Multi-modal Logical Architecture for Emergency Transportation towards Better Decision Making in Humanitarian Logistics

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ABSTRACT

Humanitarian logistics has emerged as a vital tool to reduce and alleviate the harmful impacts and suffering caused by extreme events. A significant task of planners and decision makers involved in humanitarian logistics is planning for and satisfying the vital needs of the people during highly stochastic disaster/catastrophe conditions. To accomplish this, there is a clear research need to describe and evaluate a multi-modal logical architecture of efficient emergency transportation operations that will support decision makers to generate and evaluate decision alternatives for solving the problems related to transporting vital supplies during highly stochastic disaster conditions. To be more specific, the humanitarian multi-modal logical architecture described in this paper is created as a comprehensive needs assessment effort and knowledge base that can be used in the creation of software tools for the movement of emergency supplies. This paper carefully describes the steps needed to create such a logical architecture for multi-modal humanitarian logistics with an emphasis on the sustainability and resiliency of the emergency relief system in the event of a disaster/catastrophe. During the extensive process of evaluation of the proposed logical architecture, a thorough study and general assessment of the transportation network and infrastructure based on system profiles, availability, allocation, and optimal assignment of critical resources and database requirements are also conducted, followed by a case study applied to the NY-NJ-CT-PA CSA region. Finally, future directions on the usage of this comprehensive logical architecture are discussed.
INTRODUCTION

Emergency inventory and transportation management in the context of humanitarian logistics is a critical and complex task that depends on the characteristics of an extreme event such as a disaster or catastrophe. It is also directly related with the transportation infrastructure, disaster/catastrophe area security, demand for vital supplies, availability and distribution of suppliers, allocation of inventories and shelters, the importance of the commodity (vital/perishable), material convergence, deprivation costs, etc. The need to study the unique features of emergency transportation operations as a part of humanitarian logistics have been recognized by several researchers recently ([1-8]). A significant research need identified by these researchers is to develop efficient decision support tools for better humanitarian logistics and operations. Holguin-Veras et al. ([5]) clearly states the analytical developments critical for humanitarian logistics as follows: (a) routing and emergency inventory management/pre-positioning models considering the deprivation costs, (b) location/allocation of points of distribution, (c) optimal supply flow with a focus on material convergence. An efficient management strategy to accomplish these tasks together should be based on a collaborative approach supported by efficient decision support tools on the disaster inventory management and flow of emergency supplies. Multi-modal transportation also becomes crucial in this context since these supplies can be transported to the affected disaster region by different transportation modes that include air, waterway, rail and truck (roadway) transportation where speed and reliability criteria are vital while considering the choice of this transportation mode.

The lack of such a decision support tool was a critical handicap in the aftermath of the super storm Sandy which impacted several highly developed metropolitan areas in the Northeast region of the United States, including the New York/New Jersey metropolitan area. The major problems experienced in the aftermath of Sandy were the power outages and lack of fuel. According to Fries ([9]), main factors contributing to this crisis was the damaged refineries and disrupted transportation network, power outages, a shortage of power supplies at the gas stations, and the lack of a robust emergency management plan that could accommodate the effects of a storm akin to Sandy. Kaufman et al. ([10]) added that New York City and its surrounding region experienced severe traffic congestion and gridlocks due to the closure of the subway, transit systems, bridges, and tunnels, making it difficult to rapidly provide emergency supplies to disaster victims. Moreover, according to the New York After Action Report ([11]) presented to Mayor Michael R. Bloomberg, there were 17 community food distribution centers that ultimately served 2.1 million Meals Ready to Eat (MREs) and more than 1 million bottles of water to the victims in New York City. However, the report clearly stated serious disruptions were experienced during the relief operations especially due to the impact of the storm on the transportation network. Based on these problems, the major recommendations made to Mayor Bloomberg in the report included the following ([11]):

- “Create a task force and action plan to develop food and water efficiently and ensure that these plans and forces are activated before a coastal storm.
- A transportation access plan to sites that accounts for emergency road and bridge closures
- Identify locations in high-risk areas that may be used as food and water distribution points.”
Based on these real-life examples from super storm Sandy, it is clear that, without decision support tools in order to help facilitating the adequate and efficient supply of vital commodities, satisfying the daily requirements of disaster victims without disruptions might be problematic. This need has been clearly identified by Holguin-Veras et al. (5) stating the urgent need for decision support tools that can capture the stochastic conditions of an extreme event to solve the problems related to emergency transportation, inventory management and allocation of resources as a part of the humanitarian logistics operations. To be able to create these tools, there is a need for multi-modal humanitarian logical architecture to provide emergency management agencies with practical, optimal, and efficient solutions to store and transport vital commodities in the aftermath of a disaster.

Thus, this paper focuses on the development of an efficient multi-modal logical architecture which can be used to create the decision support tools needed for delivering better humanitarian logistics services, which has not been done with a focus on the usage of different transportation modes, to the author’s knowledge. This is a vital need since the flow of emergency supply can be extremely difficult due to the disruptions in the transportation infrastructure (5). In order to help solve this problem, the proposed logical architecture makes the following contributions:

• An algorithmic approach to address the needs for fast, accessible and reliable emergency transportation operations where different transportation modes can meet the speed and reliability criteria to varying degrees.

