
Das and Hanaoka [11]																			
Davis et al. [37]		+																	
Döyen et al. [38]					+				+										
Duran et al. [39]				+								+	+				+		
Galindo and Batta [17]																			
Garrido et al. [40]																			
Hong et al. [41]																			
Klibi et al. [42]																			
Lodree and Taskin [43]												+		+		+			
Lodree [44]												+							
Lodree et al. [45]		+																	
Lodree and Taskin [46]			+	+			+				+								
Manopiniwes et al. [47]																			
McCoy and Brandeau [48]												+							
Mete and Zabinsky [49]		+		+	+	+					+	+	+				+		
Mohammadi et al. [50]																			
Natarajan and Swaminathan [51]																			
Noyan [52]					+				+			+	+						
Noyan et al. [53]																			
Ozbay and Ozguven [54]																+		+	
Ozguven and Ozbay [55]																			
Pacheco and Batta [56]																			
Paul and MacDonald [57]																			
Rabbani et al. [58]																			
Rawls and Turnquist [59]		+		+	+	+	+	+	+			+							
Rawls and Turnquist [60]		+			+			+				+							
Rawls and Turnquist [61]		+			+			+	+			+							
Renkli and Duran [62]																			
Roni et al. [63]																			
Roni et al. [64]																			
Rottkemper et al. [65]		+			+				+			+	+						
Salas et al. [66]																			
Shen et al. [67]																			
Taskin and Lodree [68]							+					+							
Taskin and Lodree [69]											+								
Tofighi et al. [70]																			
Van Hentenryck et al. [71]					+	+			+				+		+				
Yadavalli et al. [72]																			
Number of articles in common	0	10	4	6	11	3	4	5	7	1	3	16	6	2	4	5	3	1	0

2. Earlier literature surveys

In this section, we provide an overview of literature survey papers that focus on HL/DM. Our intention is not to provide an exhaustive list of all survey papers on this topic. We identify the common aspects of our study with the most related papers and specify our contribution. We investigate 19 literature survey papers on humanitarian logistics. Table 1 lists the 45 articles that are reviewed in our study (rows) and shows other survey papers (columns) citing these articles.

The earliest literature survey on HL/DM is presented by Altay and Green [15], which examines 109 papers published between 1980 and 2004, discusses the characteristics of humanitarian operations, and identifies future research needs. There has been a significant increase in the number of survey articles that focus on HL/DM over the last decade. Several surveys extend [15] in different ways such as including recent articles, considering additional classification criteria, or applying a different survey methodology (e.g., [9,26,8,21,73,22]).

There are also literature review studies that focus on a related broader topic and include HL/DM as a sub-topic. For instance, [28] focus on general emergency response services and review the articles that focus on small-scale emergencies (such as fires) and large-scale emergencies simultaneously. White et al. [29] review OR applications in developing countries, where most of the focus is on long-term development issues. Johnson and Smilowitz [20] discuss HL/DM within the context of community-based OR. Natarajarathinam et al. [24] focus on managing supply chains under crisis, which may be caused by disasters or other causes such as financial crisis.

Table 2
List of keywords used in the initial search.

Keyword set 1	Keyword set 2
Humanitarian	Inventory
Disaster	Pre-positioning
Catastrophe	Stock
Emergency	
Hurricane	
Earthquake	
Flood	

Our study is similar to the survey articles in HL/DM that focus on a specific problem type and/or phases in the disaster management cycle and examine/classify the OR models developed to assist humanitarian operations. For instance, [16] review the optimization models in humanitarian logistics by focusing on disaster preparedness and response phases, and classify the articles based on the decisions addressed and the modeling aspects (such as objectives and constraints). Özdamar and Ertem [27] particularly focus on mathematical models developed for the recovery and response phases. De la Torre et al. [14] focus on OR models for disaster relief distribution and examine problem aspects covered in the literature. Anaya-Arenas et al. [13] also review articles on relief distribution networks, focusing on facility location and transportation problems. Habib et al. [18] review the studies that present mathematical models for facility location, relief distribution, and evacuation problems. Ortuño et al. [25] classify the papers based on the disaster management phase addressed and the optimization technique used. Liberatore et al. [23] and Hoyos et al. [19] particularly focus on modeling uncertainty and present an analysis of stochastic models in the HL/DM literature.

We observe that most of the literature surveys focus on pre-positioning, distribution (routing, transportation, resource allocation), and evacuation problems in HL/DM. While inventory management is included in some of the existing surveys (e.g., [9]), the details of inventory policies/models are not discussed in detail. Furthermore, as shown in Table 1, our study includes some papers which have not been addressed by any previous survey papers. As a result, our paper contributes to the HL/DM literature by providing an in-depth discussion on humanitarian inventory management problems and models, and presenting future research directions.

3. Search methodology

In this section, we explain the search methodology followed to identify the papers cited in this survey. Table 2 shows the set of keywords used in our initial search. We search for papers using each combination of keywords (one from each column) from the Web of Science database and Google Scholar. Specifically, the first set of keywords is used to locate studies in the HL/DM literature, and the second set is to identify inventory-related studies.

In order to ensure including all relevant studies, we additionally search for the keywords *humanitarian logistics*, *disaster logistics*, and *emergency logistics* from Web of Science, and filtered the papers that are related to the fields of *Operations Research Management Science*, *Engineering*, and *Mathematics*. Next, we went through all articles on Web of Science citing the most-cited papers in our pool, i.e., Beamon and Kotleba [31], Lodree and Taskin [43], and Balcik and Beamon [30]. Finally, we identify relevant papers for our study, that specifically focus on *inventory models in HL/DM* and investigate references of these papers. The articles which take inventory-related costs into account and involve ordering and pre-positioning decisions are kept, and the studies that solely focus on *facility location*, *transportation planning*, and *network flow models* are excluded.

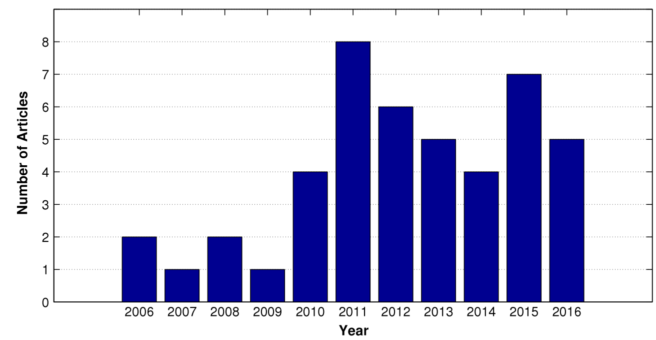

Fig. 1. Distribution of articles on humanitarian inventory management according to years.

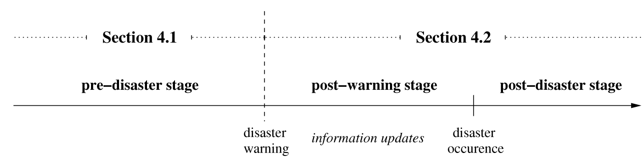

Fig. 2. Categorization of studies.

This search and screening process resulted in a total of 45 papers. One of these papers addresses both pre- and post-disaster inventory management [58], while 22 studies focus only on pre-disaster inventory planning and 22 involves only post-disaster inventory models. 43 papers are published in 25 different journals. Distribution of articles according to their publication years and journals are presented in Fig. 1 and Table 3, respectively. One technical report [42] and one conference proceeding paper [71] are not included in Table 3.

In addition to the aforementioned articles, 19 survey articles on humanitarian logistics are investigated. It should be noted that our study refers to 20 unique studies that are not covered by any other survey article. Moreover, the highest number of common studies with an existing survey paper is 16 [22]. The number of common articles with other surveys are presented in Table 1.

4. Models for humanitarian inventory management

Humanitarian organizations face different inventory management decisions in disaster preparedness and response phases. We review the studies that present models for pre-disaster and post-disaster inventory management in Sections 4.1 and 4.2, respectively (see Fig. 2). Some studies specifically focus on inventory decisions made after a *warning* for an approaching disaster. We discuss these *post-warning* studies in Section 4.2, as the planning horizon considered in the post-warning models usually extend to the post-disaster period.

