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A Humanitarian Logistics-Based Planning for Rescue and Relief Operation After a Devastating Fire Accident

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ABSTRACT

The frequency of fire disasters is fortunately low, but planning the logistics and related routings for rescue, relief, and rehabilitations operations are major issues in launching any humanitarian assistance. In addition to the logistics planning issues, the reasons for the occurrence of the fire disasters should also be determined so that measures may be put in place to prevent future disasters as well as any potential consequences that may occur after the fire is extinguished. Most cities have efficient fire departments quipped with resources and fire brigades to initiate immediate measures to control the fire and to start the rescue operation. Moreover, most governments take steps to provide relief and rehabilitation assistance to the affected population. Rescue, relief, and rehabilitation steps in traffic-congested cities, especially in heavily populated areas with many businesses and markets, are highly challenging. This research proposes a mathematical modeling-based approach for planning the transportation of relief and rescue resources; conducting relief and rescue operations; and outlining measures to prevent future recurrences. The model will be illustrated using the chemical explosion-fed fire which occurred on February 20, 2019 in the old part of Dhaka in Bangladesh.

Keywords: *humanitarian logistics, rescue and relief operations, routing of resources, fire disasters, logistics in traffic-congested areas*

1. INTRODUCTION

Natural and manmade disaster occurrences have been increasing from year to year. From 1900 to 2019 over 2000 mass disasters have been reported, and from 2000 to 2018 nearly 81.7 million people have been affected by various disasters with 1.3 million reported causalities (CRED, 2018). Humanitarian logistics (HL) plays a crucial role in providing relief to the disaster-affected area and in mitigating the disaster impacts. HL literature addresses pre-disaster readiness planning for relief operation, post-disaster rescue operation and recovery support planning. Pre-disaster planning considerations include prepositioning of assets in advance to support timely relief operations (Arnette and Zobel, 2019). Such pre- and post-disaster planning, including recovery support preparation, may also be considered as the preparation for emergency management by including measures for mitigation and safety (Wagner and Agarwal, 2014). Emergency situations and associated emergency and safety measures largely depend on the environment where the disaster occurs. Fire breakouts in densely populated urban areas can easily propagate to the adjacent buildings and engulf an entire area (Waheed, 2014; Navitas, 2014). As such, fire disasters are responsible for extensive damage to the urban environment and can cause numerous fatalities (Himoto and Tanaka, 2008). Occurrences of such fire disasters and measures for mitigation and relief operations are quite different in different situations, causing any pre-planning exercise to consider numerous scenarios (Jain and McLean, 2008). Such scenarios may be predictable, but readiness preparation does not only include planning and pre-positioning of resources based on predictable requirements. Disaster management and HL planning literature (Amideo et al, 2019) emphasizes evacuation plan and shelter location planning as a crucial step for disaster response. In the case of last February 21 fire incidents in Dhaka in 2019 inadequacy of evacuation readiness planning were felt at every moment after breaking out of the incidents (see The Daily Star report Nimtoli to Chawkbazar (2019)). Fire disaster readiness planning includes keeping ready rescue and evacuation support resources such as Ambulances, Fire Trucks and trained manpower for emergency operation. Creating trained manpower for effective evacuation and rescue operation seems to be crucial requirements considering the death toll of 117 persons. Jain and McLean (2003) included sources of several Fire accident simulations that may be used for providing effective training for creating trained manpower. NGOs often come forward to support disaster relief operations as evidenced by the media stories of Dhaka 2019 fire. But such supports are usually insignificant compared to the requirements. Government organizations play a major role in disaster relief operations (Apte *et al.*, 2016). In Bangladesh, a government organization has been founded to be responsible for pre-disaster planning and post-disaster mitigation steps.

In a heavily populated city with traffic-congested streets the challenging issues include the handling of disaster situations, post disaster rescue operations, recovery planning in addition to planning measures for recurrence prevention. Since handling of disaster situations, post disaster rescue and relief operations and recovery planning need collection of relief items and resources, effective logistics planning for the storage of relief items and transporting them to the affected areas through the transportation network is crucial. For optimum HL planning in a traffic-congested city like Dhaka the following steps are required: i) establishing an emergency monitoring cell to keep track of the entire route and to guide the transportation of the relief items based on traffic density, road condition, alternative route options, etc.; ii) defining and following the traffic and suitability indices for each route segment for effectively tackling the congestion and its complexities; iii) deciding the optimum locations and the number of collection centers to receive relief goods and resources from other cities/countries; iv) planning the optimum number of temporary DCs around the disaster-affected areas for storing and staging the relief items to improve the response time (Vanajakumari *et al.*, 2016); and v) selecting the optimum response route. Since Dhaka has established fire and emergency handling stations with proper equipment, a logical approach should be to study the city map including the feeder roads and streets in the city, the relative positions of existing fire and emergency services, in order to plan the optimum response route. The next challenge is to send suitable resources for firefighting and rescue operation in the quickest possible time.

The present research proposes a state-of-the-art HL planning network model that determines the optimum number and location of facilities with available equipment and resources for firefighting, rescue operations, and for receiving such resources from other locations, cities and countries; defines and establishes traffic and suitability indices through a monitoring cell; and includes the indices in the model to improve the planning reliability. The model also provides for alternative route planning and for government intervention in cases where the traffic density and suitability indices are not at the acceptable level. The model objectives are to optimize the costs as well as the response time. Finally, the research explores the reasons for the recent fire disasters and provides some recommendations based on the available literature. The paper is structured in the following way: review of relevant literature is included in the section 2, Section 3 includes methodology followed by the research, problem statement, Notations and formulation of the mathematical model; Section 4 illustrates model applications for optimizing response time for sending relief goods to assumed approximate fire affected locations of recent Dhaka fire incident assuming various transit locations, distribution centers and collection points, based on a Dhaka map It may be mentioned here the example is created such that the model may provide an outline to the city relief team for devising actual response plan using actual transit points, distribution centers and locations for collection centers. Section 5 discusses and concludes.