• A multi-modal transportation management approach on transporting vital supplies accounting for the difficulty in handling the chaotic conditions of emergency operations and relief response.

• Clear directions for evaluating multi-modal transportation networks with a focus on the storage and supply of vital commodities:
  ➢ Identification of mode specific travel times between origins (warehouse, inventory, intermodal facility, staging area) and destinations (staging area, shelter, local distribution center).
  ➢ Identification of major bottlenecks and critical locations within the transportation network based on affected areas and restrictions, such as truck routes and weight/height restrictions.

Details of this study can be found in the project final report (12) prepared for the NY-NJ-CT-PA Regional Catastrophic Planning Team (RCPT). This paper provides an overview of the work Rutgers University research team conducted, and it is organized as follows. Firstly, an overview of the proposed logical architecture is given that includes the description of the algorithmic approach and summary of the intense development process. This includes the evaluation of the transportation network with a detailed study of the problem from all perspectives and different transportation modes (air, rail, waterway and roadway), and a focus on travel time calculations, loss of infrastructure, and specific restrictions, necessary for the development of such an architecture. Within this evaluation, an application on NY-NJ-CT-PA Combined Statistical Area (CSA) region is also presented. Finally, a list of the conclusions and future recommendations are provided.

LOGICAL ARCHITECTURE

A multi-modal logical architecture for emergency transportation decision making in humanitarian logistics with multiple transportation modes will be described in this section.
This multi-modal architecture will help in identifying the optimal transportation modes and routes based on the available data points including the origins and destinations, and their allocation, infrastructure available, time-threshold constraints, etc. The proposed methodology consists of three steps: (a) description and components of the logical architecture, (b) data analysis for the components, (c) and multi-modal routing. As a result of these steps, a decision-making flowchart will be presented based on this logical architecture at the end of this section, followed by an application on the CSA region.

Procurement usually starts at the warehouse/inventory/depot that has the emergency supplies needed, and can be transferred by air, rail, waterway, or truck modes, and through intermodal terminals and staging areas, while being transported to the final destinations. Therefore, emergency supply transportation should be considered at two levels: extra-regional and local. Local describes network and facilities inside the affected region (including nearby facilities just beyond the affected region boundary), and extra-regional encompasses all other locations in the USA. This differentiation between the sources for vital supplies is critical since the dynamics concerning the origins and nature of these supplies can create the problem described as material convergence (5), where the unsolicited local supplies may have major negative complications for the disaster response operations. During the transportation of these supplies, particularly those originating extra-regionally, multiple modes may be used. Therefore, an airport, seaport, or railway terminal may act as an intermodal connection; a destination for one leg of the trip and an origin for the next leg. For this purpose, the logical architecture given in FIGURE 1 is proposed for an efficient decision-making framework between any origin and destination.
(a) Inside Loop
Description and Components of the Logical Architecture

Efficiency of the multi-modal transportation depends on the access and availability of all existing data points in the affected region (FIGURE 2) as well as the transportation network to facilitate trucking. Following the determination of available modes given the disaster and supply conditions and time threshold constraints for the supply operations, available routes should be identified to facilitate the flow of supply to the destination. The logical architecture for these components falls under the two loops shown in Figure 1. In (a), the mode availability and time threshold constraints determine the optimal routing analysis, whereas in (b), the real-time update of traffic, weather, or disaster data can affect the decision-making.

The research team identified two vital components within this architecture, namely: mode availability and route availability/optimal routing:

Component 1: Mode Availability - Given the disaster and supply related inputs, the logical architecture should describe the component that will determine the availability of the modes of transportation (air, waterway, rail, and roadway) between the selected origins and destinations (FIGURE 2).
Component 2: Route Availability and Optimal Routing - Following the determination of available modes, available routes could be identified to facilitate the flow of supply to the destination based on the disaster and supply conditions and time threshold constraints for the supply operations (FIGURE 2).
Data Requirements for Individual Components of Logical Architecture

Data are critical for efficient and reliable operations for each individual component of the logical architecture. Data points for each component can be seen in FIGURE 3 where decisions on mode and route choices can be updated when more information becomes available. Depending on the nature of the data, the following sections represent the types of data that were determined to be vital for the mode and route availability as a result of the review conducted by the research team.

Off-line Data

- **Static network/infrastructure data**: All the static roadway network and infrastructure, including the major highways and arterials.
- **Warehouse and inventories**: Origins for optimal routing analysis.
- **Intermodal terminals**: Mainly critical for multi-modal routing, the intermediary locations between warehouses and staging areas/shelters.
- **Contingency locations, staging areas, and shelters/local distribution centers**: Destinations, although staging areas could also be considered origins for a trucking analysis between staging areas and shelters/local distribution centers.
- **Air/Rail/Waterway modal data**: All relevant network and logistics data, in database and GIS compatible formats, for air, railway and waterway modes.
- **Truck type data**: Width, height, weight and axle configuration of trucks.
- **Truck route input data**: Available truck routes between origins and destinations to conduct optimal routing analysis for emergency supply operations.
- **Traffic data**: Data from travel demand models, sensors, and GPS-based sources, critical in order to conduct a travel time based analysis for roadway transportation.
- **Network restrictions**: Roadway restrictions for trucks due to height, length, width and weight limitations that should be available for use in database and GIS compatible formats.

