PERFORMANCE TRADE-OFFS IN LAYOUTS FOR RELIEF CENTERS

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Abstract

At a disaster affected region, relief centers distribute critical supplies and aid to the affected victims. Unlike traditional distribution centers, relief centers experience significant 'crowd effects' due to the sudden influx of victims in a confined space. Using knowledge from studies on pedestrian traffic flow, specialized state dependent queuing models are developed to model the flow of victims along the walkways setup at a relief center. The underlying queuing network model is analyzed to derive expressions for the average times that victims experience before they receive the service at the relief center. The research shows that crowd density effects lead to significant increase in congestion and queuing delays underscoring the importance of developing specialized queuing models that assess the impact of congestion effects on alternative layouts of relief centers.

1. Introduction

Every year disasters across the world kill around 75,000 people and affect over 200 million people [15]. Humanitarian logistics play a significant role in minimizing the losses following a disaster. Broadly speaking, humanitarian relief efforts can be divided into three phases: phase 1 corresponding to the preparation phase before disaster strikes, phase 2 corresponding to the immediate response phase after a disaster, and phase 3 corresponding to the reconstruction phase following a disaster. During phase 1, the preparation phase, efforts focus on minimizing the impact of a disaster and in staging supplies for relief operations. Phase 2 of a relief operation is the immediate response phase, where emergency relief plans come to action. The response phase commences with search and rescue, but quickly focuses on fulfilling the humanitarian needs of the affected population. Phase 3 of a relief operation is the reconstruction phase, where the disaster location is re-developed. Of these three phases, the immediate response phase

presents the most challenges. Efficient and timely response to the disaster can significantly limit the damage to lives and property.
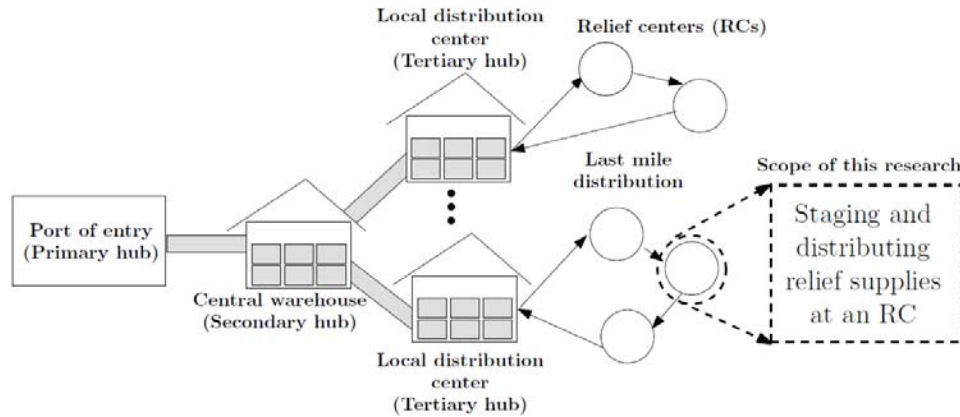

Figure 1. Flow of supplies in the relief supply chain and focus of this research
(Source: modified from [2])

Figure 1 describes the flow of supplies in supply chain distributing aid and relief supplies. In practice, supplies from a central warehouse are distributed to small local warehouse locations situated closer to the disaster sites. From the local warehouses, supplies are loaded into trailers and transported to relief centers where they are unloaded and staged at pods prior to distribution. The delivery and distribution of the supplies from the local distribution sites to the relief centers are termed as last-mile operations [2]. While there has been significant amount of research focusing on planning for disaster response, pre-positioning inventory at strategic locations, routing supplies to affected areas and relief centers in the region, the operations at the relief center itself has received limited attention.

At most disaster affected sites the relief centers are often temporary structures setup in open parking lots, school play grounds, in the immediate hours following a disaster. The nature and intensity of the disaster and the demographics of the affected area significantly impact the urgency with which aid must be distributed to victims at these relief centers. Relief centers often experience a sudden influx of victims requiring immediate attention and this creates a unique queuing phenomenon, since relief centers are often constrained in space (see Figure 2). In order to control these queues, volunteer organizations often adopt alternative layout configurations in an attempt to control victim movement, improve efficiency of distribution of relief and minimize waiting times and suffering of victims. This research investigates the fundamental tradeoffs related to congestion effects at relief centers and the impact of layout of the relief center on the efficiency of its operations.

