Chapter 2
Analytical Models for Estimating Waiting Times at a Disaster Relief Center

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2.1 Background and Introduction

Every year disasters across the world kill around 75,000 people and affect over 200 million people (Van Wassenhove 2005). Disaster logistics play a significant role in minimizing the losses following these events. Broadly speaking, these 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 (Kovács and Spens 2007). 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.

Figure 2.1 describes the flow of supplies in supply chain distributing aid and relief supplies following a disaster. Very often, supplies are received at a primary hub (seaports, airports) and stocked at a central warehouse. From this location, supplies are distributed to small local warehouse locations, which are situated closer

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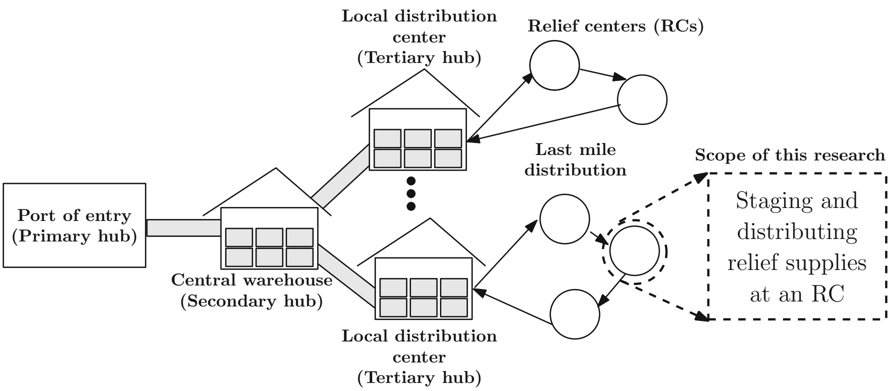


Fig. 2.1 Flow of supplies in the relief supply chain and focus of this research. (Modified from Balcik and Beamon 2008)

to the disaster sites. From the local warehouses, supplies are loaded into trailers and transported to disaster relief centers (RCs) 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 disaster relief centers are termed as last-mile operations (Balcik and Beamon 2008). In recent years, 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. This research complements this existing body of work by focusing on the operations at the relief center itself.

At most disaster affected sites, relief centers are often temporary structures setup in open parking lots, school play grounds, in the immediate hours following the a disaster. The nature and intensity of the disaster and the demographics of the affected area significantly impact the amount and urgency with which aid must be distributed to the victims at these disaster relief centers. Efficient operation of RCs at the disaster area can play an important role in saving lives and minimizing public loss (Holguin-Veras et al. 2007). Recent studies that investigate what went wrong after disasters such as Katrina reveal that "... in addition to having inadequate facilities for storing donations... there was no clear plan for the distribution of donations. Some evacuees were sent from place to place in search of assistance.... Agencies improvised and set up tents to distribute items such as clothing, medical kits, cleaning supplies, and diapers". Although relief agencies such as Red Cross, Salvation Army and others have established procedures that need to be followed in distributing aid and relief, the main challenge is that each disaster presents its unique needs and "... volunteers on the field need to quickly adapt to unknown situations assess the important needs ... and set up operations to allow rapid distribution of relief in a timely manner..." (Jody Glynn Patrick, The Salvation Army).

Most RCs often experience a sudden influx of victims requiring immediate attention and this creates a unique queuing phenomena, since RCs are often constrained

Fig. 2.2 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. (www.csmonitor.com)

in space (see Fig. 2.2). In order to control these queues, volunteer organizations involved in these efforts setup these RCs to control victim movement, yield high efficiency of distribution operations and minimize waiting of victims. This research develops analytical models to quantify these congestion effects at relief centers and the assess the impact of its layout on the efficiency of operations. 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 then used as a building block in a larger multi-class open queuing network model of a relief center that distributes multiple items to victims. The queuing network configuration changes based on the layout of the relief center, the items distributes at each pod, and the needs of the different types of the victims. These queuing network models are analyzed to derive expressions for the average times that victims might experience before they receive the service at the relief center. Using this as a key metric, relief center operations are studied. The studies show that crowd density effects lead to significant increase in congestion and queuing delays underscoring the importance of developing specialized queuing models that capture these effects. The studies also show that by choosing appropriate layouts of the relief center, queuing delays can be reduced significantly. The layout and corresponding flow of victims also seem to have a significant impact on the utilization levels of the staff supporting the center, which has a direct influence on the staffing needs at these centers. We believe that these insights could form the basis for establishing guidelines and best practices that volunteer agencies could follow while setting up relief centers.