On-line Data

On-line data is also found to be critical to be able to track the emergency supply operations in real-time and to inform the officials. Data may include the availability of truck routes, traffic and congestion on the roadway network, and any infrastructure failure and disruptions due to disaster conditions and can be obtained using the following methods:

- **Probe vehicle data**: Data (vehicle position, time, etc.) obtained explicitly or implicitly from random vehicles moving on the transportation network using the collection methods such as Signpost-Based Automatic Vehicle Location (AVL), Automatic Vehicle Identification (AVI), Ground-Based Radio Navigation, Cellular Geo-location and Global Positioning Systems (GPS).
- **Sensor data (WIM, Loop, Transmit, GPS)**: Data obtained either by conventional methods such as detectors located along the roadside, or new technologies such as mobile phones or GPS over the entire road network.

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Paper revised from original submittal.
• **INRIX data:** Real-time, historical and predictive traffic flow, congestion alerts, incident data, traffic maps and traffic cameras.

• **United States Transportation Command (USTRANSCOM) data:** Military data available for military tools.

• **On-line requests (demand):** Data on the movement of traffic, the condition of transportation network, etc. that could be obtained via on-line requests to the federal and state agencies.

• **Web-based open source data:** Open sources such as Google present web-based live traffic and network information via their Google maps application.

• **On-line commodity data:** Data obtained by real-time tracking technologies such as Radio Frequency Identification Technologies (RFID).
FIGURE 3 Data Sources for the (a) Mode Availability Component (b) Route Availability/Optimal Routing Component

Review Results of Existing Tools

The research team reviewed and evaluated the following existing tools with similar purposes related to the proposed emergency architecture:

- U.S. Army tools: Intelligent Road/Rail Information Server (IRRIS) (13) and Mobilization Movement Control (MOBCON) (14)
- Federal agency tools: Sahana Eden: Emergency Development ENvironment) for Rapid Deployment Humanitarian Response Management and Intermodal Transportation (15) and Inventory Costing Model-State Tool (ITIC-ST) (16)
- Commercial company tools: PC-MILER (17) and Axon Commercial Trucking Software (18)

Review of these tools determined the critical issues and advantages/disadvantages of existing tools. Among the commercially available tools, IRRIS was identified as the most promising tool with the following critical functionalities:

- Query Builder to view textual data in a tabular format.
- Geospatial Data and Detailed Mapping
- Asset Tracking (In-Transit Visibility)
Moreover, IRRIS was originally a military-based tool but it enabled integration with commercial tools such as PCMILER that could provide the necessary trucking database needed. There was one major drawback of IRRIS: unavailability of multi-modal transportation functionality. This problem could be solved by creating a module that uses complex routing algorithms to facilitate routing while being integrated to IRRIS platform based on the proposed architecture in this paper. A summary of the functionality comparison for three selected software was presented in TABLE 1.

TABLE 1 Comparison of Selected Existing Tools

<table>
<thead>
<tr>
<th>Functionality</th>
<th>IRRIS</th>
<th>PC*MILER</th>
<th>AXON</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routing</td>
<td>Routing algorithms are not built in, ESRI and other platforms are used to perform routing.</td>
<td>Routing algorithms are built in. Shortest, practical, least cost and fastest routing available.</td>
<td>Routing algorithms are not built in, has to connect to PC*MILER to conduct routing.</td>
</tr>
<tr>
<td>Multi-Modal Routing</td>
<td>Not available.</td>
<td>Multi-modal routing available with only rail and truck transportation.</td>
<td>Not available.</td>
</tr>
<tr>
<td>Security</td>
<td>Enhanced security protocols due to military usage.</td>
<td>Not as enhanced as IRRIS.</td>
<td>Not as enhanced as IRRIS.</td>
</tr>
<tr>
<td>Databases</td>
<td>Databases are used as overlays on existing IRRIS maps.</td>
<td>All databases can be integrated with the original network and each other.</td>
<td>All databases can be integrated with the original network and each other.</td>
</tr>
<tr>
<td>Critical Locations (Airports, ports, railway terminals)</td>
<td>Mostly military locations are available.</td>
<td>All locations within U.S. are available with coordinates and addresses.</td>
<td>All locations within U.S.</td>
</tr>
<tr>
<td>Rail Network and Data Points</td>
<td>Available</td>
<td>Available.</td>
<td>Not available.</td>
</tr>
<tr>
<td>Truck Specific Restrictions</td>
<td>Available through an interface with PC*MILER.</td>
<td>Available.</td>
<td>Available.</td>
</tr>
<tr>
<td>Weather Data</td>
<td>Available</td>
<td>Not available.</td>
<td>Not available.</td>
</tr>
<tr>
<td>Emergency Applications</td>
<td>Available.</td>
<td>Not available, daily truck operations are considered. Network links can be manually updated when lost.</td>
<td>Not available, daily truck operations are considered.</td>
</tr>
</tbody>
</table>
Multi-Modal Routing and Transportation of Vital Supplies