Next, we present an analysis of the pre- and post-disaster inventory management literature in terms of the important *problem aspects* considered (e.g., stakeholders, disaster types, commodities, facilities, etc.) and the *methodologies* (i.e., type of models and solution approaches) developed/used.

4.1. Pre-disaster inventory management

In this section, we discuss the characteristics of studies, which focus on pre-disaster inventory planning and management. We observe that studies addressing the pre-disaster stage mostly focus on long-term pre-positioning decisions, which involves storing emergency relief supplies at strategic locations before a disaster occurs to improve post-disaster response. Given the uncertainties regarding timing, location, and size of demands for emergency

Table 3
Distribution of humanitarian inventory management articles according to journals.

Journal name	Number of articles
International Journal of Production Economics	5
European Journal of Operational Research	4
OR Spectrum	4
Socio-Economic Planning Sciences	4
Journal of the Operational Research Society	4
International Journal of Logistics: Research and Applications	2
Computers & Operations Research	2
The International Journal of Logistics Management	1
Journal of Humanitarian Logistics and Supply Chain Management	1
Manufacturing & Service Operations Management	1
Transportation Research Record: Journal of the Transportation Research Board	1
Transportation Research Part C	1
Uncertain Supply Chain Management	1
Omega	1
Annals of Operations Research	1
International Journal of Environmental Research and Public Health	1
Optimization Letters	1
Interfaces	1
IIE Transactions	1
Industrial engineering & Management systems	1
Applied Mathematical Modeling	1
Transportation Research Part B	1
Human and Ecological Risk Assessment: An International Journal	1
Transportation Science	1
Transportation Research Part E	1

supplies, effective pre-positioning is essential for humanitarian organizations in order to mobilize and deliver supplies quickly after a disaster occurs. There is a growing OR literature that addresses a variety of problem settings and presents mathematical models to determine the location and amount of relief supplies to pre-position in a humanitarian supply network. We particularly focus on studies that determine the amount of relief supplies to keep in the humanitarian supply network along with the locations of the storage facilities.

We identified **23** studies that focus on pre-disaster inventory decisions. Below, we first evaluate the literature in terms of the characteristics of the problems addressed and then discuss the methodological approaches. Tables 4–6 summarize characteristics of each study that addresses pre-disaster inventory management.

4.1.1. Problem aspects

4.1.1.1. Decision maker and the stakeholders. There are several stakeholders with different roles in humanitarian supply chains, including humanitarian organizations (local and international), affected populations, donors, host governments, and relief suppliers; the stakeholders considered in the reviewed studies are exhibited in Table 4. We observe that all of the papers, which focus on determining the amount of inventory to pre-position before a disaster, consider a single humanitarian organization as the decision maker. That is, the stocks at the located facilities are owned and managed by a humanitarian organization that performs disaster response operations and delivers supplies to the people in need.

In most studies, the humanitarian supply network involves two tiers; that is, emergency supplies kept at facilities are sent to beneficiaries (see Table 4). There are some studies, in which procurement of relief commodities from the suppliers is also considered; suppliers may send supplies directly to the demand locations or to other facilities (e.g., [34,39,42]). In these studies, the humanitarian organization is still the only decision maker; that is, delivery amounts from the supplier(s) are determined by the humanitarian organization.

4.1.1.2. Disaster type. We investigate whether the pre-disaster inventory management models address a specific disaster type such as sudden-onset disasters, slow-onset disasters, or man-made disasters. We observe that most of the studies are motivated by sudden-onset disasters such as earthquakes, floods and hurricanes (see Table 4). There is a high level of uncertainty associated with the occurrence of sudden-onset disasters, and it is challenging and essential to account for this uncertainty while making pre-positioning decisions. Most of the pre-positioning models in the literature characterize the uncertainty regarding the location and amount of demand through a finite set of scenarios and use a two-stage stochastic programming approach. We observe that most of the studies specify a disaster type for the purpose of framing the problem setting and/or illustrating their approach by realistic case studies. That is, the proposed two-stage models can be used to make inventory pre-positioning decisions in a generic sudden-onset disaster setting, in which post-disaster uncertainties can be characterized by discrete scenarios.

We also examine whether a real-world/realistic case study is presented in the studies that focus on pre-disaster inventory management. As shown in Table 4, a majority of papers present case studies on earthquakes (e.g., [30,49,34]), hurricanes (e.g., [59,17]), and floods (e.g., [47,40]). These studies generally process historical real-world data obtained from various databases or software (e.g., [1,74]) to specify a network with potential demand locations and generate scenarios. Other parameters required for applying the models (e.g., candidate facilities and their capacities, costs) are usually set hypothetically. Only a few papers focus on designing a network for a specific humanitarian organization (e.g., [39]). We observe that most studies focus on pre-positioning supplies at city (e.g., [49]), regional (e.g., [59]), or global (e.g., [30]) level. Country-level settings are also considered in a few papers (e.g., [47,58]).

4.1.1.3. Demand characteristics. A variety of emergency relief supplies are pre-positioned in humanitarian supply chains such as tents, blankets, medical kits, mosquito nets, hygiene kits, etc. As shown in Table 4, most of the studies consider pre-positioning of multiple items. In these studies, commodities may be differentiated in terms of their demands, urgencies (i.e., coverage requirements) and other parameters such as unit costs (e.g., procurement, transportation, inventory, shortage penalty) and unit capacities (e.g., [30,59,40]). A few studies propose single item models; for instance, Campbell and Jones [35] and

Table 4
Problem aspects in pre-disaster inventory management.

Article	Network, case study (Disaster type)	Demand: Randomness	Demand: Number of items	Demand: Perishability	Facilities: Capacitated	Facilities: Damage possibility	Stakeholders	Number of tiers
Balcik and Beamon [30]	Global, case study (Earthquake)	Stochastic	>1	–	+	–	HO, beneficiaries	2
Bozkurt and Duran [33]	Global, case study (Sudden onset disasters)	Stochastic	>1	–	–	–	HO, suppliers, beneficiaries	3
Bozorgi-Amiri et al. [34]	Regional, case study (Earthquake)	Stochastic	>1	–	+	+	HO, suppliers, beneficiaries	3
Campbell and Jones [35]	Hypothetical	Stochastic	1	–	–	+	Suppliers,beneficiaries	2
Chakravarty [36]	Hypothetical	Stochastic	1	–	–	–	HO,suppliers, beneficiaries	3
Döyen et al. [38]	Hypothetical (Earthquake)	Stochastic	>1	–	+	–	HO, beneficiaries	3
Duran et al. [39]	Global, case study (Sudden onset disasters)	Stochastic	>1	–	+	–	HO, suppliers, beneficiaries	3
Galindo and Batta [17]	Case study (Hurricane)	Stochastic	1	–	+	+	HO,beneficiaries	3
Garrido et al. [40]	Hypothetical, case study (Flood)	Stochastic	>1	–	+	–	HO, supplier, beneficiaries	3
Hong et al. [41]	Case study (Hurricane)	Stochastic	1	–	+	–	HO,beneficiaries	2
Klibi et al. [42]	Regional, case study (Natural disasters)	Stochastic	>1	–	+	–	HO, suppliers, beneficiaries	3
Lodree and Taskin [43]	Hypothetical (Sudden onset disasters)	Stochastic	1	–	–	–	HO, beneficiaries	2
Manopiniwes et al. [47]	Country, case study (Flood)	Deterministic	>1	–	+	–	HO, beneficiaries	2
Mete and Zabinsky [49]	City, case study (Earthquake)	Stochastic	>1	–	+	–	HO, beneficiaries	2
Mohammadi et al. [50]	City, case study (Earthquake)	Stochastic	>1	–	+	–	HO, beneficiaries	2
Noyan [52]	Regional, case study (Hurricane)	Stochastic	>1	–	+	+	HO, beneficiaries	2
Paul and MacDonald [57]	City, case study (Earthquake)	Stochastic	1	–	+	+	HO, beneficiaries	2
Rabbani et al. [58]	Country, case study (Earthquake)	Stochastic	>1	+	+	–	HO, beneficiaries	2
Rawls and Turnquist [59]	Regional, case study (Hurricane)	Stochastic	>1	–	+	+	HO, beneficiaries	2
Rawls and Turnquist [60]	Regional, case study (Hurricane)	Stochastic	>1	–	+	+	HO, beneficiaries	2
Renkli and Duran [62]	City, case study (Earthquake)	Deterministic	>1	–	+	–	HO, beneficiaries	2
Tofighi et al. [70]	City, case study (Earthquake)	Stochastic	>1	–	+	+	HO, beneficiaries	3
Van Hentenryck et al. [71]	Hypothetical (Hurricane)	Stochastic	1	–	+	–	HO, beneficiaries	2

Chakravarty [36] focus on single-item settings and derive optimal inventory and/or delivery amounts analytically. Hong et al. [41] assume that several emergency items (such as tents, blankets, kitchen sets) are bundled into standard kits/pallets and consider a single bundled commodity.