2. REVIEW OF RELEVANT LITERATURE

The literature on HL planning is reasonably rich, but the number of such studies dealing with fire disasters in cities and urban areas is very limited. However, the approach to preplanning of logistics to mitigate fire disaster impact on locality and relief operations have some commonalities with the general HL planning for other disasters. This literature review is concerned with: a) a select number of general HL planning research works with relevance to the relief operations aspects of this research; b) research on urban and other fire disasters for mitigation and resilience planning; and c) literature on relief operations in similar urban fire disasters.

a) Literature review study of Ozdamar and Ertem (2015) reported that the Model based HL planning in general concentrated in three planning stages of disaster life cycle that included pre-disaster preparedness; post disaster response and recovery phase (Ozdamar and Ertem (2015). The study also observed that HL planning models may be classified as vehicle network planning for optimizing response and recovery time. Our research falls in this general category for optimizing response time. Humanitarian Logistics (HL) may be concisely defined as the planning and controlling flow and storage of relief goods from the point of collection(origin) to the consumption points for meeting the end beneficiary requirements (Kovacs and Spens (2009). According to Balcik and Beamon (2008) except for the focus on the end beneficiary, this definition is comparable to business logistics planning. For responding quickly to disaster situations to provide food, medicine and other aids, humanitarian organizations (HO) such as Red Cross and Red Crescent need to plan effective supply network considering the location of warehouses, vehicle network planning, various resources, uncertainties, and other constraints. Similar situation may be applied to Dhaka city relief operation team also. Charles *et al.* (2016) conducted an extensive literature search and examined limitations of existing models for supply network design and proposed a model-based method (mentioned as tooled methodology) for overcoming the limitations of existing models and thus to support the HL planners for obtaining efficient supply network. The research mentioned that their contributions consider definition of aggregate scenarios to reliably forecast demand using past disaster data and future trends. HL planning is a critical part of effective relief operations in a disaster situation. Apte (2009) defined HL as a special branch of logistics that manages the response supply chain and provides critical supply and services while facing challenges including demand surges, uncertain supplies, and critical time windows in the presence of various vulnerabilities and the vast scope and size of the operations. In a densely populated city the challenges, vulnerabilities, and uncertainties have been found to increase in multiple ways (Himoto and Tanaka, 2012; Waheed, 2014; Navitas, 2014). Providing logistical response depends on the predictability of the disasters (Apte, 2009). For natural disasters and similar predictable events, preparedness actions such as pre-positioning of relief items improve the response time for relief operations. Hu and Dong (2019) studied the influence of integration of supplier selection in pre-positioning strategy for relief items. The study also considered maintaining close relation between supplier and the relief agencies in addition to cooperation of suppliers. Their finding showed that, when responding to disasters, cooperative suppliers supported the relief operations from their own physical inventory at lower prices. Fire disasters in urban areas, such as Dhaka, are not predictable. As such preparedness, response, and reconstruction phases of the disaster management operations, as covered in Vanajakumari *et al.* (2016) following Apte (2009), can be applied on a limited scale. In the case of Dhaka fire management, such planning may include identification of existing fire stations that are close to the fire-affected areas to be used as temporary DCs and government maintained permanent large fire stations as main DCs. Since government organizations play the major role in disaster relief operations, the recent findings on the rising cost of HL operations is a critical factor for government planning in developing countries. According to Apte *et al.* (2016), based on Jones (2013), the cost has risen from \$16.1B/year in 1992-2002, to \$40.1B/year in 2002-2011.

Dufour *et al*. (2018) have pointed out that outsourcing of management and humanitarian logistics activities for the HL-based relief operations have become a common strategy for the relief agencies and the United Nations Humanitarian Response Depot (UNHRD) following commercial supply chains to reduce their operational costs. Their findings also showed that service providers are to be offered incentives for the services, and that outsourcing service providers may be engaged for the entire relief operations from preparation stage to relief distribution.

In HL planning responsiveness is of paramount importance. Such responsiveness is equally important in military missions. Boer *et al.* (2020) studied the contributory role of additive manufacturing for a mission critical spare parts which was high tech and highly specific and difficult to obtain with the required responsiveness. But the unique capability of additive manufacturing could make it available with the required responsiveness. Considering the frequencies of hazardous chemical accidents for the last decade, Du *et al*. (2020) attempted to create an emergency response network (ERN) for mitigating, as well as offering other HL support, for chemical fire accidents. The study focused on the 2019 chemical plant explosion accident of Jiangsu Xiangshui in which 78 people were killed and 566 were injured. Referring to Wang *et al*. (2018), during the last decade up to 2018, losses from chemical hazard accidents exceeded \$100 million in HL expenses. Du *et al*. (2020) also evaluated the difference in the response performance for centralized and decentralized ERNs. According to the study, decentralized or hybrid ERNs have a better chance for improving the response. The study suggested to plan the response based on the demand of the affected zone. For example, at the early stage of the fire, rescue resources should be sent in, and at the later stages environmental monitoring should be deployed to check the hazardous and toxic gas releases. In HL planning in addition to minimization of distribution cost, quick distribution of relief goods should be an important objective. In a recent paper on humanitarian supply chain planning Kobayashi *et al*. (2019) emphasized the importance of relief goods distribution planning such that these items can be delivered quickly to satisfy demand for shelters. Improving the responsiveness to market by ensuring product delivery according to customer priority is a critical element in any standard supply chain planning so as to make the chain competitive in the marketplace and to enhance the company image in terms of customer responsiveness (Das and Lashkari, 2015).

b) Mitigation and resilience planning for fire and other types of disasters: Mitigation planning in fire or in any humanitarian disasters (natural calamity) or manmade disasters like fire in Dhaka needs to include shelter at an optimum location and evacuation of the children, aged people, and sometimes entire affected population. Such shelter and evacuation planning are crucial for optimum disaster response time and mitigation of disaster effects (Amideo *et al*., 2019). Since various organizations, like NGOs, public private civil society organizations are involved in relief operations in addition to government organization, collaborations of the organizations are crucially important for successful relief operations in fire and any other disaster situations. Menya and K'Akamu (2016) conducted a study in the county government situation of Nairobi that was facing capacity limitations. The authors mentioned that the county government does not have any formal framework for inter-agency collaboration. Based on the study the authors argued that since county government have been facing capacity shortages to address fire disaster management, the government should embrace the interagency collaboration to overcome the limitations. Himoto and Tanaka (2008) studied the physics of fire spread in densely populated areas and reported that temperature rise and thermal radiation by the building materials are the two reasons out of several others for the quick spread of fire in such areas. In a similar research Himoto and Tanaka (2012) recommended the judicious selection of the nearby buildings by the firefighting teams in preparation for fire suppression and relief materials delivery to effectively extinguish the fire and start the mitigation planning for the disaster affected area. Flame igniting attributes and factors affecting the propagation of fire as studied by Himoto and Tanaka (2008, 2012) including disaster relief operations and suppression resources and strategies applied in wildfire situations are the lessons that may also be applied in urban fire emergency management.