Based on the available modes and routes given the inputs and time threshold constraints, intermodal routing options between the origin and destination are identified based on multi-modal routing models and algorithms. A decision support tool that can be based on this logical architecture should work with routing algorithms that are compatible with GIS applications and databases and should provide the planners and emergency officials with the ability to find the optimal path that he/she can use to transport emergency supplies from origin to destination by highlighting the dynamically generated shortest path over a digital map (possibly web-based). Routing algorithms are available within GIS tools such as ArcGIS (ESRI) (19) as well as open source platforms such as pgRouting (20). PC*MILER, on the other hand, has built-in truck-specific routing and mileage calculations for Shortest, Practical, Least Cost, and Fastest (requires real-time traffic data) routes (17).

One important step for the routing is to first pre-process all the network components (nodes and links) for their availability after the disaster. Thus, the adopted routing algorithm should work with an almost dynamic network which could be continuously updated to make sure that link conditions accurately represents current situation. FIGURE 5 depicts the time line for a sample network. The information fed into decision making framework at any time step includes the following:

- At \( t_0 \) all the network is available for use,
- At \( t_1 \) several links and nodes are lost,
- At \( t_2 \) some of those links and nodes are recovered,
- At \( t_3 \), there is full recovery.

Therefore, at any time, the logical architecture can be based on the latest information for optimal routing where the links available and lost are clearly identified, using the GIS databases and following the logic given in FIGURE 4. In order to complete the transfer of vital supplies into the affected region, the planner/engineer will focus on optimal routing between origins and destinations using different modes. This multi-modal transportation requires the evaluation of all existing data points in the affected region and incorporating them into the logical architecture with the addition of trucking evaluations. For multi-modal routing, the concept of supernetworks is useful. Supernetworks are integrated multi-modal networks that show all possible routes with respect to different modes between an origin and destination. Supernetworks can be obtained easily once all the modes and routes are determined. For the original networks illustrated in FIGURE 4, a sample illustration on how supernetworks are created where (1: node, 2: mode) in the supernetwork.
Based on the information presented in the previous sections, the pseudo-code for overall multi-modal routing can be presented as follows:

**Input 1:**

1. **Origin and Destination** (see Figure 9 for representative origins and destinations in the CSA Region, and Figure 1 for MCT component logic): User Entry or Selection from Pre-defined Lists
2. **Commodity** (availability, handling and perishability): User Entry
3. **Time Threshold** (Default as a function of commodity and disaster): User Entry or Selection from a Table

**Call Routing Function using available software (ESRI, PC*MILER, etc.)**

*Calculate Truck Route and Travel Time*

*If Travel Time (Truck) > Time_Threshold Then*
Repeat for Truck+Air+Truck and Air+Truck and Truck+Air and Air_Only and Truck+Rail
and Rail+Truck and Rail+Rail+Truck+Port+Truck and Port+Truck and
Truck+Port

Input 2 (Presented for air transportation only):
Enter closest airport (Different for each combination location to the supply)

Call Multi-Modal Route Generation Function (Origin -> Airport_Origin ->
Airport_Destination -> Destination)

Input 2 (Presented for air transportation only):
Enter closest airport (Different for each combination location to the supply)

Call Multi-Modal Route Generation Function (Origin -> Airport_Origin ->
Airport_Destination -> Destination)

Call Routing Function (PC-Miler, ESRI, etc.) to calculate Truck_Travel_Time (Origin ->
Airport_Origin)

Call Air_Travel_Time Function (Airport_Origin -> Airport_Destination )

Call Routing Function (PC-Miler, ESRI, etc.) to calculate Truck_Travel_Time
(Airport_Destination -> Destination)

Multi-Modal Decision-Making

A multi-modal decision making logic for implementing the multi-modal pseudo-code
presented in FIGURE 5 where the logic is presented for the case with air and truck
transportation only. Here, the multi-modal routing alternatives (depending on the origin
and destination) may include the following options and legs with different modes:

- Uni-modal Options (Note that last leg to the shelter/local distribution center may
  still include trucking):
  - Truck Only: Emergency transportation is performed by trucking only.
  - Air Only: Emergency transportation is performed by air transportation only to
    the destination (airport). If destination is a staging area, shelter or a local
distribution center, trucking may still be needed for the last leg.
Waterway Only: Emergency transportation is performed by waterway transportation only to the destination (port). If destination is a staging area, shelter or a local distribution center, trucking may still be needed for the last leg.

Rail Only: Emergency transportation is performed by rail transportation only to the destination (railway terminal, intermodal terminal). If destination is a staging area, shelter or a local distribution center, trucking may still be needed for the last leg.