The rest of this chapter is organized as follows. Section 2.2 reviews the relevant literature. The queuing model of a relief center is analyzed in Sect. 2.3. 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 Sect. 2.3.1 and 2.3.2, respectively. Expressions for the waiting times of victims at a relief center are derived in Sect. 2.3.3. Alternative layout configurations for relief centers are analyzed in Sect. 2.4, and the corresponding queuing network models analyzed to determine expressions for average waiting time of victims in these settings in Sect. 2.4.1 and 2.4.2. Section 2.5 reports the results of numerical studies conducted to evaluate the various design and performance tradeoffs at relief centers. Section 2.6 summarizes the main conclusions of this study.

2.2 Literature Review

This research lies at the intersection of two main areas, namely disaster logistics and facility design. Consequently, the review of literature is structured to present the relevance of the work in relation to these different areas.

Disaster logistics We briefly review the literature addressing issues in the three phases of disaster logistics operations, namely, 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 purpose of reviewing work related to disaster logistics is to illustrate the breadth of issues and highlight the larger context in which operations of a relief center need to be considered. The reader can refer to Larson et al. (2006), Simpson and Hancock (2009), Altaya and Green (2006), and de la Torre et al. (2011) for a comprehensive review of issues and mathematical models related to humanitarian and disaster logistics operations.

A key aspect in planning for disasters is ensuring that inventory of critical relief supplies are pre-positioned in adequate quantities at strategic locations. Prior research in this area focuses on estimating optimal inventory levels required at various nodes along a supply chain, purchasing quantities and frequencies, and optimum of safety stock levels. Beamon and Kotleba (2006) develop a stochastic inventory control model to determine optimal order quantities and reorder points for a long-term emergency relief response. In a subsequent work, they compare the optimal solution of the previous model with a heuristic based inventory model. Akkihal (2006) determine the optimal warehouse location for inventories to support disaster relief by solving a p-median problem. Balcik and Beamon (2008) 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. (2011) develop a mixed integer programming model to evaluate the effect of pre-positioning relief items on reducing response times.

Two key issues in the immediate response phase correspond to (i) the design of relief distribution systems focuses on the flow of relief supplies into a disaster affected zone, and (ii) the design of evacuation systems. Knott (1987) 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. Haghani and Oh (1996) analyze a variation of this problem as a multiple commodity network flow problem with time windows and develop strategies that minimize loss of life. Barbarosoglu et al. (2002) and Barbarosoglu and Arda (2004) 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. Özdamar et al. (2004) investigates the logistics of dispatching commodities to warehouses near disaster affected areas. Tzeng et al. (2007) use multi-objective programming methods to design delivery systems for relief supplies. The model is evaluated on three objectives: minimizing the total cost, minimizing the total travel time, and maximizing the minimal satisfaction during the planning period. Balcik et al. (2008) propose a mixed integer programming model that determines the delivery schedules for vehicles that would equitably allocate resources so as to minimize transportation costs and maximize benefits to aid recipients. Lin et al. (2011) propose a multi-item, multi-vehicle, multi-period logistics model for delivery of prioritized items in disaster relief operations that incorporates time windows and a split delivery strategies. Horner and Downs (2010) analyze 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.

The design of evacuation systems focuses on the flow of victims out of a disaster affected zone. Sheffi et al. (1982) investigate 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. Kimms and Maassen (2011) develop a heuristic using a combination of simulation and optimization for optimal routing the traffic flows during a disaster relief operation. Cova and Johnson (2003) analyze a network flow model to identify the optimal lane-based evacuation routing plans in a complex road network and Fanga et al. (2011) develop heuristic algorithms for evacuation networks. Smith (1991) utilizes state-dependent queueing network models to design of emergency evacuation plans and model the nonlinear effects of increased occupant traffic flow along emergency evacuation routes. At a facility level, Smith and Towsley (1981) derive queuing models to model the egress of victims from a building affected by a disaster. A common aspect to relief center operations and the evacuation models existing in the literature is the crowd management challenges created by the sudden influx of victims. Our analysis of the layout and operations of a relief center draws upon the knowledge related to the design of evacuation systems and queuing models for evacuation networks to build realistic models that capture the crowd effects due to influx of victims at a relief center.