Most of the studies focus on a generic emergency supply. Exceptions to this include [49], which specifically focus on pre-positioning of medical supplies distributed to hospitals after a disaster occurs. Rabbani et al. [58] specifically focus on pre-positioning and distribution of perishable commodities; more specifically, their model considers replacement of close-to-expiry supplies with fresh ones.

As indicated in Table 4, most studies consider stochastic demand for relief supplies. We observe that a majority of papers use discrete scenarios to characterize the uncertainty in demands (e.g., [49,52]). The scenario-based approach does not require assuming a particular probability distribution for random demand. Klibi et al. [42] and Garrido et al. [40] use Monte-Carlo approaches to generate disaster scenarios. Campbell and Jones [35] and Chakravarty [36] assume that demand follows Normal and Weibull distribution, respectively. Some studies incorporate an expected demand parameter into the models, which is estimated by processing historical data (e.g., [17,57]).

4.1.1.4. Decisions and planning horizon. All of the models analyzed in this section focus on long-term pre-positioning of inventory to prepare for sudden onset disasters. More specifically, they focus on determining the amount of relief supply inventories to keep at various facilities by considering future disaster scenarios and decisions. The pre-disaster decisions involve locating facilities and determining the amount of stocks to keep at each facility, while post-disaster decisions are mostly operational decisions about shipment/delivery of supplies to the beneficiaries. Some studies model the post-disaster operations in a more detailed way; for instance, transshipment of supplies among the facilities (e.g., [34]), routing of vehicles (e.g., [49]), or possibility of damaged facilities and stocks (e.g., [57]) are considered.

In almost all studies, a single-period problem is formulated for the post-disaster stage. That is, relief deliveries, which are usually made over multiple periods during the post-disaster environment, are aggregated to one period and one-time satisfaction of demand is assumed. Consequently, the unsatisfied demand in the second

Table 5
Performance measures in pre-disaster inventory management studies.

Article	Metrics/Objectives
Balcik and Beamon [30]	[Max] Total expected demand covered Cost of transporting supplies and locating facilities
Bozkurt and Duran [33]	[Min] Expected average response time
Bozorgi-Amiri et al. [34]	[Min] Expected total costs (facility, ordering, transportation, transshipment, holding, shortage) [Min] variability of the total cost [Min] Sum of maximum shortage across items
Campbell and Jones [35]	[Min] Expected total costs (ordering, restocking/disposal, transportation, shortage)
Chakravarty [36]	[Max] Buyer's expected surplus [Min] Expected ordering, holding, and transportation costs [Min] Expected response time
Döyen et al. [38]	[Min] Expected total costs (facility, holding, transportation, shortage) Response time
Duran et al. [39]	[Min] Expected average response time
Galindo and Batta [17]	[Min] Expected total costs (facility, transportation, destroyed supplies)
Garrido et al. [40]	[Min] Expected total costs (holding, transportation) Probability of demand satisfaction
Hong et al. [41]	[Min] Expected total costs (facility, ordering) Probability of satisfying demand within a target response time Equity in demand satisfaction (in terms of fraction of demand satisfied)
Klibi et al. [42]	[Min] Total shortage cost Cost of locating facilities and holding inventory
Lodree and Taskin [43]	[Min] Expected total cost (ordering, holding, shortage)
Manopiniwes et al. [47]	[Min] Expected total costs (facility, holding, transportation) Response time
Mete and Zabinsky [49]	[Min] Expected total costs (facility, ordering, transportation, shortage)
Mohammadi et al. [50]	[Max] Total expected demand coverage [Min] Expected total costs (facility, supply, transportation) [Min] Maximum difference between demand nodes' satisfaction rates (equity)
Noyan [52]	[Min] Expected total costs (facility, holding, transportation, shortage)
Paul and MacDonald [57]	[Min] Expected total costs (facility, ordering, fatalities)
Rabbani et al. [58]	[Min] Expected total costs (facility, ordering, transportation, shortage, spoilage)
Rawls and Turnquist [59]	[Min] Expected total costs (facility, holding, transportation, shortage)
Rawls and Turnquist [60]	[Min] Expected total costs (facility, holding, transportation, shortage) Probability of satisfying demand within a target response time
Renkli and Duran [62]	[Min] Total weighted response time Probability of satisfying demand
Tofighi et al. [70]	[Min] Expected total costs (facility, ordering, holding, transportation) [Min] Total weighted response time [Min] Maximum weighted response time (equity) [Min] Shortage and surplus
Van Hentenryck et al. [71]	[Min] Expected total costs (facility, inventory, transportation, shortage)

stage is usually assumed to be lost and penalized. Multi-period models are presented in [58,40], which consider periodic replenishment of commodities in the post-disaster stage.

4.1.1.5. Facilities. There may be several facilities at different sizes/levels managed by a humanitarian organization in the humanitarian supply chain. The facilities that hold pre-positioned supplies for disaster preparedness are usually permanent structures (e.g., large warehouses). We observe that most of the studies consider a two-tier network with a set of facilities at the second tier serving the beneficiaries at the first tier. As shown in Table 4, a few studies consider a third tier, which may correspond to upstream suppliers or a central warehouse (e.g., [34,17]). The locations of these third-tier facilities and their capacities are generally assumed to be fixed and known, and most studies focus on inventory planning at the second-tier facilities. An exception is [70], which determines locations and inventory levels of the central warehouses and the local distribution centers. The authors assume that critical relief items (such as water and medical first aid kits) are kept at both facility types, but less critical items (such as blankets) are only held in the central warehouses. Also, Döyen et al. [38] consider different facility types and assume that pre-disaster inventory is only kept at the central warehouse, and local facilities are located and used in the post-disaster phase.

As shown in Table 4, almost all studies consider capacitated facilities. Furthermore, some studies differentiate facilities within the same tier based on their sizes (e.g., [59,52,70,57]). Table 4 also shows the studies which consider possibility of destructive effects of the disasters on facilities and the pre-positioned stocks (e.g., [52,

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Table 6
Methodological approaches in pre-disaster inventory management studies.