- Multi-modal Options (Based on maximum four different mode alternatives for one route, the last leg is always considered as trucking):
  - Truck + Air, Waterway, Rail + Truck: The first leg is to transport commodities from the warehouse to airport, port or railway terminal which includes trucking. The last leg to the destination also has to include trucking.
  - Air, Waterway, Rail + Truck: There may not be a need for trucking at the beginning. Commodities may already be at the airport, port or railway terminal or transporting commodities to those origins are of no interest for the emergency officer.
  - Truck + Air, Waterway, Rail + Air, Waterway, Rail + Truck: There may be a need for multiple modes in addition to trucking both at the first and at the last leg (i.e., Truck + Air + Rail + Truck).
  - Air, Waterway, Rail + Air, Waterway, Rail + Truck: There may be a need for multiple modes in addition to trucking at the last leg (i.e., Air + Rail + Truck).
  - Truck + Air, Waterway, Rail + Air, Waterway, Rail + Air, Waterway, Rail + Truck: There may be a need for multiple modes in addition to trucking both at the first and at the last leg (i.e., Truck + Air + Waterway + Rail + Truck).
  - Air, Waterway, Rail + Air, Waterway, Rail + Truck: There may be a need for multiple modes in addition to trucking at the last leg (i.e., Air + Waterway + Rail + Truck).
FIGURE 5 Multi-modal Decision Making Flowchart for the Logical Architecture

Supply Specific Data Points
availability and type of those commodities, handling strategies, and perishability issues

Data Points: Transportation Modes
airway, waterway, railway and roadway

Data Points: Origins and Destinations
airports, ports, railway terminals, warehouses, inventories, intermodal facilities, staging areas, shelters and local distribution centers

Check the time threshold constraints

Call routing functions

Routing Software (PC*MILER, ESRI)

Calculate truck route and travel time

Enter the closest airport

Yes

Check if truck travel time is larger than the time threshold

No

Call multi-modal route generation function

Routing Software (PC*MILER, ESRI)

Use the travel times for trucking

Outputs:
Top Three Combinations
Total Travel Times
ANALYSIS AND ASSESSMENT OF NETWORK CHARACTERISTICS FOR DISASTER LOGISTICS OPERATIONS: AN APPLICATION ON CSA REGION

Based on the steps of the proposed logical architecture provided above, this section presents an application example for the CSA region, and carefully describes a series of tasks that need to be performed to analyze site specific characteristics of any region along with several numerical examples for which disaster logistic operations using the above proposed routing architecture are considered. We discuss and present the results of our methodology based on analyzing the available transportation network of CSA region with respect to three critical criteria: (a) accessibility, (b) travel time analysis, (c) disaster (natural or man-made) sustainability. Such an evaluation will capture the capabilities of the region for facilitating the supply flows.

Vital supply procurement starts at the warehouse/inventory/depot that has the emergency supplies needed, and can be transferred by air, rail, waterway, or truck modes, and through intermodal terminals and staging areas, while being transported to the final destinations. Therefore, emergency supply transportation should be considered at two levels: extra-regional and local. Local describes network and facilities inside the CSA region (including nearby facilities just beyond the CSA region boundary), and extra-regional encompasses all other locations in the USA. In the transportation of goods, particularly those originating extra-regionally, multiple modes may be used. Therefore, an airport, seaport, or railway terminal may act as an intermodal connection; a destination for one leg of the trip and an origin for the next leg. Following the determination of available modes given the disaster and supply conditions and time threshold constraints for the supply operations, available routes are identified to facilitate the flow of supply to the destination.

Among all the available transportation modes for CSA region, trucking is identified to be the critical mode of transportation of vital supplies, therefore it becomes critical to determine and disseminate trucking routes that could be used to move emergency supplies from their origin to their destination. The delivery of these emergency supplies by trucks requires the availability of sufficient roadway infrastructure. Therefore, critical roadways in the affected region should be investigated after evaluating the following available infrastructure data. For the CSA region, FIGURE 6 shows the major truck routes, restrictions and major access points as well as the emergency shelters available in the region based on the evaluation of the available data. In the CSA region, trucks are prohibited from all Parkways with the exception of the Garden State Parkway south of Exit 105. As shown in FIGURE 7, parkways comprise a significant portion of the CSA region’s highway network, particularly within New York City. In order to support the long-term recovery and humanitarian assistance as a part of humanitarian logistics operations, the proposed architecture can be successfully implemented to account for the uncertainty in demand and supply and transportation network disruptions. Depending on the truck type and roadway restrictions due to physical limitations, it may not be possible to deliver supplies to a destination using a selected truck route; therefore alternative truck routes or modes should be considered. Optimal routing analysis within a decision support tool should provide the ability to select different routes between selected origins and destinations, and should be able to show all the truck restrictions on those routes. With this information, if there is a physical limitation present such as low bridges for trucking operations, the officials can make decisions on how to optimally and safely deliver the vital supplies to the affected region.
In the immediate aftermath of a disaster, thousands of donors send donations to the affected region in terms of commodity and equipment, which creates the problem of material convergence (5). Therefore, it is important to note that emergent behaviors such as manpower and material convergence can make it relatively difficult to use the proposed approach in the very early stages of disasters (7). However, it is hoped that the logical architecture presented in the paper can be a significant step towards better decision making for post-disaster humanitarian logistics (initial response and short-term recovery phases) where manpower and material convergence have a substantial effect on the supply transportation operations.