c) Literature on relief operations in similar urban fire disasters: In terms of disaster effects, as well as the complexity of logistics in high density buildings and heavy traffic, the 2019 fire disaster in Dhaka is almost similar in nature to the Karachi, Pakistan, fire studied by Waheed (2014), although the reasons for the fires have been found to be different. In Karachi, the fire started in a garments factory in Baldia, a suburb of Karachi, and resulted in a higher number of casualties due to the poor design of the building as well as the firefighting abilities of the rescue and relief team. Waheed (2014) recommended a comprehensive disaster management plan for improving the current situation.

Based on the brief literature review, effective logistics planning is a crucial requirement for disaster relief operations. Optimally responsive logistics planning should organize the required resources and relief items, identify and establish locations to serve as collection and distribution centers (preparedness), and plan transportation and distribution of relief items (response phase) and resources for mitigation and recovery. It is important to study and understand the reasons for a disaster and take measures to prevent its recurrence.

3. METHODOLOGY

Considering the numerous entry routes to Dhaka to deliver relief and resource items from outside, and the numerous routes for transporting items to hazard-affected areas from the collection centers and later from the DCs around hazard affected areas. This study proposes a mathematical modeling-based approach to the planning of the collection centers at the main entry points and the transportation of the items to the affected areas at a minimum response time. In a city like Dhaka, obstacles such as high traffic density, road accidents, physical road condition, and occasional political processions hinder the orderly flow of transportation. Thus there is a need to define and set up some indices to monitor the transportation routes as a precondition for the modeling-based optimization of the response time to disaster-affected areas. A mathematical modeling-based approach will facilitate the consideration of such factors and conditions.

To understand the reasons for the occurrence of the fire, the research explores news reports and government circulars published in Dhaka newspapers. However, the study mainly considered the reports and circulars published in *"The Daily Star"*, which is considered to be the most trusted and highly circulated newspaper in the country.

3.1 Reasons for Dhaka Fire and the Government Initiatives

The old part of Dhaka (that includes Chawkbazar fire-disaster area) houses more than 87 warehouses (Nimtoli to Chawkbazar, 2019) for chemicals used in industries. Some of these chemicals are flammable. According to the Fire Service and Civil Defense authority, generating awareness among people is very important so that they do not allow any chemical storage/ warehouse in their area. After the Nimtoli disaster in April 2011(Nimtoli to Chawkbazar, 2019), the government decided to shift all chemical warehouses from residential areas to industrial zones in Keraniganj, by introducing a US$252.3M project called "Chemical Shilpa Nagar." The project, to be implemented on a 50-acre land, is scheduled to be completed in June 2021.

A similar situation to the Dhaka fire was reported by Shook (1997) in which fire broke out in a chemical storage facility at the Klong Toey Port of Bangkok, Thailand. The Port Authority firefighters used water, the traditional fire suppression material, but they failed to extinguish the fire. The fire killed 7 people and exposed another 50,000 to 60,000 to toxic fumes of methylene bromide and other hazardous chemicals. The Thai government thoroughly studied the risks and vulnerabilities by involving experts and the affected people and implemented measures to improve the handling of chemicals and firefighting practices. Dhaka could learn lessons from Bangkok on chemical storage control and implementation.

3.2 Problem Statement

Fire disaster management plan: Dhaka has been facing many fire disasters for a long time. The two large fire disasters in recent years are:1) A fire on June 3, 2010 in Nimtoli area of the old Dhaka (as reported in Nimtoli to Chawkbazar, 2019) that killed 117 people and left 150 people with fire burns; 2) A fire on February 21, 2019 in Chawkbazar area of the old Dhaka that killed 71 people (Nimtoli to Chawkbazar, 2019). Both of these incidents drew the attention of the international media, the entire country, the prime minister's office, and the city mayor. Although some actions had previously been taken to prevent the repetition of such incidents, especially after the Nimtoli disaster, the devastating occurrence of the February 21, 2019 incident revealed the ineffectiveness of those actions.

This research is motivated to study and understand the problem from the perspective of the challenges Dhaka has faced with respect to its heavy population density, traffic congestion, and inadequate fire and emergency handling resources and conditions. The study considers a set of emergency handling stations that are also used as collection centers $i \in I$ (henceforth referred to as CNs) for humanitarian relief items and resources, at suitable locations, mostly at the entry points into the city from Dhaka Airport, Port City of Chittagong, Sadarghat (Dhaka Riverport), Khulna Maowa, and Jamuna Bridge highway. These locations are suitable insofar as they are prepared to receive humanitarian relief items (henceforth referred to as HI) and resources for relief operations from other cities and other countries through air, water and multimodal transportation systems. In addition, they are positioned at a relatively closer distance to the old Dhaka city. A set of distribution centers (DCs) $k \in K$ are also planned to collect relief items transported from the collection centers for distribution in a more focused and planned way to the demand points $h \in H$. Most of the time, such DCs are temporarily organized based on the disaster area's requirements; the existing fire stations, if available around the disaster area, are always a good choice.

This study also estimates the quantity of HI $d \in D$ and resources for relief operations is based on the affected population in the fire-devastated areas $h \in H$ based on Dhaka Census Data. The estimation is to be based on the expertise of a team of experienced government and non-government emergency relief handling experts to consider the requirements of relief resource types for 100 persons (20 families) and HI for 5 persons (1family) under various probabilistic scenarios. The model considers city routes based on transportation system junction/transit points centers $j \in J$ (henceforth referred to as TNs). To overcome the limitations of slow movement, or no-movement of relief items, the model defines a traffic density index (to be monitored by a satellite-based system) to generate alternative routes and to select one with minimum congestion. Finally, the plan allows for the city administration /government to control the traffic, when necessary, to help relief-carrying vehicles to move faster, as if it were an emergency, when alternative options are not good.