Article	Model type	Solution approach
Balcik and Beamon [30]	Two-stage stochastic programming	Exact; Optimization solver
Bozkurt and Duran [33]	Two-stage stochastic programming	Exact; Optimization solver
Bozorgi-Amiri et al. [34]	Robust optimization, two-stage stochastic programming; Multi-objective optimization	Exact; Optimization solver
Campbell and Jones [35]	Stochastic programming	Exact; Numerical techniques; Heuristic
Chakravarty [36]	Stochastic optimization	Exact; Numerical techniques
Döyen et al. [38]	Two-stage stochastic programming	Exact; Optimization solver; Heuristic; Lagrangian relaxation
Duran et al. [39]	Two-stage stochastic programming	Exact; Optimization solver
Galindo and Batta [17]	Stochastic optimization	Exact; Optimization solver
Garrido et al. [40]	Stochastic programming; Chance-constraints	Heuristic; Sample average approximation; Optimization solver
Hong et al. [41]	Two-stage stochastic programming; Chance-constraints	Exact; Optimization solver; Gale-Hoffman inequalities; Combinatorial pattern-based method
Klibi et al. [42]	Two-stage stochastic programming	Exact; Optimization solver; Sample average approximation
Lodree and Taskin [43]	Newsvendor model	Exact; Numerical techniques; Mathematical computing software
Manopiniwes et al. [47]	Mixed integer programming	Exact; Optimization solver
Mete and Zabinsky [49]	Two-stagestochastic programming	Exact; Optimization solver
Mohammadi et al. [50]	Two-stage stochastic programming; Multi-objective optimization	Heuristic; Particle swarm optimization
Noyan [52]	Two-stage stochastic programming; Conditional Value-at-Risk	Exact; Optimization solver; Benders-decomposition algorithm
Paul and MacDonald [57]	Stochastic optimization	Heuristic; Evolutionary algorithm; Newsvendor approach
Rabbani et al. [58]	Two-stage stochastic programming	Exact; Optimization solver
Rawls and Turnquist [59]	Two-stage stochastic programming	Exact; Optimization solver; Lagrangian L-shaped method
Rawls and Turnquist [60]	Two-stage stochastic programming; Chance-constraints	Exact; Optimization solver
Renkli and Duran [62]	Mixed integer programming; Chance-constraints	Exact; Optimization solver
Tofighi et al. [70]	Two-stage possibilistic-stochastic programming; Multi-objective optimization	Exact; Optimization solver; Heuristic; Tailored differential algorithm
Van Hentenryck et al. [71]	Two-stage stochastic programming	Exact; Optimization solver

34,17]); a scenario-based approach is usually used to incorporate this possibility in the models.

4.1.1.6. Performance measures. Table 5 presents the performance measures considered for pre-disaster inventory management. The proposed models incorporate these measures either through objectives or constraints. The main types of performance measures are summarized below:

- *Costs*. As discussed in [30], the costs associated with pre-positioning inventory can be prohibitive for many humanitarian organizations. Consequently, the majority of pre-positioning models in the literature consider cost as a primary concern and minimize expected total costs in the objective function, and some models incorporate costs by using budget constraints. Bozorgi-Amiri et al. [34] focus on minimizing both expected total costs and variability of total costs. The most commonly considered cost items are related to locating facilities, purchasing supplies, holding inventory, transporting supplies, and shortage penalties. In the two-stage stochastic programming models, facility location, purchasing and inventory holding costs are usually considered in the first stage, whereas transportation and shortage costs incur in the second stage.
- *Response time*. Since the main purpose of pre-positioning inventory is to deliver supplies quickly after a disaster occurrence, response time (i.e., the time to reach beneficiaries from the located facilities) is considered as an important concern in several studies. Some models minimize expected total or average response time (e.g., [39]), while some limit maximum response time through constraints (e.g., [38]).
- *Coverage (or Shortage)*. Coverage, which is the proportion of total demand that can be covered from the pre-positioned inventory, is one of the common performance metrics used in the models. Most studies incorporate response time expectations while defining coverage. Some studies focus on maximizing coverage (e.g., [30]); and equivalently, some of them minimize the penalty costs due to shortages (unsatisfied demand) (e.g., [59]). Rawls and Turnquist [60] and Hong et al. [41] limit the probability of satisfying demand within a target response time.
- *Equity*. Providing equitable service to demand locations is considered as an important concern in some studies; for instance, Tofighi et al. [70] consider equity in terms of response time, while Hong et al. [41] and Mohammadi et al. [50] aim to ensure equitable service in terms of the fraction of demand satisfied.

4.1.2. Methodological aspects

In this section, we provide an overview of the modeling and solution approaches used in studies that focus on pre-disaster inventory planning, which are summarized in Table 6. As observed from the table, almost all of the studies focus on developing stochastic models to support pre-positioning decisions; only a few studies follow a deterministic modeling approach (e.g., [47]). Specifically, two-stage programming is the most common modeling approach (e.g., [49,59,38]); these studies characterize the uncertainties in the post-disaster demand locations and amounts by using a set of scenarios. In some studies, scenarios additionally involve uncertainties regarding post-disaster conditions of the transportation network and facilities (e.g., [59,38,17,41]), costs (e.g., [70]), and supply availability (e.g., [34]). The pre-positioning literature generally follows a risk-neutral approach, in which expected values of the performance measures are optimized. As discussed in [52], the solutions obtained by optimizing expectations may perform poorly under certain realizations of the random data. Noyan [52] proposes a risk-averse model for pre-propositioning supplies by incorporating Conditional Value-at-Risk (CVaR) as a risk measure on the total cost in addition to the expectation criterion. Bozorgi-Amiri et al. [34] introduce a robust optimization model that minimizes variability of total costs. Rawls and Turnquist [60], Hong et al. [41] and Renkli and Duran [62] introduce probabilistic (chance) constraints to ensure that at least a certain portion of demands is satisfied within a target period of time. Tofighi et al. [70] develop an approach that incorporates imprecise (possibilistic) and random data simultaneously; in other words, the authors assume that scenario dependent data can be fuzzy and propose a two-stage possibilistic-stochastic programming approach.

The proposed two-stage stochastic programming models are mostly solved using various optimization solvers (such as CPLEX, LINGO, Gurobi) (e.g., [30,49,39]). However, these general-purpose

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solvers may not find good solutions for large problem instances within a reasonable amount of computation time, in particular when the number of scenarios is large. Hence, some studies develop exact and heuristic solution approaches to solve the proposed models. For instance, Döyen et al. [38] develop a heuristic based on Lagrangian relaxation; the initial solution found by the Lagrangian heuristic is further improved by a local search algorithm. Mohammadi et al. [50] and Tofighi et al. [70] develop population-based metaheuristic algorithms based on particle swarm-optimization and differential evolution, respectively. Studies that develop effective exact algorithms by utilizing the special structures of the proposed models involve [59,52,41].

While most studies consider multiple performance measures critical to pre-positioning humanitarian inventories, the proposed models mostly involve a single objective and incorporate other relevant metrics via constraints (see Table 5). Only a few studies use multi-objective modeling and optimization techniques, which are presented in Table 6. For instance, Bozorgi-Amiri et al. [34] consider two objective functions to minimize expected total costs and variability of total costs, and minimize total shortages; they use Compromise Programming to solve the proposed multi-objective model. Mohammadi et al. [50] develop a three-objective stochastic model, which maximizes demand coverage, minimizes costs and ensures equity by minimizing the maximum difference in demand satisfaction rate between the demand locations; a multi-objective particle swarm optimization metaheuristic is developed to solve this model. Tofighi et al. [70] develop a two-stage mathematical model, whose second stage objective focuses on response times, inventory costs and equitable distribution of supplies; the authors use a weighted ϵ-constraint method to convert the multi-objective second stage problem to a single-stage one, and then find an efficient (Pareto-optimal) solution for the whole problem.

There are only a few papers that use other stochastic optimization methods than two-stage stochastic programming models to support pre-disaster inventory management. These studies usually consider more stylized problem settings and focus on deriving optimal inventory amounts analytically. Lodree and Taskin [43] develop a newsvendor model, which accounts for demand uncertainty as well as the uncertainty related to occurrence of a disaster. The authors associate an insurance framework with retailers' proactive inventory management policies on extreme events; specifically, the premium and payoff associated with an insurance policy are interpreted as the costs and benefits associated with holding inventory, respectively. Campbell and Jones [35] derive equations for the optimal positioning of supplies to serve a single demand point from a single supply point; the authors consider possibility of destructions of supply points. Chakravarty [36] determine the optimal amounts to stock before a disaster analytically, and study the interaction between response time and quantity.

4.2. Post-disaster and post-warning inventory management

In this section, we discuss characteristics of studies which focus on inventory planning *after a disaster occurs* or *signs for an approaching disaster emerges*. These studies address short-term planning decisions, given the information about an upcoming or occurred disaster. In addition to developing inventory policies, some of these studies also focus on locating facilities close to the region of interest. In total, we identified **14** studies on post-disaster and **9** studies on post-warning inventory decisions. Tables 7–9 summarize the characteristics of the studies that address post-disaster/post-warning inventory management.