(a)
During an emergency situation, commodities will likely come into the region directly via truck, or by air, rail, or sea and trucked to their final destinations from facilities within or near the region (depending on the origin and nature of these supplies, material convergence problem can be experienced). Therefore, origins for truck routes could be within the region or anywhere in the entire USA. However, destinations are located within or near the affected region. In this section, to assess the anticipated impact of truck restricted roadways on travel times, planning model-based output is used to measure congested travel times using the shortest path given all available roadways, and only roadways without truck restrictions for the CSA region. NYBPM model (21) is used to compare model-estimated congested travel times (TABLE 2) where names of the origins and destinations are not provided due to the confidentiality agreement the research team had with RCPT.
**TABLE 2 Travel Time Comparison with and without Truck Restrictions**

<table>
<thead>
<tr>
<th>Origins</th>
<th>NYBPM Travel Times without Truck Restrictions (min)</th>
<th>NYBPM Travel Times with Truck Restrictions (min)</th>
<th>Average Difference (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AM</td>
<td>MD</td>
<td>PM</td>
</tr>
<tr>
<td>Airport 1</td>
<td>107</td>
<td>103</td>
<td>106</td>
</tr>
<tr>
<td>Airport 2</td>
<td>41</td>
<td>40</td>
<td>47</td>
</tr>
<tr>
<td>Railway Intermodal Terminal 1</td>
<td>336</td>
<td>324</td>
<td>324</td>
</tr>
<tr>
<td>Railway Intermodal Terminal 2</td>
<td>46</td>
<td>44</td>
<td>47</td>
</tr>
<tr>
<td>Port 1</td>
<td>32</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>Port 2</td>
<td>189</td>
<td>177</td>
<td>180</td>
</tr>
</tbody>
</table>

**NYBPM Travel Times from Selected Origins to Shelter 2, NJ**

<table>
<thead>
<tr>
<th>Origins</th>
<th>NYBPM Travel Times without Truck Restrictions (min)</th>
<th>NYBPM Travel Times with Truck Restrictions (min)</th>
<th>Average Difference (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AM</td>
<td>MD</td>
<td>PM</td>
</tr>
<tr>
<td>Airport 1</td>
<td>90</td>
<td>85</td>
<td>84</td>
</tr>
<tr>
<td>Airport 2</td>
<td>34</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>Railway Intermodal Terminal 1</td>
<td>333</td>
<td>321</td>
<td>317</td>
</tr>
<tr>
<td>Railway Intermodal Terminal 2</td>
<td>30</td>
<td>28</td>
<td>27</td>
</tr>
<tr>
<td>Port 1</td>
<td>49</td>
<td>43</td>
<td>40</td>
</tr>
<tr>
<td>Port 2</td>
<td>169</td>
<td>156</td>
<td>152</td>
</tr>
</tbody>
</table>

**NYBPM Travel Times from Selected Origins to Shelter 3, CT**

<table>
<thead>
<tr>
<th>Origins</th>
<th>NYBPM Travel Times without Truck Restrictions (min)</th>
<th>NYBPM Travel Times with Truck Restrictions (min)</th>
<th>Average Difference (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AM</td>
<td>MD</td>
<td>PM</td>
</tr>
<tr>
<td>Airport 1</td>
<td>111</td>
<td>112</td>
<td>107</td>
</tr>
<tr>
<td>Airport 2</td>
<td>97</td>
<td>97</td>
<td>97</td>
</tr>
<tr>
<td>Railway Intermodal Terminal 1</td>
<td>358</td>
<td>358</td>
<td>352</td>
</tr>
<tr>
<td>Railway Intermodal Terminal 2</td>
<td>89</td>
<td>88</td>
<td>91</td>
</tr>
<tr>
<td>Port 1</td>
<td>141</td>
<td>133</td>
<td>142</td>
</tr>
<tr>
<td>Port 2</td>
<td>237</td>
<td>227</td>
<td>225</td>
</tr>
</tbody>
</table>

**AM: AM peak, MD: Mid-day, PM: PM peak, NT: Night**

Planners/officials could not know where a disaster will strike, nor do they know where exactly victims will be evacuated to. Although these estimations would not be directly used for real-time emergency management operations, a widely dispersed group of origins and destinations would provide more choices while delivering emergency supplies to the emergency planners. In addition, it would also help in understanding the feasibility of certain routes and the use of trucks. Before conducting the optimal routing analysis, officials could be aware of the estimated travel times between origins and destinations with and without including daily congestion (free flow time), and therefore could make decisions related to the origin selection and routing based on this information.
Disruption (Hazard) Analysis

The focus of emergency relief studies has evolved due to changes in the frequency and types of incidents that require emergency operations. For example, recent interest in emergency response to man-made disasters could be attributed to concerns about terrorism. However, hurricanes and floods have been the most frequent and dangerous hazardous events in the USA continuing to be one of the major focus areas. Thus, this step discusses potential issues resultant from disruption of highways within the affected region due to disasters.