The overall objectives are to improve the response time by transporting relief items in the minimum amount of time and cost. Based on the available data from news reports, the research work also attempted to include some recommendations regarding the prevention of fire incidents in the future.

3.3 Notations

3.3.1 Indices

- I: set of collection nodes CNs represented by $i \in I$
- D: set of humanitarian relief items HIs represented by $d \in D$, food, water, medicines
- G: set of relief support items and resources defined as $g \in G$, such as ambulances, fire trucks, axes, tents (henceforth referred to as resources)
- M: set of transportation modes TM defined $m \in M$, such as trucks, helicopters, drones, and small trucks
- J: set of transit nodes TNs, defined as $j \in J$ and destination centers/distribution centers (DCs) $k \in K$
- H: set of fire incident locations (HNs) $h \in H$, or demand points or the demand nodes (DN)
- SC: set of scenarios, $sc \in SC$; represented by $e \in E$; scenarios are used for estimating requirements for relief item d and relief support item g at three severity/damage scenarios with probability 0.33 for each scenario considered for the affected populations at affected area h. The scenario-based demand estimation procedure is defined in equations (3) and (4) to follow.
- T: set of population types (t=1 child; t=2 adult; t=3 disabled, sick, old) $t \in T$
- $h \in H$: affected locations for obtaining census data; these are the demand points/nodes defined above.

3.3.2 Decision Variables

- a_i: 1, if CN i is opened to accommodate resources, 0 otherwise
- b_i: 1, if CN i is opened to accommodate HIs, 0 otherwise
- ars_{ij}: 1, if route segment ij is used to transport relief items between CN i and TN j, 0 otherwise
- $ars_{jj'}$: 1, if route segment $j\,j'$ is used to transport relief items between two transit nodes j to j' where $j \neq j'$ $j' \geq j$; 0 otherwise
- ars_{kh}: 1, if route segment k to h is used to transport relief items between DC k and demand node h, 0 otherwise
- $atd_{jj'}$: 1 if the alternative route's traffic density and suitability indices are acceptable for navigation, 0 otherwise
- v_k 1, if DC k is opened, 0 otherwise
- $x_{id:}$ total HI d including food, medicine, treatment aid, clothes collected at CN i
- y_{ig} resources (henceforth mentioned as resources only) g collected at CN i
- $gv_{jj'}$: 1 if government intervention is applied between TNs j and j' for transporting relief items, 0 otherwise
- rf_{ijgm}: flow of resources g from CN i to TN j using transportation mode m
- $rf_{jj'gm}$: flow of resources g from TN j to TN j' using transportation mode m
- $rf_{jk\,gm}$: flow of resources g from TN j to DC k using transportation mode m
- hf_{ijdm}: flow of HI d from CN i to TN j using transportation mode m
- $hf_{jj'dm}$: flow of HI d from TN j to TN j' using transportation mode m
- $hf_{jk\,dm}$: flow of HI d from TN j to DC k using transportation mode m
- rz_{khgm}: distribution of resources g using transportation mode m from DC k to HN h
- hz_{khdm}: distribution of HI d using transportation mode m from DC k to HN h
- re_{ig}: resources g received at CN i
- hre_{id}: HI d received at CN i
- res_{ijm}: response time in minutes for the flow of relief items on the assigned route CN i to TN j using transportation mode m
- $res_{jj'm}$: response time in minutes for the flow of relief items on the assigned route segment between two TNs
- res_{jkm}: response time in minutes for the flow of relief items on the assigned route from a TN to a DC around the hazard- affected area using transportation mode m
- res_{khm}: response time from a DC to a demand node at the hazard location
- $td_{jj'}$:1, if traffic density index between TNs j and j' is found acceptable, 0 otherwise

3.3.3 Parameter

- CPD_{di}: capacity of CN i for HI d
- CD_{ijm}: distance between CN i and TN j in terms of travel time in minutes using transportation mode m
- $dis_{jj'm}$: distance in minutes between TNs j and j'
- $CPgD_{kg}$: capacity of DC k for accommodating resource g
- $CPdD_{kd}$: capacity of DC k for accommodating HI d
- dis_{jkm}: distance in minutes between TN j and DC k using transportation mode m
- $distr_{khm}$: distance in minutes between DC k demand points h using transportation mode m
- CC_d: cost of collecting HI d
- $CR_{g:}$ cost of collecting resource g
- $Po_{ht:}$ population of type t in the fire-affected demand point h
- Pr_e: probability of scenario e
- pi_{de}: estimated requirements of HI item d, including food, water, medicine, warm clothes, baby food, safety items at scenario e (wrapper, shoes per family of 5)
- pr_{ge} estimated requirements of resource g for relief operations (rescuing, mitigating, fire extinguishing), and emergency handling resources (fire trucks, cranes, ambulances, drones, helicopters) per 100 persons under scenario e
- PBe: probability for scenario e
- $su_{jj'}$: 1, if the road segment between TNs j to j' is not broken (i.e., the road is clear), monitoring team entered value
- thr_d: total HI items collected at the collection nodes CNs
- trs_g: total resources g collected at the collection nodes CNs
- re_{idg}: total relief items collected at each collection center/node (CN)

- $TRD_{jj'}$: traffic density as found by the monitoring team between the TNs j to j'
- $ACC_{jj'}$: acceptable limit for traffic density
- TRC_{dm}: cost of transporting 1 ton of HI d for a distance equivalent to one unit of time (we consider 30 minutes as one equivalent unit)
- $TRSC_{gm}$: cost of transporting 1 ton of resource g for a distance equivalent to one unit of time (we consider 30 minutes as one equivalent unit)
- FCE_i: fixed cost of opening an emergency handling center/fire station i to be used as a collection center
- FC_j^w: fixed cost of opening distribution center j^w