4.2.1. Problem aspects

4.2.1.1. Decision makers and stakeholders. Similar to pre-disaster problems, studies that focus on post-disaster/post-warning inventory management mostly assume a humanitarian organization as the decision maker (see Table 7). As shown in the table, the humanitarian organization may interact with a variety of stakeholders in different settings. Specifically, we can classify the existing studies into three broad groups based on the stakeholders involved, discussed below.

The first group of studies focus on *replenishment of relief supplies at a humanitarian warehouse from an external supplier*. Beamon and Kotleba [31] and Beamon and Kotleba [32] focus on disaster response in a complex emergency setting and design an inventory policy for a humanitarian organization, which orders supplies from multiple suppliers to meet random demand that occur periodically at a single warehouse. Other studies that focus on ordering decisions of a humanitarian organization from an external supplier to replenish its inventory include [55,63]. In some cases, suppliers are differentiated based on their lead times (e.g., [63,64,31]); in these studies, urgent orders can be satisfied from the faster and more expensive suppliers. In [31], normal and emergency supply options represent placing orders with a local and an international supplier, respectively.

Secondly, there are studies that focus on *a single humanitarian organization, which replenishes the inventory at its local facilities (points of distribution or shelters) from a central warehouse* (e.g., [66,11,56]). In these studies, local facilities serve the beneficiaries, and all facilities (the central and local warehouses) are owned and managed by the humanitarian organization.

Most of the studies that focus on a humanitarian organization as the decision maker assumes a setting with a single organization. However, there are many examples in practice where multiple organizations stock inventory at the same warehouse, which may be coordinated by a separate umbrella organization (e.g., The United Nations Humanitarian Response Depots). For instance, [31,32,48] are actually motivated by real-world cases where multiple humanitarian organizations keep stocks and serve beneficiaries from the warehouses; however, the proposed models in these studies focus on a single organization. One exceptional study is Davis et al. [37], which address multiple humanitarian organizations managing their inventory in a cooperative way in a post-warning scenario; specifically, the authors consider multiple local warehouses, managed by different organizations. The inventory kept at these local facilities are reallocated as more information about the intensity and path of an approaching hurricane are obtained; the objective of shifting supplies among warehouses is to prevent supplies from getting destructed and provide timely service to the affected people by the disaster.

Finally, there is a stream of literature that focuses on *inventory management decisions of private companies (such as manufacturers, retailers) to prepare for a potential demand surge* due to an approaching/expected disaster. For instance, Lodree and Taskin [46] and Taskin and Lodree [69] consider a retailer/manufacturer, which experiences demand surge for various items (such as flashlights, batteries) due to an observed storm. The ordering decisions can be made more effectively as more information about the hurricane are obtained; however, it may be riskier and more expensive to postpone ordering supplies. The authors focus on determining the optimal inventory level for hurricane supplies by considering the trade-off between forecast accuracy and logistics costs. Lodree [44] compares proactive versus reactive inventory ordering strategies for a retailer, which observes signs of an approaching storm system, which may or may not induce a demand surge. The author focuses on a regret-based approach and analyzes the implications of ordering before or after the demand surge occurs. Lodree et al. [45]

Table 7
Problem aspects in post-disaster/post-warning inventory management.

	Article	Network, case study (Disaster type)	Demand					Facilities		Stakeholders	Number of tiers
			Randomness	Backorder/Lost	Number of items	Perishability	Regular/Emergency	Capacitated	Damage possibility		
	Beamon and Kotleba [31]	Casestudy (Complex emergency)	Stochastic	Backorder	1	–	–	–	–	HO, supplier, beneficiaries	2
	Beamon and Kotleba [32]	Casestudy (Complex emergency)	Stochastic	Backorder	1	–	–	–	–	HO, supplier, beneficiaries	2
	Das and Hanaoka [11]	Case study (Earthquake)	Stochastic	Lost	> 1	–	–	–	–	HO, beneficiaries	2
	McCoy and Brandeau [48]	Case study (Complex emergency)	Stochastic	Lost	1	–	–	–	–	HO, supplier, beneficiaries	2
	Natarajan and Swami-nathan [51]	Hypothetical	Stochastic	Backorder	1	–	–	–	–	HO, beneficiaries	2
Post-Disaster	Noyan et al. [53]	City, Case study (Earthquake)	Stochastic	Lost	1	–	–	+	–	HO, beneficiaries	3
	Ozbay and Ozguven [54]	Hypothetical	Stochastic	Lost	1	–	–	+		HO, supplier, beneficiaries	2
	Ozguven and Ozbay [55]	Case study (Hurricane)	Stochastic	Lost	> 1	+	–	+	–	HO, supplier, beneficiaries	2
	Rabbani et al. [58]	Case study (Earthquake)	Stochastic	Backorder	> 1	+	–	+	–	HO, beneficiaries	2
	Roni et al. [63]	Hypothetical	Stochastic	Lost	1	–	+	–	–	HO, supplier, beneficiaries	2
	Roni et al. [64]	Hypothetical	Stochastic	Lost	1	–	+	–	–	HO, supplier, beneficiaries	2
	Rottkemper et al. [65]	Country, Case study (Earthquake)	Stochastic	Backorder	1	–	–	–	–	HO, beneficiaries	2
	Shen et al. [67]	Case study (Anthrax attack)	Deterministic	Lost	1	+	–	–	–	Government, manufacturer	2
	Yadavalli et al. [72]	Hypothetical	Stochastic	Lost	> 1	+	–	+	–	HO, supplier, beneficiaries	2
	Davis et al. [37]	Regional, Case study (Hurricane)	Stochastic	Lost	1	–	–	+	+	Multiple HOs, beneficiaries	2
	Lodree and Taskin [46]	Case study (Hurricane)	Stochastic	Lost	1	–	+	–	–	Manufacturer or retailer, supplier	2
	Lodree [44]	Case study (Hurricane)	Deterministic	Lost	1	–	+	–	–	Retailer, supplier	2
	Lodree et al. [45]	Regional, Case study (Hurricane)	Stochastic	Lost	1	–	–	–	–	Manufacturer, retailer	2
Post-Warning	Pacheco and Batta [56]	Hypothetical (Hurricane)	Stochastic	Lost	1	–	–	+	+	HO, beneficiaries	3
	Rawls and Turnquist [61]	Regional, Case study (Hurricane)	Stochastic	Lost	> 1	–	–	+	–	HO, beneficiaries	2
	Salas et al. [66]	Case study (Hurricane)	Stochastic	Lost	1	+	–	–	–	HO, beneficiaries	2
	Taskin and Lodree [68]	Case study (Hurricane)	Stochastic	Lost	1	–	+	–	–	Manufacturer or retailer, supplier	2
	Taskin and Lodree [69]	Case study (Hurricane)	Stochastic	Lost	1	–	+	–	–	Retailer, supplier	2

focus on a manufacturer, which starts pre-positioning emergency supplies in its supply network involving a set of geographically dispersed retailers, once the signs of an approaching disaster are observed. The retailers experience a spike in demand for various emergency supply items just before a storm hits and also following the storm. Lodree et al. [45] develop a model for determining the quantity of supplies to stockpile at each retailer prior to a potential demand surge. Once more information about demand become available, pre-positioned supplies can be transshipped among retailers; however, such post-disaster shipment decisions are also made by the manufacturer. That is, a vendor-managed inventory (VMI) system is considered in [45]. Shen et al. [67] focus on another VMI setting, where the federal government pays pharmaceutical companies to produce and store large inventories of perishable health supplies to keep them ready for use in case of an emergency such as an anthrax attack. The study proposes an inventory model from the manufacturer's perspective by considering government-controlled system parameters.