Figure 2. Members of World Food Program distribute vitamin-enriched biscuits to Haitians while United Nations soldiers control the crowd in a tent city in Port-au-Prince, Haiti (Source: www.csmonitor.com)

Using knowledge from studies on pedestrian traffic flow, specialized state dependent queuing models are developed to model the flow of victims along the walkways setup at a relief center. These queuing models are analyzed to derive expressions for the average times that victims experience before they receive the service at the relief center. Using this as a key metric, relief center operations are analyzed. The analysis shows that crowd density effects lead to significant increase in congestion and queuing delays underscoring the important of developing specialized queuing models that capture these effects.

The rest of this paper is organized as follows. Section 2 reviews the literature from the last-mile operations in supply chains distributing aid and relief supplies. The queuing model of a relief center is analyzed in Section 3. The model consists of two key components, a queuing model of a walkway, and a queuing model of a pod distributing aid and relief supplies. These are described in Sections 3.1 and 3.2, respectively. Expressions for the residence times of victims at a relief center are derived in Section 3.3. Section 4 reports the results of numerical studies and Section 5 summarizes the main conclusions of this study.

2. Literature Review

Humanitarian relief efforts can be broadly divided into three phases: phase 1 - the preparation phase before disaster strikes, phase 2 - the immediate response phase after a disaster, and phase 3 - the reconstruction phase following a disaster. The following paragraphs summarize the recent literature in three categories, namely the pre-positioning

of inventory of relief items, design of evacuation systems, and the design of relief distribution systems.

Pre-positioning inventory of relief items: Most of the existing research in inventory management focuses on estimating optimal inventory levels required at various nodes along a supply chain, purchasing quantities and frequencies, and optimum of safety stock levels. Akkihal [1] determine the optimal warehouse location for inventories to support disaster relief by solving a p-median problem. Balcik and Beamon [2] determine the optimal location for distribution centers in a network with a known set of suppliers and determine strategies to minimize response times. Duran et al. [6] develop a mixed integer programming model to evaluate the effect of pre-positioning relief items on reducing response times.

Design of evacuation systems: The design of evacuation systems focuses on the flow of victims out of a disaster affected zone. Sheffi et al. [11] investigates the effect of spatial and temporal profiles of the loads on an evacuation network through a simulation based model and estimate their effect on total evacuation times. Smith [13] utilizes state-dependent queuing network models to design of emergency evacuation plans and model the nonlinear effects of increased occupant traffic flow along emergency evacuation routes.

Design of relief distribution systems: The design of relief distribution systems focuses on the flow of relief supplies into a disaster affected zone. Knott [9] analyzes the problem of delivering food items from a distribution center to relief camps at the disaster zone using a linear programming formulation that maximizes the amount of food delivered. Barbarosoglu et al. [3] formulate a two-stage stochastic program to analyze a multi-commodity, multi-modal network formulation that evaluates the impact of demand uncertainty and network reliability on the distribution of relief. Ozdamar et al. [10] investigates the logistics of dispatching commodities to warehouses near disaster affected areas. Horner [8] analyzes a variant of the capacitated warehouse location model to analyze the flow of goods from logistical staging areas to the victims via intermediate points of distribution.

Simpson and Hancock [12] and de la Torre et al. [5] provide a comprehensive review of additional mathematical models that address a variety of issues related to disaster relief operations. Despite the recent growth of research in this area, the challenges associated with the actual distribution of supplies at the temporary relief centers in a disaster affected region have received limited attention. This research focuses on this important issue and develops queuing network models to evaluate the joint impact of layout and victim flow on the efficiency of distribution of supplies at a relief center.