Storm Surges and Flooding

For the flooding analysis, the hazard analysis procedure assesses the potential impact on the truck route if such an event did occur, rather than addressing the probability of an event. Within this effort, each truck route is ranked as high, medium, or low in terms of vulnerability for storm surge and flooding. For storm surge in the CSA region, the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) maps \(^{(25, 26)}\) are used to estimate storm surges resulting from tropical storms and assess the vulnerability of each facility to storm surge with the following categorization as presented in TABLE 3:

- **High:** Truck route is vulnerable to storm surge and flooding from a Category I or II storm.
- **Medium:** Truck route is vulnerable to storm surge and flooding from a Category III or higher storm.
- **Low:** Truck route is not vulnerable to storm surge and flooding.

TABLE 3 Evaluation of Major Truck Routes for Storm Surge and Flooding

<table>
<thead>
<tr>
<th>Roadway</th>
<th>States</th>
<th>Vulnerability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate 95</td>
<td>NJ-NY</td>
<td>Highly Vulnerable to Flooding in densely populated north NJ-NY region</td>
</tr>
<tr>
<td>Interstate 80</td>
<td>PA-NJ</td>
<td>Low Vulnerability</td>
</tr>
<tr>
<td>Interstate 78</td>
<td>PA-NJ-NY</td>
<td>Low Vulnerability</td>
</tr>
<tr>
<td>Interstate 84</td>
<td>PA-NY-CT</td>
<td>Low Vulnerability</td>
</tr>
<tr>
<td>Interstate 87</td>
<td>NY</td>
<td>Highly Vulnerable to Flooding in densely populated NY region</td>
</tr>
<tr>
<td>Interstate 287</td>
<td>NJ-NY</td>
<td>Highly Vulnerable to Flooding in densely populated north NJ-NY region</td>
</tr>
<tr>
<td>Interstate 278</td>
<td>NJ-NY</td>
<td>Highly Vulnerable to Flooding in densely populated north NJ-NY region</td>
</tr>
<tr>
<td>Interstate 295</td>
<td>NY</td>
<td>Medium Vulnerability</td>
</tr>
<tr>
<td>Interstate 495</td>
<td>NY</td>
<td>Low Vulnerability</td>
</tr>
<tr>
<td>Interstate 678</td>
<td>NY</td>
<td>Medium Vulnerability</td>
</tr>
</tbody>
</table>

Man-made Disasters/Accidents

Since there is no formal index or model to predict man-made disasters and accidents, subjective judgment is used to assess the vulnerability of each facility. Location specific rating criterion is as follows:

- **High:** Truck route passes within 10 miles of a chemical or nuclear power plant.
- **Medium-High:** Truck route passes 10–25 miles from a chemical or nuclear power plant.
- **Medium-Low:** Truck route passes 25–50 miles from a chemical or nuclear power plant.
For the CSA region, FIGURE 7 shows roadways that pass through the High and Medium-High risk areas according to the criteria where the information for the plants is obtained from publicly available sources (27, 28, 29).

- **Low**: All others.

**FIGURE 7 CSA Region Roadway Vulnerability Map (12)**

**Discussions**

The following critical conclusions were reached as a result of this evaluation step:

- Roadway network and infrastructure are found to be capable of facilitating the optimal multi-modal transportation of emergency supplies in the CSA Region which would significantly contribute to effective relief and response.
- Despite this capability, the existing network might not be sufficiently utilized for the emergency transportation operations during and/or after the disasters due to the possible disruptions, restrictions or capacity degradations that can occur due to extreme events such as hurricanes, storms, accidents and man-made attacks. Moreover, massive amounts of supplies can be sent to the affected region from various sources, which will create the problem of material convergence in the highly populated CSA region (5).
- It is important to note that some of the origins presented are military owned which indicate the need for efficient planning and coordination between military and non-military organizations to facilitate the transportation of emergency supplies optimally to the affected areas. Therefore, planning and coordination between
Military, federal and state agencies and private companies are identified to be critical for the emergency transportation operations (i.e., emergency transportation from military owned airports to American Red Cross shelters). Decisions regarding humanitarian logistics should be made jointly by these agencies that must work together during disasters, which is most of the time one of the most important drawbacks in large-scale disasters and catastrophes, as stated in (5).

- Decision support tools, a critical research need identified in (5), can also be created based on this logical architecture that should primarily consider the following requirements:
  - Provide a user interface for the emergency planner to enter:
    - Scenario-specific information such as network or mode disruptions, unavailable facilities, etc.
    - Commodity-specific information such as size, perishability, etc.
  - Air and waterway transportation modes
  - Multi-modal routing
  - Time constraints in conjunction with multi-modal routing
  - Pre-loaded origins and destinations based on likely destinations of goods and key terminals throughout the region.

The research conducted has the following novel contributions that differentiates the proposed architecture clearly from the previous works:

- **Identification of critical data points for better planning and/or modeling:** The availability of data points (sources of data, description of data sets, major attributes of available data, usefulness and applicability for the architecture, and possibly GIS-based visual representations of data) for future responses are critical in order to enable better planning since the databases for the commercial tools are usually not available to the public; therefore, private companies may not want to share their databases and networks.