4.2.1.2. Disaster type. As discussed in Section 4.1, the pre-disaster inventory management studies do not indicate any significant modeling differences in addressing different disaster types. We observe that several models developed for shorter-term post-disaster/post-warning inventory planning specifically address the characteristics of different disaster types such as civil war, earthquake, hurricane, flood, and famine. Table 7 presents the

Table 8
Performance measures in post-disaster/post-warning inventory management studies.

Article	Metrics/Objectives
Beamon and Kotleba [31]	[Min] Expected total costs (ordering, holding, backorder)
Beamon and Kotleba [32]	[Min] Expected total costs (ordering, holding, backorder) Maximum proportion of emergency order cycles Response time
Das and Hanaoka [11]	[Min] Expected total cost (fixed and variable ordering, inventory, shortage) Expected relief shortage
Davis et al. [37]	[Min] Expected total costs (transportation, shortage, supply loss) Equity in demand satisfaction (in terms of fraction satisfied) Response time
Lodree and Taskin [46]	[Min] Expected total costs (ordering, holding, shortage)
Lodree [44]	[Min] Maximum total costs (ordering, holding)
Lodree et al. [45]	[Min] Expected total costs (production, pre- and post- hurricane transportation, holding, shortage)
McCoy and Brandeau [48]	[Min] Expected total response penalty (based on units of unsatisfied demand) Inventory and shipment costs
Natarajan and Swaminathan [51]	[Min] Expected total costs (ordering, holding, backorder)
Noyan et al. [53]	[Max] Expected total accessibility Maximum response time (equity) Equity in demand satisfaction (in terms of fraction of demand satisfied)
Ozbay and Ozguven [54]	[Min] Expected total cost (inventory, shortage, surplus) Probability of meeting demand
Ozguven and Ozbay [55]	[Min] Expected total cost (inventory, shortage, surplus) Probability of meeting demand
Pacheco and Batta [56]	[Min] Expected total costs (facility, transportation, shortage, acquisition, destroyed supplies)
Rabbani et al. [58]	[Min] Expected total costs (ordering, holding, backorder, shortage)
Rawls and Turnquist [61]	[Min] Expected total costs (facility, holding, transportation, shortage) Probability of demand satisfaction within a target response time
Roni et al. [63]	[Min] Expected total costs (ordering, holding, shortage)
Roni et al. [64]	[Min] Expected total costs (ordering, holding, shortage)
Rottkemper et al. [65]	[Min] Expected total costs (facility, ordering, transportation, shortage)
Salas et al. [66]	[Min] Expected total costs (ordering, variable, holding, shortage, disposal)
Shen et al. [67]	[Min] Expected total costs (ordering, holding, variable, salvage)
Taskin and Lodree [68]	[Min] Expected total costs (variable, holding, shortage)
Taskin and Lodree [69]	[Min] Expected total costs (variable, holding, shortage)
Yadavalli et al. [72]	Average number of satisfied demands Average number of lost demands Average inventory level Average number of substituted demands

disaster type addressed in each post-disaster/warning inventory management study.

As shown in Table 7, there are several studies that develop inventory management approaches for hurricanes. Interestingly, pre-disaster inventory management literature does not differentiate disasters that give previous warning (such as hurricanes) and the ones that hit without any prior notice (such as earthquakes). On the other hand, post-disaster/post-warning studies that focus on hurricanes consider their distinct characteristics. For instance, hurricanes mostly occur in specific regions in certain seasons, give initial warning, and have a life cycle. Once a potential storm is detected, humanitarian organizations and private companies may have several days to prepare for the upcoming disaster and/or update their decisions. However, not all storm warnings turn into catastrophic events, and the intensity and path of the hurricane are uncertain. Therefore, most of the inventory policies proposed in the literature for hurricane planning and response incorporate the dynamic information that becomes available over a hurricane's lifecycle. For instance, Lodree and Taskin [46] and Taskin and Lodree [69] develop inventory models using a Bayesian framework to incorporate the effects of forecasted wind speeds. Taskin and Lodree [68] focus on pre-planning stage before the hurricane season and consider a scenario approach to model demand predictions over the hurricane season. Ozguven and Ozbay [55] propose an online control methodology to update the required level of safety stock depending on the dynamic hurricane strength. Salas et al. [66] and Rawls and Turnquist [61] focus on multi-period settings and determine the inventory at shelters by considering scenarios for dynamic arrival of beneficiaries to the shelters, which is affected by how a storm activity develops. Davis et al. [37] determine the location and amount of inventory to pre-position in a post-warning disaster network by considering short-term forecasts for the affected area. Several studies that focus on pre-positioning and ordering decisions for hurricanes illustrate their approaches on case studies developed based on real-world networks by processing historical hurricane data (e.g., [68,37]).

There are a few studies that consider response activities for complex emergencies. Complex emergencies are man-made

Table 9
Methodological approaches in post-disaster/post-warning inventory management studies.

Article	Model type/Policy	Solution approach
Beamon and Kotleba [31]	Multi-supplier (Q, r) policy	Exact; Numerical techniques
Beamon and Kotleba [32]	Multi-supplier (Q, r) policy	Exact; Numerical techniques; Heuristic; Silver Meal; Simulation
Das and Hanaoka [11]	(Q, r) policy	Exact; Numerical techniques
Davis et al. [37]	Two-stage stochastic programming	Exact; Optimization solver
Lodree and Taskin [46]	Newsvendor policy; Optimal stopping with Bayesian updates	Exact; Dynamic programming algorithm; Mathematical computing software & postwarning
Lodree [44]	EOQ policy	Exact; Numerical techniques & postwarning
Lodree et al. [45]	Two-stage stochastic programming	Exact; Optimization solver
McCoy and Brandeau [48]	Base stock policy	Exact; Dynamic programming; Numerical techniques; Simulation
Natarajan and Swaminathan [51]	Base stock policy	Exact; Numerical techniques
Noyan et al. [53]	Two-stage stochastic programming	Exact; Optimization solver; Benders decomposition
Ozbay and Ozguven [54]	Hungarian Inventory Control Model; Stochastic Programming	Heuristic; pLEPs algorithm
Ozguven and Ozbay [55]	Hungarian Inventory Control Model; Stochastic Programming	Heuristic; pLEPs algorithm; Mathematical computing software
Pacheco and Batta [56]	Stochastic programming	Exact; Optimization solver
Rabbani et al. [58]	(Q, r) policy	Exact; Numerical techniques; Fuzzy ranking method
Rawls and Turnquist [61]	Two-stage stochastic programming	Exact; Optimization solver
Roni et al. [63]	(Q, r) policy	Exact; Optimization solver; Mixed Integer Programming; Level crossing method
Roni et al. [64]	(Q, r) policy	Heuristic; Tabu Search; Level crossing method
Rottkemper et al. [65]	Mixed Integer Programming	Exact; Optimization solver
Salas et al. [66]	Newsvendor policy; Stochastic programming	Exact; Optimization solver & postwarning
Shen et al. [67]	Modified Economic Manufacturing Quantity policy	Exact; Unconstrained optimization; Numerical techniques
Taskin and Lodree [68]	Multi-stage stochastic programming	Exact; Optimization solver; Heuristic (scenario reduction)
Taskin and Lodree [69]	Newsvendor policy with Bayesian updates	Exact; Mathematical computing software & postwarning
Yadavalli et al. [72]	Multi-item joint (s, S) replenishment policy	Exact; Numerical techniques; Steady state analyses

disasters, which usually necessitate long-term relief efforts and usually cause people to be displaced from their homes. Beamon and Kotleba [31], Beamon and Kotleba [32] and McCoy and Brandeau [48] focus on long-term inventory decisions in humanitarian warehouses that respond to *complex emergencies* created by conflict situations in Africa; these studies develop inventory policies for meeting fluctuating demands over multiple periods. Beamon and Kotleba [31] and Beamon and Kotleba [32] illustrate their approach on case examples; the associated data were collected during field research conducted at a warehouse managed by World Vision International in Kenya. McCoy and Brandeau [48] specifically focus on developing an inventory control policy at a warehouse, managed by the United Nations High Commissioner for Refugees (UNHCR), which serves refugee camps or any downstream relief operation. Although Roni et al. [63] and Roni et al. [64] do not specify a disaster type, their modeling framework incorporate demand fluctuations and can be applied for responding to complex emergencies.