3. Queuing Analysis of a Relief Center

Figure 3(a) shows the layout of a typical relief center. Each relief center consists of multiple pods that distribute a variety of items to the victims. For illustrative purposes, it is assumed that the relief center has four distribution pods. Each distribution pod is staffed by a single volunteer who distributes one or all of four items (for instance: Water-1, Ice-2, MRE-3, and Tarp-4) to each victim at each pod. In the figure, z_{11}, z_{21}, z_{31}, and z_{41} denote the coordinates where victims enter the relief center, z_{14}, z_{24}, z_{34}, and z_{44} denote the coordinates where victims exit the relief center, and x_1, x_2, x_3, and x_4 denote the coordinates of the four distribution pods. Victims that arrive at the relief center are categorized into distinct classes based on the items requested. It is assumed that here are 2^4-1 i.e. 15 classes of victims and let **S** = {(1), (2), (3), (4), (1, 2), (3, 4), (1, 3), (1, 4), (2, 3), (2, 4), (1, 2, 3), (2, 3, 4), (3, 4, 1), (4, 1, 2), (1, 2, 3, 4)} denote the set of victim classes.

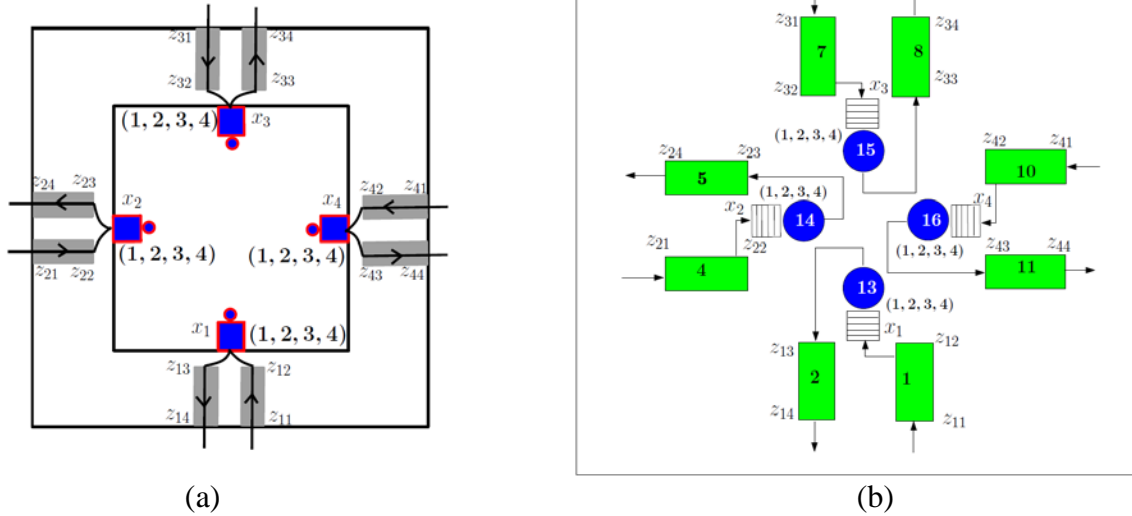(a)   (b)

Figure 3. Queuing Network Model of a Relief Center.

Victims approach a distribution pod in the relief center via one of the four entry walkways in the direction: $z_{11}z_{12}$, $z_{21}z_{22}$, $z_{31}z_{32}$, or $z_{41}z_{42}$ queue at the corresponding distribution pod (located at coordinates x_1, x_2, x_3, or x_4), receive their supplies, and leave the relief center using the corresponding exit walkway in the direction $z_{13}z_{14}$, $z_{23}z_{24}$, $z_{33}z_{34}$, or $z_{43}z_{44}$. Each walkway corresponds to a pathway separated by tape or rope to guide the flow of victims in and out of the relief center. Since all four items are

available at each distribution pod, each victim needs to visit only one pod to receive service.

The queuing delays at the relief center depend on several factors including (i) the number of items distributed at each pod, (ii) the routing of the victims in the layout, (iii) the dimensions (length and width) of the walkways, (iv) arrival rate of victims, and (v) service times at each distribution pod. These queuing delays are analyzed by separately modeling the congestions on the walkways (where movement of victims is less coordinated) and congestions in front of the distribution pods (where the movement of victims are more coordinated). The dimensions of the walkways determine their capacity (the number of victims per square unit area). At each walkway, the movement of the victims towards the distribution pod is less coordinated. Consequently, the arrival rate of victims and capacity of the walkways determine the crowd density at each walkway. These crowd densities in turn affect the travel time of the victims through the walkway; with the travel times increasing as the crowd density increases. This effect of crowd density on queuing delays experienced by victims on the walkway is captured by modeling each walkway as an *M/G/C/C* queue with state dependent service rates. The *M/G/C/C* queues representing the walkway between the two coordinates *a* and *b* (with a direction of travel from *a* to *b* being represented by *ab*). Closer to the distribution pod, the victim movement is more coordinated (typically through the use of ropes or barriers) and crowd density effects on queuing delays are negligible. Hence, the queuing effects closer to a distribution pod are modeled using an *M/M/1/K* queue.