- **Introduction of multi-modal transportation logic into vital commodity transportation:** This research provides a detailed multi-modal commodity transportation logical architecture focusing on the emergency assistance that can be provided using different transportation modes supported by real-life experiences and practices. Since the previous approaches do not support the multi-modal transportation logic (13-18), public and/or private humanitarian agencies will clearly benefit from this research by including the assessment results of this research in their disaster plans specifically on how multi-modal transportation related problems can be solved for different situations.

Holguin-Veras et al. (2012) states that, in the immediate aftermath of a disaster, thousands of donors send donations to the affected region in terms of commodity and equipment, which creates the problem of material convergence. Therefore, it is important to note that emergent behaviors such as manpower and material convergence (Wachtendorf, 2013) can make it relatively difficult to use the proposed architecture in the very early stages of disasters. However, it is hoped that the online feedback-based approach presented in the paper can be a significant step towards obtaining an analytical model for post-disaster humanitarian logistics (initial response and short-term recovery phases) where manpower and material convergence have a substantial effect on the supply transportation operations.
CONCLUSION AND FUTURE DIRECTIONS

This study proposes a state-of-the-art logical architecture for humanitarian logistics that is expected to serve as a critical step towards decision making in the aftermath of an extreme event and that can assist the planners/emergency personnel to get prepared with in terms of transportation of emergency commodities. A vast amount of knowledge is extracted from available resources, existing tools and models, and data sets in order to create the logical architecture, followed by a case study application and example assessment of the transportation infrastructure for the CSA region (12). As a result of this study, the following results and recommendations are made by the research team:

- The humanitarian multi-modal logical architecture described in this paper is created as a comprehensive needs assessment effort and knowledge base that can be used in the creation of software tools for the movement of emergency supplies. This architecture can be successfully used as a part of regular humanitarian logistics operations (long-term recovery and humanitarian assistance) for a super storm such as Sandy, where a substantial level of uncertainty for the demand and supply operations, and disruption in the transportation networks are present (5). Potential solutions for vital supply transportation operations can be evaluated based on the extensive list of requirements presented in this paper, which is a critical research area identified in (5).

- The decision-making architecture can account for the unexpected fluctuations likely to happen during emergency relief operations such as the drastic changes for food, water, medicine, fuel and power after super storm Sandy. These conditions that can occur due to the fact that fuel powered vehicles may not be able to make deliveries, or that some supplies may be lost due to disaster effects, can be identified and evaluated based on the multi-modal logic presented in this paper. The architecture can also be used to support different humanitarian logistics structures (regular and post-disaster humanitarian logistics) defined in (5).

- For different disasters with distinct characteristics, airway, waterway, railway and roadway modes will meet the speed, reliability and cost criteria to varying degrees. Therefore, although trucking will almost always be used as the main mode of transportation for the emergency operations, selection of an alternative and/or additional mode based on the type of the emergency as well as network conditions and other disaster specific characteristics is critical to efficient relief operations.

- Metropolitan regions such as the CSA region pose challenges due to their size, population, and transportation complexity, which are magnified under emergency conditions as observed during super storm Sandy. Thus, while modeling emergency travel in such a region, the research team’s findings suggest that officials should take into account the following factors when making time critical logistic decisions:
  - High population density and total population
  - Complexity and the size of the transportation network
  - Length of trip lengths and travel times
  - Level of interaction between evacuation and emergency operations traffic
  - Lack of experience in emergency operations
  - Lack of effective management mechanisms
  - Material convergence.
A GIS database including highways, airport, port, and railway terminal locations within a single source is necessary to represent the locations of these facilities, and their proximities to roadways are especially critical for the trucking transportation analysis. Therefore, data should be stored in shape files in GIS/GeoMedia format and/or compatible database files (SQL, Microsoft Access, etc.). This will be extremely useful to support the emergency commodity transportation with a focus on the challenges at the airports, ports and railway terminals.

Four-step transportation models such as The New York's Best Practice Model (NYBPM) model are valuable sources for deriving highway and congestion performance measures due to their extensive coverage of the large regions they cover. Moreover, their calibrated and validated individual modules that can be used for emergency transportation analysis purposes.

The proposed framework can also be extended by the addition of real-time tracking capabilities of emergency supplies and demands through the integration of emerging technologies such as Radio Frequency Identification Devices (RFID). This integration has the advantage of synchronizing the critical supply and transportation network to facilitate the sustainable disaster tracking, and to provide an efficient distribution of supply flow.

Qualitatively, the effectiveness or success of emergency inventory management measures in a particular country or region for a given disaster can be affected by the following critical variables or issues: (a) the nature of public-private sector relationships; (b) the economic system; (c) the existence of a disaster/emergency management agency or disaster relief process; (d) cultural traditions; (e) whether the country is a poor, developing nation or a relatively robust industrialized nation; (f) whether the nation is a democracy, monarchy or dictatorship; (g) the role or power of the military and the nature of military support to civil authorities; (h) the state of critical infrastructure, such as energy, water, transportation, food and agriculture, water, etc. This paper does not address the effect of these variables on the efficiency of the emergency management, which is a very interesting area of future work.

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