Some of the post-disaster models focus on earthquake relief operations. In these models, there is a central warehouse which replenish the points of distribution that directly serve beneficiaries. Das and Hanaoka [11] develop an inventory ordering policy for such a system while assuming stochastic demand and lead time parameters. Noyan et al. [53] present a model for determining the locations of distribution points and the amount of inventory to keep to ensure accessibility and serve beneficiaries. Rottkemper et al. [65] focus on long-term relief operations, during which overlapping disasters occur; for instance, an humanitarian organization may be performing relief operations to respond to an earthquake, and an epidemic may outbreak in the region. The proposed model helps humanitarian organizations to relocate and distribute relief supplies in the network to respond to a new situation quickly while continuing their existing operations.

A number of case studies also present real-world data and evidence on the importance of effective inventory management. For example, Rabbani et al. [58] develop a case study related to activities of Iranian Red Crescent Society for earthquakes. The case study in [55] takes medicines and ready to eat meals into consideration. Shen et al. [67] deal with anthrax attack in their case study. Rawls and Turnquist [61] develop a case study based on historical hurricane data, which are utilized also in [37,45]. Noyan et al. [53] *use* the data of Van earthquake, which occurred in Turkey in 2011. Rottkemper et al. [65] consider a vaccination program in Burundi as a long term relief operation.

4.2.1.3. Demand characteristics. Table 7 shows that demand is assumed to be stochastic in most of the post-disaster studies. The demand in these studies follow uniform, normal, Poisson (see e.g., [72,48]), compound Poisson, and triangular (see [58]) distributions. In hurricane models, no specific distribution has to be assumed to use the approaches in [46,69], and normal distribution is considered in numerical analysis. We observe that demand is assumed to be uniformly distributed in models developed to manage inventory during conflicts (e.g., [31,32]). Some studies assume demand is uncertain and periodic, and distribution/transshipment decisions can be made according to information updates on demand during relief operations [61,45]. On the other hand, Lodree [44] and Shen et al. [67] consider *deterministic* demand and use economic order quantity (EOQ) models.

A realistic demand distribution is presented by Roni et al. [63], where a system faces two types of demands: Poisson distributed *regular* demand and compound Poisson distributed *surge* demand. The surge demand has a lower arrival rate but higher demand volume per arrival. Roni et al. [64] extend this by allowing split deliveries from the supplier. Other studies that consider independent surge demand are [46,44,68,69].

Another aspect of demand is what happens to *unsatisfied demand*. As unsatisfied needs may result in loss of human lives, unsatisfied demand is assumed to be *lost* in most of the studies. This proposition is further extended by penalizing consecutive shortages [66]. There are a number of studies that allow backordering of unsatisfied demand (see Table 7). Beamon and Kotleba [31] state that backordering cost in humanitarian operations must be attributed to increased human pain, suffering, and death, unlike commercial supply chains which usually represent backorders with lost profits. Rabbani et al. [58] assume backordered demand is lost after a pre-defined time period.

Majority of the studies focus on single product systems, but there are a few articles dealing with two or more products (see e.g., [55,72,61]). Most of the articles do not specify a certain product type or perishability, so it can be concluded that these models are more appropriate for durable goods such as relief equipment, clothing, plastics, or technological items. Perishability is addressed in some models, which can be used to manage food or medicine stocks (see e.g., [58,67]). Salas et al. [66] focus on food operations in shelters and consider disposal cost of perished items in their model. Yadavalli et al. [72] consider two substitutable perishable products such as blood-sachets and medicine.

4.2.1.4. Decisions and planning horizon. The studies discussed in this section focus on building up stocks after the occurrence of a disaster, or after receiving a warning for an approaching disaster but before the actual disaster happens. These models focus on *short-term decisions* in contrast to pre-disaster inventory models reviewed Section 4.1 that study *long-term decisions*.

In the area of post-disaster inventory management, decisions are usually made on *order quantity*. According to the approach used, *reorder point* might become another decision variable. Furthermore, special inventory variables such as *emergency order quantity* and *emergency reorder point* are defined in some articles (see e.g., [31,11,63]). Emergency orders are placed for more expensive substitutes of mainstream products because their lead times are shorter. Other decision variables considered in the literature include *additional safety stock levels* (the amount added to regular safety stock after a disaster), *storage capacities* for different products [54,55], *amounts to relocate among facilities* [65], *locations and capacities of facilities* [61,53].

Post-disaster/warning studies usually focus on replenishment policies in contrast to the pre-disaster approaches that typically address stockpiling decisions. There are a few single-period approaches (see e.g., [31,46]); however, most of the studies focus on multi-period replenishment policies (see e.g., [11,40]). Some of the models also take *information updates* regarding an upcoming disaster (e.g., storm intensity and track) into account (see e.g., [69, 45]).

4.2.1.5. Facilities. Most of the post-disaster studies avoid decisions regarding facility locations and sizes, in contrast to the long-term decisions presented in Section 4.1. Instead, post-disaster studies consider a single facility without capacity limitations and aim to adopt a replenishment policy on a two-stage network. Exceptions to this include [54,55,58], where warehouses are capacitated. In addition, Yadavalli et al. [72] consider individual capacities for two separate products. In the post-disaster literature, decisions on locations and capacities of facilities are only considered in [53,56, 61].

4.2.1.6. Performance measures. Performance metrics considered in post-disaster/warning studies, which are incorporated into the models either through objective functions or constraints, are presented in Table 8. Cost, service level, and equity are different types of measures considered in these models.

Similar to pre-disaster models, majority of studies for post-disaster/warning models consider expected total costs as a measure. Typical cost components taken into account are fixed and variable ordering, holding, transportation, and shortage costs. Rabbani et al. [58] consider shortage costs both for lost demand and backordered demand. Ozbay and Ozguven [54] consider the costs associated with adjusting safety stock levels after the disaster. Natarajan and Swaminathan [51] consider uncertainty in funding levels while limiting operational costs.

Another metric used in these studies' objectives and constraints is service level, which is defined in terms of response time, demand satisfaction rate, and expected relief shortage. Davis et al. [37] and Noyan et al. [53] ensure that a maximum response time limit is not exceeded. Rawls and Turnquist [61] consider demand satisfaction through chance constraints to ensure demand is satisfied with a certain probability. Salas et al. [66] add a constraint to prevent backlogging products beyond a certain time period. Das and Hanaoka [11] utilize expected relief shortage as an objective in their model.

Equitable response is also considered as an important concern in some post-disaster inventory models. For instance, Davis et al. [37] and Noyan et al. [53] introduce equity constraints that ensure a certain fraction of demand is satisfied in each location.

4.2.2. Methodological aspects

Table 9 provides an overview of modeling and solution approaches used in post-disaster/post-warning inventory planning studies. Most of the studies focus on extending classical inventory models and developing stochastic or deterministic mixed integer models. Integer models presented are usually solved using optimization solver, and exact solutions are obtained for small instances. Noyan et al. [53] propose a two-stage stochastic optimization model for a post-disaster case to decide on facilities and their capacities, and how much to store in each facility within a last mile relief network. Das and Hanaoka [11] propose a stochastic model based on first order differential equations to estimate lead-time demand, expected shortages, expected inventory levels per cycle and cycle lengths. Yadavalli et al. [72] use renewal theory to analyze the steady-state behavior of an inventory system with two substitutable and perishable products.