Figure 3(b) shows the corresponding queuing network model of the relief center described in Figure 3(a). In the figure, the nodes 1, 4, 7 and 10 (2, 5, 8, and 11) correspond to the *M/G/C/C* queues that model the four walkways through which the victims enter (exit) the relief center. The nodes 13, 14, 15, and 16 denote the four *M/M/1/K* queues in front of the four distribution pods located at coordinates x_1, x_2, x_3, and x_4 respectively. The arrival process of victims is assumed to be Poisson with parameter, λ_o. An arriving victim is assumed to belong to any particular class with equal probability. Hence, the arrival process of each victim class is assumed to be Poisson with parameter $\lambda_o/15$. Under these assumptions, the queuing network shown in Figure 3(b) is analyzed to determine performance measures such as expected residence times of the victims (from entry to exit), utilization of the distribution pods, and the distribution of victims at different pods and walkways. The approach used to determine these performance measures is as follows. First, queuing models for individual walkways and distribution pods are developed. Subsequently, using routing information of each class of victims, expected residence times for each class of victim is obtained. The details are described in the next section.

3.1 Queuing Analysis of an Individual Walkway

Each walkway is modeled as an *M/G/C/C* queue with state-dependent travel times that have a general distribution. The main reason for modeling them as *M/G/C/C* queue with state-dependent travel times is because the congestion delay on the walkways is affected by the crowd density at the walkway. One would expect that, with the increase in the number of victims using the walkway, the effective walking velocity of the victim decreases. Consequently, the average total travel time on the walkway would increase with crowd density on the walkway. This phenomenon was captured in an empirical state-dependent curve derived in Tregenza [14] and is shown in Figure 4. In the figure, the y-axis denotes the speed of an individual pedestrian and the x- axis denotes the density of the number of pedestrians, so that the travel speed decreases with increasing crowd density. The curves corresponding to the letter *a* in Figure 4 represents an empirical study referenced by Tregenza [14].
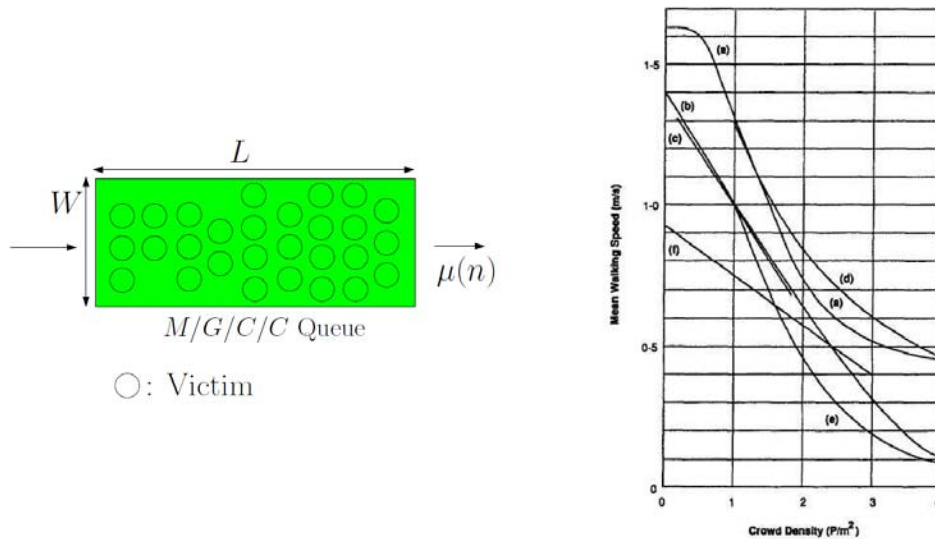

Figure 4. *M/G/C/C* model of the walkways (left) and empirical pedestrian speed-density curves, adapted from Cheah and Smith [4] (right)