3.4 Formulation of the Model

Equations (1) and (2) determine resources and HI needed to be collected by the CNs for a successful relief operation. Constraints (3) and (4) ensure the provision of various resources and HI needed at the fire-affected locations based on population estimates obtained from city census records (resource requirements are based on a 100-person cluster needs, and the HI requirements are based on a 5-person family needs) at various scenarios:

$$trs_g = \sum_{i\in I} y_{ig} \qquad \forall g \tag{1}$$

$$thr_d = \sum_{i\in I} x_{id} \quad \forall d \tag{2}$$

$$trs_g \geq (1/100)\sum_{t\in T} po_{ht}\, pr_{ge} \sum_{e\in E} PB_e \;\forall h, g \tag{3}$$

$$thr_d \geq (1/5)\sum_{t\in T} po_{ht}\, pi_{de} \sum_{e\in E} PB_e \;\forall h, d \tag{4}$$

Constraints (5) and (5.a) limits the collection of resources and HI items at CNs based on their capacities. Equations (6) and (6.a) balance the flow of rescue and relief resources and HI from CN to TN with the outward flow on the route to the DCs around the fire-affected areas.

$$\sum_{g\in G} y_{ig} \leq CAP_i b_i \qquad \forall i \tag{5}$$

$$\sum_{d\in D} x_{id} \leq CPD_i a_i \qquad \forall i \tag{5.a}$$

$$\sum_{i\in I} y_{ig} + \sum_{i\in I}\sum_{m\in M} gf_{ijgm} = \sum_{j'\in J'}\sum_{m\in M} gf_{jj'gm} \quad \forall g, j', j' \neq j, j' \geq j, \tag{6}$$

$$\sum_{i\in I} x_{id} + \sum_{i\in I}\sum_{m\in M} hf_{ijdm} = \sum_{j'\in J}\sum_{m\in M} hf_{jj'dm} \quad \forall d, j', j' \neq j, j' \geq j, \tag{6a}$$

Constraints (7) and (7a) assign routes for flowing of inputs (resources and HI) to transit network for outward flow areas when such route for each CN to transit route is found suitable by the monitoring team according to constraint (8). Constraint (9) determines response time for the flow of relief items from CN to transit route by ensuring assignment of routes that provides minimum distance for the flow from each CN.

$$gf_{ijgm} \leq ars_{ij} M \qquad \forall i, j, g \tag{7}$$

$$hf_{ijdm} \leq ars_{ij} M \qquad \forall i, j, d \tag{7.a}$$

$$ars_{ij} \leq su_{ij} \qquad \forall i, j \tag{8}$$

$$res_{ijm} = ars_{ij} \min_{j\in J}(CD_{ijm}) \quad \forall i, j, m \tag{9}$$

The emergency monitoring team checks the traffic density and suitability indices and assigns a route segment for transporting relief items according to the combined decision of constraints (10) to (14). If the traffic density or the road condition is not suitable for the movement of relief items on the existing route, constraint (12) takes over when tdjj'= 0. The model decides if government intervention is needed or an alternative route is to be selected. Based on the checking by the emergency monitoring team if the available alternative routes are not suitable at this transit location, the team will trigger alternative routes to zero based on the combined decision of constraints (11) through (14). Equation (15) ensures continuing flow of goods through the existing or alternative route and balances the flow between TNs, and constraint (16) balances the flow from TN to DCs. It In equations (17) and (17.a) flow of relief items continue from distribution node to demand points. Constraints (18) and (18a) limits the flow of relief goods to DCs based on their capacities. Constraints (19) and (19a) distributes relief items to HNs and makes sure that the quantity of relief material flows at the HNs inside the devastated area are balanced against the estimated required resource relief items.

$$ACC_{jj'} - TRD_{jj'} \leq td_{jj'} M \quad \forall j, j' \tag{10}$$

$$su_{jj'} \leq td_{jj'} \qquad \forall j, j' \tag{11}$$

$$gv_{jj'} + atd_{jj'} \leq (1 - td_{jj'}) M \qquad \forall j, j' \tag{12}$$

$$gv_{jj'} + atd_{jj'} = 1 \qquad \forall j, j' \tag{13}$$

$$atd_{jj} \leq su_{jj'} \qquad \forall j, j' \tag{14}$$

$$hf_{jj'dm} \leq M(ars_{j'j} + atd_{j'j}) \qquad \forall j, j' \tag{15}$$

$$\sum_{j'\in J'}\sum_{m\in M} hf_{jj'dm} = \sum_{k\in K}\sum_{m\in M} hf_{jkdm} \;\; \forall d \tag{16}$$

$$\sum_{k\in k}\sum_{m\in\{1,4\}} hf_{jkdm} = \sum_{h\in h}\sum_{m\in\{1,4\}} hz_{khdm} \;\forall d \tag{17}$$

$$\sum_{k\in K}\sum_{m\in\{1,4\}} gf_{jkgm} = \sum_{h\in H}\sum_{m\in\{1,4\}} gz_{khgm} \;\forall g, d \tag{17a}$$

$$\sum_{k\in k}\sum_{m\in\{1,4\}} hf_{jkdm} = v_k CW_{kd} \qquad \forall d \tag{18}$$

$$\sum_{k\in K}\sum_{m=1,4} gf_{jkgm} \le v_k CGW_{k\ g} \qquad \forall g \tag{18a}$$

$$\sum_{k\in K}\sum_{h\in H}\sum_{m\in M} hz_{khdm} = thr_d \qquad \forall d \tag{19}$$

$$\sum_{k\in K}\sum_{h\in H}\sum_{m\in M} gz_{khgm} = trs_g \qquad \forall g \tag{19a}$$

Equation (20) defines the response time between two neighboring TNs for the transportation mode used. The response time from a junction point to a DC is defined in equation (21), and that from a DC to an HN (demand point) is defined in equation (22). constraint imposes integrality.

$$res_{jj'm} = dis_{jj'm} ars_{jj'} \quad \forall j, j'; j' > j, j \ne j' \tag{20}$$

$$res_{jkm} = dis_{jkm} ars_{jk} \qquad \forall j,k \tag{21}$$

$$res_{khm} = dis_{khm} ars_{kh} \qquad \forall k,h \tag{22}$$

$$a_i \in \{0,1\}, i \in I; v_k \in \{0,1\}, k \in K; gv_{jj'}, ars_{jj'}; atd_{j\,j}, td_{jj'} \in \{0,1\}, j, j' \in J; \tag{23}$$

Objective 1, defined in equation (24), minimizes the total response time TRES, and TRES is defined in equation (25) considering the response time to send relief goods (resources and HI) from a CN to a nearby TN on a given transportation route, the time to send goods from one TN to the next, the time to send goods from a TN to a DC, and the time to transport goods from a DC to an HN in the affected areas. The research considered flow of HI and Resources separately. Although both the items followed same optimum route making response times same, cost of transportation and cost for collecting the items are different as may be observed in model output to follow. Objective (2), defined in equation (26), minimizes the total cost TC, which is defined in equation (27) as the sum of the procurement cost (PRC) and the logistics cost (LGC). PRC as defined in equation (28) includes the collection costs of HI and resources for relief operation. Logistics cost LGC as defined in equation (29) includes the cost for transporting relief goods on the optimal routes as selected by the model from the collection centers to Transit routes, and transportation cost on the Transit routes, from the transit routes to Distribution centers around the fire affected zone, and from the distribution centers to demand points affected by the fire. In addition to costs for transportation it also includes the fixed cost for opening collection centers; and the fixed cost for opening distribution centers around the fire-affected areas.