Several stochastic optimization models utilize *information updates* that are received after a disaster warning. In contrast to the pre-positioning models discussed in Section 4.1, these post-warning pre-positioning models focus on short-term inventory planning. Taskin and Lodree [68] introduce a multi-stage stochastic programming model for pre-hurricane situations, which includes order quantity decisions for multiple time periods under different scenarios. Rawls and Turnquist [61] formulate a two-stage model, which considers relevant updates on anticipated demand for multiple time periods after a disaster occurs. Handling of short term unsatisfied demand is also covered in this study. Pacheco and Batta [56] include pre-positioning and distribution decisions with dynamic information updates on hurricanes in a setting where potential destruction of selected supply points is possible. Lodree et al. [45] make stocking decisions before and after a disaster, with information updates on demand and dynamic costs for ordering and transportation. Davis et al. [37] study pre-positioning and distributing a limited number of supplies in the most efficient way for both cost and demand satisfaction in case of a disaster. Second stage decisions in this model are taken after knowledge about the disaster is obtained.

There are a number of studies that extend newsvendor problem utilizing information updates. Lodree and Taskin [46] consider the inventory control problem as an optimal stopping problem with Bayesian updates. According to characteristics of updates, they try to categorize the upcoming hurricane as extreme or not, and then take a one-time decision. Taskin and Lodree [69] expand this model to a multi-retailer setting, where both strength and path of the storm are considered. Ozbay and Ozguven [54] and Ozguven and Ozbay [55] also utilize information updates and adapt a Hungarian inventory control model to minimize additional safety stocks.

Extensions of classical inventory policies are also studied in the area of HL/DM. Beamon and Kotleba [31] develop a continuous review (i.e., (Q, r)) model for the case of civil war in South Sudan. Their model includes two different order quantities and two different reorder points, denoted as regular and emergency, where emergency orders have smaller lead time but higher cost. Regular reorder point and order quantity are determined using

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the calculated stockout probability, and the unsatisfied portion of sudden demand is satisfied via emergency orders. Beamon and Kotleba [32] provide a simulation study for the results obtained in [31]. Another study that presents simulation results is [48], where the aim is to allocate the budget of a relief provider for shipping and stockpiling. They study a base-stock inventory management policy and use dynamic programming to determine the optimal shipping policy. Rabbani et al. [58] propose a continuous review inventory policy for recovery phase of disaster relief operations. There are also studies that extend the classical EOQ model. For instance, Lodree [44] introduce surge demand with an intensity and duration and choose between proactive and reactive inventory management strategies. Shen et al. [67] develop a model based on economic manufacturing quantity to be applied in production of different vial sizes for the US National Stockpile.

5. Conclusions and future research directions

This article provides an in-depth review and analysis of analytical approaches developed for humanitarian inventory management. Although there is a well-established inventory management literature addressing the basic inventory questions (when/where/how much to store) within commercial supply chain settings, the existing models and policies cannot be directly applied to manage humanitarian inventories. As a result, there has been a growing attention in the HL/DM literature addressing these decisions in recent years. To the best of our knowledge, this article is the first one that specifically examines the characteristics of the inventory policies and models developed for different HL/DM settings.

To identify the papers that focus on inventory management in HL/DM, we perform an exhaustive search in the well-known research databases using keyword combinations related to inventory planning and disaster management. We classify the papers based on the planning phase addressed. Our review and analysis show that the number of papers that focus on inventory management in disaster preparedness and response phases are about the same. We find that the pre-disaster inventory management literature primarily focuses on long-term pre-positioning problems for sudden onset disasters; whereas, the post-disaster inventory planning literature addresses a wider range of disaster types, problem settings, and inventory policies. Based on our analysis, we identify several gaps and future research directions for humanitarian inventory management.

The pre-disaster inventory management literature presents several modeling approaches to determine the location and amount of inventory to store before a sudden-onset disaster so as to deliver supplies to the affected areas as soon as possible. Although studies are mostly motivated by two types of disasters (earthquakes and hurricanes), we observe that each study focuses on a different set of aspects and objectives, formulates a new problem, and presents numerical analysis based on developed data sets, as discussed in Section 4.1. The growing richness of the literature on this topic is exciting, as about a decade ago, only a few studies focused on pre-positioning supplies for humanitarian operations. However, as the field matures, it would be beneficial to investigate the implications of considering different problem aspects, objectives, and compare solutions of different modeling approaches on benchmark data sets. For instance, there are a number of studies that incorporate objectives to ensure equitable access to supplies among demand locations in the second stage models. It would be interesting to see whether/how stocking locations and inventory amounts are affected by different equity objectives. Moreover, there are several problem aspects that are considered by some studies and ignored by others such as multiple items, capacitated facilities, variable lead times, additional facility tiers, or different cost items. Then the question is whether there are some aspects that are *essential* in determining pre-positioned inventory levels for humanitarian operations, and whether *standard problems* can be defined for different disaster types.

Our review suggests that it would be extremely valuable to create some *benchmark case study data sets* to test different approaches proposed for disaster inventory planning. We observe that researchers spend a lot of effort and time to process raw historical data from several databases to generate problem instances to test and illustrate their approaches. Different methods are used and a variety of assumptions are made to develop disaster scenarios and associate probabilities to these scenarios; hence, even if the same raw data are used, different problem instances are generated in general. Future initiatives for generating a set of instances that focus on different humanitarian supply networks (e.g., city, regional, country, global) would be very valuable. This would allow researchers to compare the solutions from different modeling approaches (e.g., risk-neutral versus risk-averse) on these standard humanitarian inventory pre-positioning, post-warning, or post-disaster problems and data sets.

The need for future research addressing *multi-agency coordination* is mentioned in [15]. Although the importance and need of coordination are consistently highlighted in HL/DM research over the years, we observe that there are not many studies in humanitarian inventory management literature addressing this topic. We observe that most studies focus on a single humanitarian organization, making inventory planning/ordering decisions independently than other possible collaborators/stakeholders. One exception is [37], which considers collaboration among several agencies in managing inventories in a post-disaster environment. Lodree et al. [45] consider a VMI system, in which a manufacturer determines the stocks at retailer points. Future research may address the benefits and challenges (e.g., infrastructure, regulations etc.) of coordination among agencies in pre-positioning and managing inventories after a disaster. Opportunities for coordination with suppliers in inventory planning can also be explored; for instance, potential implications of making contracts with relief suppliers on pre- and post-disaster inventory planning can be examined (see e.g., [75]).

Post-disaster inventory management literature covers a larger variety of disasters than pre-disaster studies. Despite the richness of approaches and variety of assumptions discussed in Section 4.2, post-disaster literature also lacks benchmark data sets for a fairly standard set of assumptions. We observe that most of the studies covering post-disaster activities concentrate on inventory decisions for one item. *Multiple commodity* cases can be studied further, as victims of disasters need various kinds of commodities with different demands in relief distribution points. Correlation between multiple items can also be assumed, which would be realistic for post-disaster activities. Another important aspect of existing studies is the behavior of *unsatisfied demand*. Most of the models implement a lost-sales approach, yet backordering is also adopted in some studies. Unlike commercial inventory management, backordering costs can have different interpretations within the HL/DM context. Therefore, further analyses on backordered items can be performed in inventory management for humanitarian relief efforts. For instance, future work can consider incorporating deprivation costs, which are discussed in [12], into inventory modeling.

We observe that the existing studies focus on a variety of uncertainties related to the location and amount of demand for relief items, and the post-disaster transportation infrastructure and the condition of warehouses and stocks. Although funding uncertainty may highly affect pre- and post-disaster inventory management decisions, it is addressed by only one study [51]. Most studies assume fixed and known pre- and post-disaster budgets, which is rarely the case in practice. Future research can address further issues regarding funding uncertainty and how it impacts inventory decisions.

While the existing humanitarian inventory management literature addresses a variety of disasters (as specified in Tables 4 and 7), only three papers consider inventory management in the case of conflicts (i.e., [31,32,48]). To the best of our knowledge, McCoy and Brandeau [48] is the only study which exclusively addresses inventory management for refugee operations. Conflicts and refugee crises are unique situations as they typically affect millions of people, a large geographical area, and sometimes several countries for many years. There are significant logistical challenges associated with serving affected populations by conflicts (such as accessing dangerous zones, serving huge populations in camps, serving populations on the move, etc.). It is essential for humanitarian logistics research to characterize the inventory management problems that are unique to these settings and investigate/identify strategies and methods to bring aid to the people affected by conflicts effectively.

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