Let *L* and *W* denoted the length and width of the walkway (expressed in meters) and *C* denote the capacity of the walkway. The *C* parallel servers of the *M/G/C/C* walkway model imply that *C* victims can travel on the walkway simultaneously. However, the travel times would vary depending on the number of victims present in the walkway. According to Tregenza [14], the pedestrian traveling speed *V(n)* decreases exponentially with the increase in the number of victims, *n* and the pedestrian traffic flow comes to a relative halt when the population density approaches five pedestrians per square meter (5 peds/m^2). Thus, the walkway capacity, $C = \lfloor 5LW \rfloor$. Let the average walking velocity, *A* = 1.5 m/s; L, the length of the walkway; *W*, the width of the walkway (1 m); V_a, the average walking speed (0.64 m/s) when number of people per sq m = 2; V_b,

the average walking speed (0.25 m/s) when number of people per sq m = 4; $a = 2LW$, and $b = 4LW$. Then, based on the analysis in Smith [13], the traveling speed $V(n)$ when there are n victims on the walkway is given by

$$V(n) = A\exp\left[-\left(\frac{n-1}{\beta}\right)^{\gamma}\right]$$ (1)

and the state-dependent service rate, $\mu(n)$ is given by expressed by

$$\mu(n) = \frac{nV(n)}{L}$$ (2)

where $\gamma = \dfrac{\ln\left(\dfrac{\ln(V_a/a)}{\ln(V_b/b)}\right)}{\ln\left(\dfrac{a-1}{b-1}\right)}$ and $\beta = \dfrac{a-1}{[\ln(a/V_a)]^{1/\gamma}}$.

Then, for each walkway i, the distribution of customers $P_i(n)$ on the walkway is provided by

$$P_i(n) = \frac{[\lambda_i E(S)]^n / n! f(n)...f(2)f(1)}{1 + \sum_{i=1}^{C}[\lambda_i E(S)]^i / i! f(i)...f(2)f(1)} \quad \text{for } i = 1, ..., 12$$ (3)

and the expected residence time of a victim on the walkway i, W_i, is given by:

$$W_i = \frac{\sum_{j=1}^{C} jP_i(j)}{\sum_{j=1}^{C} \mu(j)P_i(j)} .$$ (4)

where λ_i is the arrival rate of victims to walkway i, $E(S) = \mu_i(1)^{-1}$ is the average travel time on walkway i, and $f(n) = V(n)/V(1)$ denotes the service rate of each server in the $M/G/C/C$ queue. The queuing analysis of an individual distribution pod is discussed next.

3.2 Queuing Analysis of an Individual Distribution Pod

As mentioned earlier, the four distribution pods at x_1, x_2, x_3, and x_4, are denoted by nodes with indices i = 13, 14, 15, and 16. For simplicity of analysis, the internal traffic flows in the network are assumed to be Poisson processes. Consequently, the arrival process of victims of different classes to a distribution pod i is assumed to be Poisson with rate, λ_i. Further, each distribution pod is served by a single volunteer and the service time is assumed to have an exponential distribution with mean, μ^{-1}. The queue at each distribution pod has a finite capacity K. Based on these assumptions, the queuing dynamics at each pod is analyzed as an *M/M/1/K* queue. The queue length distribution and the expected waiting time at the *M/M/1/K* queue is given by Equations 5 and 6 respectively [7].

$$P_i(n) = \frac{(1-\rho_i)\rho_i^n}{1-\rho_i^N} \text{ for } n = 0, 1, ..., K ; i=13, 14, 15, 16.\tag{5}$$

$$W_i = \frac{1-\rho_i^K - K\rho_i^K(1-\rho_i)}{\mu_i(1-\rho_i)(1-\rho_i^K)} \text{ for } i=13, 14, 15, 16\tag{6}$$

where $\rho_i = \lambda_i / \mu_i$ denotes the utilization of pod i. Next, using the expressions for the mean residence times at each walkway and at each distribution pod, expressions for the mean residence time in the network are derived for each class of victims.