Objective 1: Minimize Response time TRES (24)

$$TRES = \sum_{i\in I}\sum_{j\in J}\sum_{m\in M} res_{ijm} + \sum_{j\in J}\sum_{\substack{j'\in J'\\ j<j'}} dis_{jj'm} + \sum_{j\in J}\sum_{k'\in K} dis_{jkm} + \sum_{k\in K}\sum_{h\in H} dis_{kh\ m} \tag{25}$$

Objective 2: Minimize TC (26)

$$TC = PRC + LGC \tag{27}$$

$$PRC = \sum_{d\in D} CC_d thr_d + \sum_{g\in G} CR_g trs_g \tag{28}$$

$$LGC = \sum_{m\in M} \Big(\sum_{d\in D} TRC_{dm} thr_d + \sum_{g\in G} TRSC_{gm} tre_g\Big)(CD_{ijm} + dis_{jj'm} + dis_{jk\ m} + DISTR_{khm}) + \sum_{k\in K} FC_k v_k + \sum_{i\in I} FCE_i a_i \tag{29}$$

Objective 3: Minimize GAPS

$$GAPS = \Big(\sum_{g\in G} trs_g - \sum_{h\in H}\sum_{m\in\{1,4\}} gz_{khgm}\Big) + \Big(\sum_{d\in D} thr_d - \sum_{k\in K}\sum_{h\in H}\sum_{m\in M} hz_{khdm}\Big)$$

The model also optimized the GAPS between the relief goods distributed to the fire-affected zones and the total goods collected. The first part of the GAPs in the equation is for resources and the second item is for HI.

4. NUMERICAL EXAMPLE

The research studied the map of Dhaka and chemical storage locations where the fire incidents occurred. By considering Dhaka's current road network, firefighting strategy, and fire stations, the study proposed 40 transit points (TNs) on the transportation routes of Dhaka, located at a reasonable distance of 15 to 30 minutes of transportation time for the delivery of relief items to hazard affected areas. **Figure 1** in the Appendix presents a schematic map for the flow of relief items through the suggested transportation routes. On this map the CN positions are approximately at the points described in Subsection 2.1. The location of fire-affected area is shown on the map from a satellite-based picture provided by the BBC. The study also selected the locations for setting up 5 DCs around the hazard area, and 5 HNs as demand points to receive relief items. The proposed TNs, CNs, DCs and HNs (shown on the map as FAs for fire affected areas) are shown on network diagram prepared on a map used by the BBC for a report on the Dhaka fire disaster (We could not get any link to get the BBC's permission to use their map).

The study also proposed a disaster monitoring cell formed by Dhaka City Corporation which will become active when there is a fire or any other disaster. The cell may use a satellite enabled system to monitor the traffic density, traffic movement suitability on various routes considering road closures for any reason including accidents, and the physical road condition. The monitoring cell will continuously update the relief operations team on the suitability of a route segment for transportation of relief items based on traffic density and suitability indices defined in subsection 2.2.

4.1 Input Data

For minimizing the response time (Objective 1) for relief and rescue operations and for the mitigation of disaster situation, the model considered 6 CNs for the collection of required six types of humanitarian relief items (as included in **Table 1**) HI and eighteen types relief support items and resources and resources and sending them to HNs as quickly as possible. Typical relief support resources items include Fire trucks; bulldozer; ambulances; cranes; axes, drones, freezer, wagon, and containers. The main sources of HI and resources include the Bangladesh Government (GOB), the city of Dhaka, NGOs, and foreign donations that are collected in warehouses in various cities including Dhaka, port cities of Chittagong, Khulna, and Narayanganj. From these warehouses the relief items will be transported to Dhaka by train, ships, and air. Foreign donations will mostly come through airports, river ports and seaports. As such, the 6 CNs were positioned at the important city entry points into Dhaka as described earlier in Subsection 2.2. The model also considered 5 DCs around he , as discussed before, to receive relief items from the CNs nearby the affected and keep them in staged condition to be distributed to the HNs. We also assumed the collection costs of relief items and the truck-based transportation costs to account for the total costs (Objective 2). The HI and resources used as inputs including the estimation bases are shown in **Table 1.**

Table 1 Typical input data for humanitarian relief items (HI) and resources

Items	HI	Basis unit/ 5-person family	Support Resources	Basis unit/100 persons
1	Food	5pks/day	moveable container	1
2	Water	15 gallons/day	emergency cot	6
3	Medicine	1pk with all essentials/day	tent	6
4	Suitable Clothes	1pk with all essentials	ambulance	1
5	Baby Food	3pks/day (3 babies)	bulldozer	0.33
6	Safety Items	Shoes/wrapper	crane	0.25

4.2 Model Solutions

For response time the model considers the transportation times of the relief items along various possible routes originating at the 6 CNs, then moving through the TNs to reach the DCs, and finally from the DCs to the HNs. **Table 2** presents typical example routes selected by the model and the corresponding response times. The response times presented here are the distances that are expressed in equivalent transportation times along the selected route segments.