3.3 Analysis of Residence Times

As seen in Figure 3(b) victims enter the relief center through one of the nodes 1, 4, 7, or 10, wait at one of the nodes 13, 14, 15, or 16 to receive their supplies, and leave the relief center using the corresponding exit node 2, 5, 8, or 11. For each class of victim, the average residence time in the network equals the sum of (i) the average residence time in the walkway used to reach the distribution pod, (ii) the average residence time at the distribution pod (wait time and service time), and (iii) the average residence time in the walkway used exit the relief center. By symmetry in the layout shown in Figure 3(b), the total arrival rate of victims at each of the four pods is $\lambda_o / 4$. This also leads to the following equalities:

$$W_1 = W_4 = W_7 = W_{10}$$
$$W_2 = W_5 = W_8 = W_{11}$$
$$W_{13} = W_{14} = W_{15} = W_{16}$$

Therefore the residence time for any class of victim receiving items from node 13 (or by symmetry from nodes 14, 15, or 16) is given by:

$$\overline{RT} = W_1 + W_{13} + W_2$$

This completes the queuing network analysis of a relief center. As seen from the analysis above, the residence time of victims depend on the dimensions (length and width) of the walkways, arrival rate of victims, and service times at each distribution pod. The next section describes results from numerical experiments that illustrate the performance tradeoffs related to the layout of a relief center.

4. Numerical Experiments

This section describes the numerical experiments that investigate how the average residence times at a relief center depends on factors such as (i) the number of items distributed at each pod, (ii) the dimensions (length and width) of the walkways, (iii) the routing of the victims in different layouts, and (iv) the service times at each distribution pod. The parameters used in the numerical experiment are summarized in Table 1.

Table 1. Parameter Setting for Numerical Experiments

Parameter	Value
Walkway width, W	1 meter
Walkway length, L	10 meters, 30 meters
Traveling velocity of victims, v	1.5 meters/second
Size of finite buffer in front of pods, K	100
Rate of victims arriving at the relief center, λ_0	330 victims/hour
Service rate at each pod, μ	360 victims/hour

One of the key features of the queuing network model for the relief center, is the use of state dependent $M/G/C/C$ queue to model the effects of crowd density on walkway delays. The estimates of average residence times obtained from this queuing network are compared the average residence time estimates obtained from analysis of a queuing network where the walkways are modeled as state independent $M/G/C/C$ queues. Further, the experiment also considers two scenarios of service times at each pod. In the first scenario, when $\alpha = 1$, the service times at a pod are independent of the number of items being requested at the pod. In the second scenario, the service times at a pod decreases with the increase in the number of items requested. In particular, the service times are $\alpha^2 \mu$ when four items are requested by a victim at a pod.

Table 2. Effect of Crowd Density on Mean Residence Times

Walkway Length (m)	Service Time Factor	Walkway Travel Time Dependent on Crowd Density (mins)	Walkway Travel Time Independent of Crowd Density (mins)	Utilization
L	α	$\overline{RT}$	$\overline{RT}$	$\rho_{13,1}$
10	0.50	9.97	8.21	0.92
30	0.50	14.33	8.66	0.92
10	1.00	2.19	0.44	0.23
30	1.00	6.55	0.88	0.23

Table 2 reports results for two values of L, $L = 10$, 30 and two values of α, $\alpha = 1.0$, 0.5. The results indicate that increasing crowd density leads to significant increases in the expected residence time in the network. Further, as the length of the walkways increase, the average residence time increases significantly. The results also indicate that when the service rate at a pod decreases with the number of items, average residence times and pod utilizations increase considerably. These results indicate the important impact of both crowd density and walkway lengths on residence times at a relief center.

5. Conclusions and Extensions

This research investigates the effect of layout of a relief center on the expected residence times experienced by victims that queue to receive aid at these relief centers. These queuing delays are modeled in detail by using developing a multi-class closed queuing network model of a relief center. The network is composed of state dependent *M/G/C/C* queues that capture the impact of crowd density on residence times at the walkways. Closer to the distribution pod, where the victim movement is more coordinated, the queuing effects are modeled using an *M/M/1/K* queue. Numerical studies suggest that both layout and crowd density effects can be significant, thereby underscoring the important of queuing network models that capture these effects explicitly. The insights obtained from this research can be useful to practitioners involved in the setup and operations of relief centers.

Acknowledgements

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