Considering all the optimum routes for supplying HI and resources from the 6 CNs to the 5-disaster affected HNs, the optimal Objective 1 value for response time came 6420 minutes, or 107 hours. However, since these routes are working in parallel, the response time is equivalent to only one of the routes. The model considered 16 routes based on the minimum-time route options from the CNs to the HNs. As such, the response time is 107/16=7 hours on average. Based on the Dhaka city map the longest distance is from c4 (**Figure 1** in the appendix) which is the assumed location for the CN at the Dhaka Airport Road entry point. The optimal Objective 2 (total cost) is $13.55 million that includes the procurement cost of $7.3 million and the logistics cost of $6.25 million. The procurement cost applies to the resources and HI items as shown **Table 1**.

Table 2 Typical model output for response time in minutes for various transportation routes

Route from CN	Route details and corresponding time				Total time
CN 1: Route 1	CN1-TN11:40	TN11-TN40 :30	TN40-DC1:30	DC1-HN1:30	130
Route 2	CN1-TN13:30	TN13-TN39 :60	TN39-DC4:30	DC4-HN1:30	140
CN 2: Route 1	CN2-TN5:30	TN5-TN9:15	TN9-DC1:30	DC1-HN5:20	95
Route 2	CN2-TN5:30	TN5-TN7:60	TN7-DC3:30	DC3-HN2:40	160
CN3: Route 1	CN3-TN1: 15	TN1-TN7:80	TN7-DC3:30	DC3-HN2:40	165
Route 2	CN3-TN2: 30	TN2--TN8:30	TN8-DC3:30	DC3-HN2:40	130
CN4: Route 1	CN4:-TN19:40	TN19-TN23:30	TN23-TN27:40		
		TN27-TN38:40	TN40-DC1:30	DC1-HN5:20	200

The GAPS computed by the model are 719,167 units of HI items (each unit is equivalent to a packet needed per day for a 5-person family; and 3,039 units of total resources for the 18 items discussed above. Each unit is equivalent average utility all 18 items for the city. This gaps only provide feeling to Emergency relief operation team to collect more items for effectively containing the fire disaster considered.

5. CONCLUSIONS

The proposed research contributed to the humanitarian logistics planning literature by developing a model-based approach for optimizing disaster response time to initiate relief operations in a densely populated city facing a fire-based humanitarian crisis. The study considers a set of collection centers (positioned mainly on the outskirts of the city) for the accumulation of relief items, as set of distribution centers that (positioned primarily within the city perimeter) that receive relief items and distribute them in a more focused and planned way to the demand points. To determine the optimal distribution routing, the research introduced traffic density and suitability indices as they apply to the various routes in the city. A novel feature of the model formulation is to allow for government intervention when the traffic density, suitability indices, and the alternative routes provision cannot be applied. The model supports the relief operations team to pinpoint the problem(s) causing relief flow hindrance in the logistics network, and to find a solution.

The research considered the schematic map of Dhaka, and the actual location of the occurrence of the fire incident that recently devastated the old part of the city. The proposed model and the overall approach may be applied in similar situations.

The research may be expanded by linking the model to a simulation-based planning tool to investigate the dynamics of the distribution of the relief items as the operation encounters traffic problems that randomly crop up in a congested city such as Dhaka, and to use the observations to enhance the incorporation of such random events in the mathematical model.

REFERENCES

Amideo, A.E., Scaparra, M.P., and Kotiadis, K. (2019), Optimizing shelter location and evacuation routing operations: The critical issues. *European Journal of Operational Research*, 279(2), pp. 279-295.

Apte, A. (2009). Humanitarian logistics: A new field of research and action, Foundations and Trends® in Technology. *Information and Operations Management* 3(1), pp. 1–100.

Apte, A., Khawam, J., Reginer, E., and Simon J. (2016). Complexity and self-sustainment in disaster response supply chains. *Decision Sciences*, 47(6), pp. 998-1015.

Arnette, A.N., Zobel, C.W. (2019). A Risk-Based Approach to Improving Disaster Relief Asset Pre-Positioning. *Production and Operations Management*, 28(2), pp. 457-478.

Balcik, B. and Beamon, B.M. (2008). Facility location in humanitarian relief. *International Journal of Logistics: Research and Applications*, 11(2), pp. 101-21.

Boer, J.D, Lambrechts, W., Krikke, H. (2020). Additive manufacturing in military and humanitarian missions: advantages and challenges in the spare parts supply chain, *Journal of Cleaner Production*, 257 (1 June), 120301.

Charles, A., Lauras, M., Van Wassenhove, L.N., and Dupont, L. (2016). Designing an efficient humanitarian supply network, *Journal of Operations Management*, 47-48(1), pp. 58-70.

CRED (2018) Advanced Search, Université Catholique de Louvain, Brussels, available at: www.emdat.be/advanced_search/index.html

Das, K. and Lashkari,R.S. (2015). A supply chain product delivery and distribution planning model, *Operations and Supply Chain Management*, 8(1), pp.22-27

Du, L., Feng, Y, Tabg, L.Y., Lu, W., Kang, Y. (2020), Time dynamics of emergency response network for hazardous chemical accidents: A case study in China, *Journal of Cleaner production*, 248(March 1,2020), pp. 119-239.

Dufour, E., Laporte, G., Paquett, J., Rancourt, M-E. (2018). Logistics service network design for humanitarian response in East Africa, *Omega*, 74(January), pp. 1-14.

Hu, S. and Dong, J.S. (2019). Supplier selection and pre-positioning strategy in humanitarian relief, *Omega*, 219 (March), pp. 287-298.

Himoto, K., Tanaka, T. (2008). Development and validation of a physics-based urban fire spread model. *Fire Safety Journal* 43, pp. 477-494.

Himoto, K., Tanaka, T. (2012). A model for the fire-fighting activity of local residents in urban fires. *Fire Safety Journal* 54, pp. 155-166.

Jain, S., McLean, C. (2008). Components of an incident management simulation and gaming framework and related developments. *Simulation* 84(1), pp. 3–25.

Jain, S. and C.R. McLean. (2003), Modeling and Simulation of Emergency Response. Workshop Report, Relevant Standards and Tools, National Institute of Standards and Technology Internal Report, NISTIR-7071. www.nist.gov/msidlibrary/doc/nistir7071.pdf, last accessed on 12/14/2019.

Jones, E. (2013). Director of American Red Cross Regional Disaster Services Presentation. Presentation made at the Second Mini conference in Humanitarian Operations and Crisis Management, POMS College of Humanitarian Operations and Crisis Management, Denver, CO.

Kovacs, G. and Spens, K. (2009). Identifying challenges in Humanitarian logistics, *International Journal of Physical Distribution & Logistics Management,* 39(6), pp. 506-528.

Kobayashi, T., Khojasteh,Y. and Kainuma,Y. (2019). Analysis of multi-objective decision problems in humanitarian supply chains, *Operations and Supply Chain Management*,12(2), pp.60-67

Nimtoli to Chawkbazar (2019). Daily Star Report: https://www.thedailystar.net/frontpage/news/dhaka-fire-nimtoli-chawkbazar-lesson-not-learnt-1705771.

Navitas, P. (2014). Improving Resilience against Urban Fire Hazards through Environmental Design in Dense Urban Areas in Surabaya, Indonesia, *Procedia - Social and Behavioral Sciences,* 135 (2014), pp. 178–183.

Menya, A.A., and A'akmu, O.A.(2016), Inter-agency collaboration for fire disaster management in Nairobi City. *Journal of Urban Management*, 5(1), pp. 32-38.

Ozdamar, L. and Ertem, M.A. (2015), Model, solutions and enabling technologies in Humanitarian logistics. *European Journal of Operational Research*, 244(1), pp. 55-65.

Pedraza-Martinez, A. J., & Van Wassenhove, L. N. (2016), Empirically grounded re- search in humanitarian operations management: The way forward. *Journal of Operations Management*, 45, pp. 1–10.

Shook, G. (1997). An assessment of disaster risk and its management in Thailand. *Disasters* 21(1), pp. 77-88.

Vanajakumari, M., Kumar, S., Gupta, S. (2016). An integrated logistics model for predictable disasters. *Production and Operations Management* 25(5), pp. 791-811.

Wagner, N., Agarwal, V. (2014). An agent-based simulation system for concert venue crowd evacuation modeling in the presence of a fire disaster. *Expert Systems with Applications*, 41(2014), pp. 2807-2815.

Waheed, M. A.A. (2014). Approach to fire-related disaster management in high-density urban areas. *Fourth International Symposium on Infrastructure Engineering in Developing Countries*, IEDC, 2013, published in Procedia Engineering 77(2014), pp. 61-69.

Wang, B., Wu, C., Reniers, G., Huang, L., Kang, L., & Zhang, L. (2018). The future of hazardous chemical safety in China: opportunities, problems, challenges and tasks. *Science of Total Environment.*643 (12), pp. 1-11.

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APPENDIX 1: SCHEMATIC MAP OF DHAKA AND THE PROPOSED TRANSPORTATION ROUTES FOR THE RELIEF OPERATION

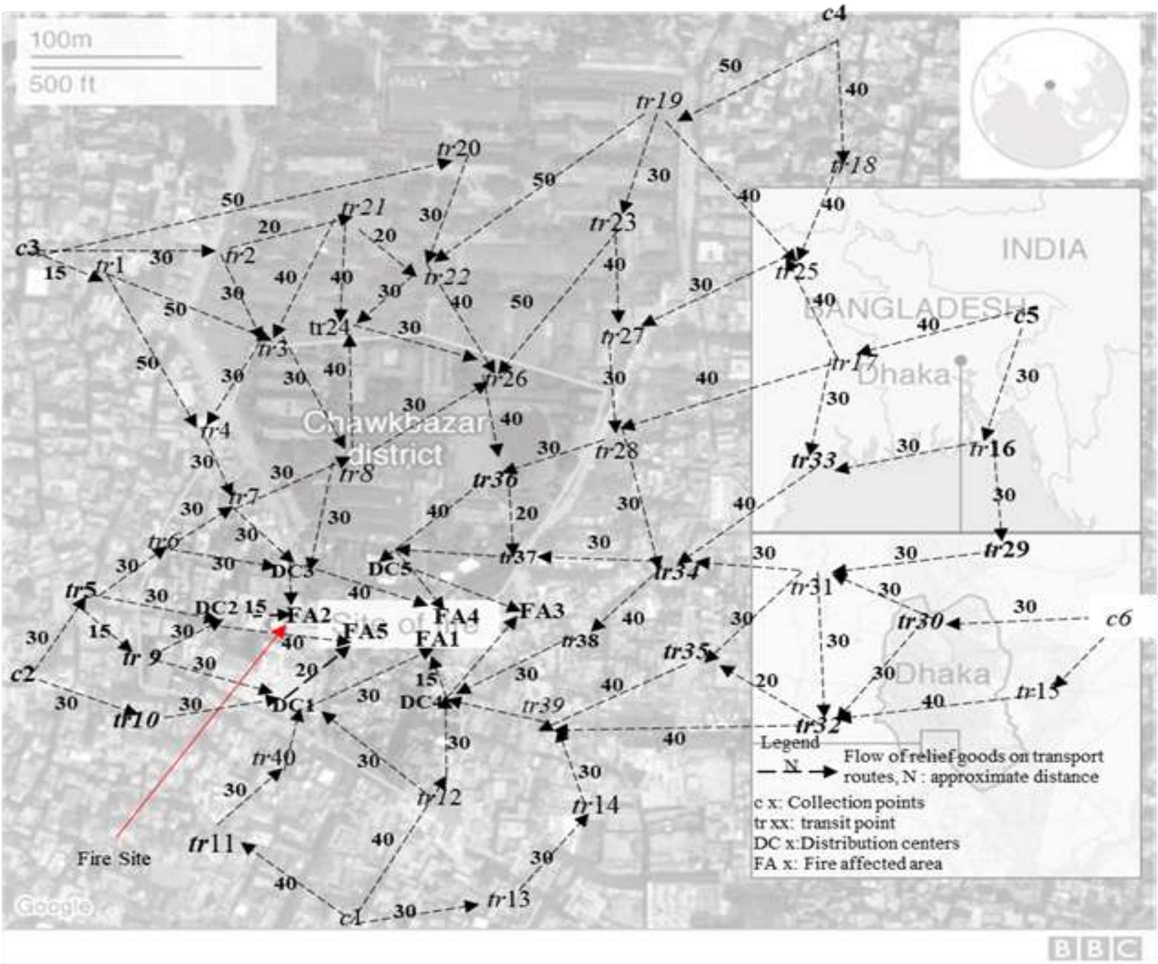

Figure 1. Proposed transportation routes