Facility Design This research also bears close relevance to facility design issues related to traditional distribution center (DC), that has been and continues to be the focus of several research studies. Although both the traditional DC and the RC at a disaster site are essentially setup to distribute goods and services, RC operations are considerably different and in some ways more complex compared to operations in a traditional DC. For example: multiple criteria (costs, tax incentives, labor, and infrastructure) are considered while determining the location and layout of a DC; however, the nature of the disaster affected region constrains the choice on the available locations for an RC. Moreover, there is very little time to conduct analysis on the optimal choice of location for an RC. In most cases, RCs must be setup and operational within hours of the disaster. Further, in traditional DCs, automation technologies (conveyors, cranes) can be implemented to increase throughput and reduce transaction cycle times. However, automation is often not feasible in an RC. Almost all activities in RC are manual. Also, generally well established infrastructure and information systems are available in DCs whereas in RCs, they are often unreliable, incomplete or non-existent; many RCs operate on temporary or limited power. Finally, the primary performance metric in traditional DCs is reducing operating costs and maximizing profitability whereas the performance metric in RCs is to deliver relief supplies to as many as possible, minimize loss of life, and alleviate suffering. These differences make the facility design of an RC an interesting research problem of immense practical relevance.

Through our research we intend to capture some of these unique characteristics of an RC and develop performance evaluation models that could be used to compare alternative layouts of RC. In that sense, we do build on the existing principles of facility design. This work also builds on the principles of design of evacuation systems and the queuing model constructs used to analyze relief centers builds upon the knowledge used to model crowd effects in evacuation systems. By bridging the theory in the areas of disaster logistics and facility design, we provide insights that not only improve our understanding of the research issues related to the design and operations of relief centers, but also provide guidelines that would influence practice. Sections 2.3, 2.4, and 2.5 provide details of the analysis.

2.3 Queuing Analysis of a Relief Center

Immediately following a disaster, relief agencies survey the affected area, assess potential sites for a disaster relief center and set them up as temporary structures in an a safe area such as an open parking lot or school yard. Figure 2.3a shows a layout used for disaster relief center commonly used by relief agencies and Fig. 2.3b shows the corresponding queuing model. In this section, we first develop the queuing model for performance evaluation of relief centers using this example layout. Subsequently, in Sect. 2.4, the queuing analysis is extended to analyze the performance of two alternative layouts.

Referring to Fig. 2.3a, note that the 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.

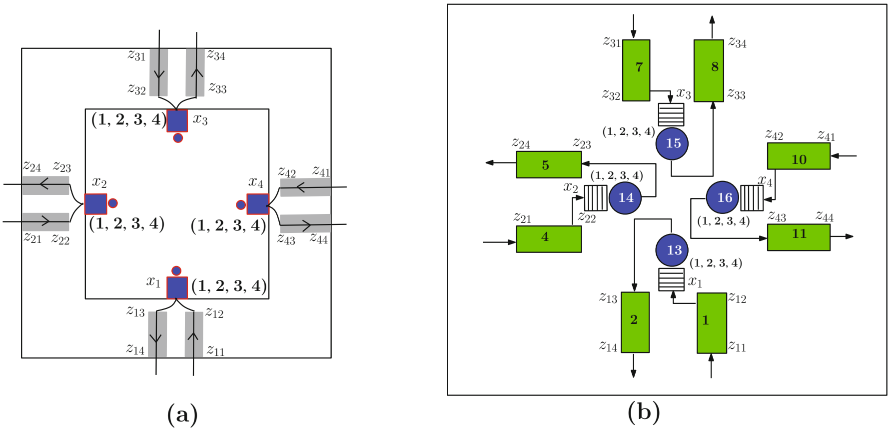


Fig. 2.3 Queuing network model of a relief center

Victims approach a distribution pod in the relief center via one of the four entry walkways in the direction: $\overrightarrow{z_{11}z_{12}}$, $\overrightarrow{z_{21}z_{22}}$, $\overrightarrow{z_{31}z_{32}}$, or $\overrightarrow{z_{41}z_{42}}$, 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 $\overrightarrow{z_{13}z_{14}}$, $\overrightarrow{z_{23}z_{24}}$, $\overrightarrow{z_{33}z_{34}}$, or $\overrightarrow{z_{43}z_{44}}$. Each walkway corresponds to a segmented area in the open parking lot or school yard that guides the flow of victims in and out of the relief center. Since all four items are available at each distribution pod, a victim needs to visit only one pod to receive service. While this could have advantages, the queues in the walkways and at each distribution pod could be potentially longer because victims with different requirements share a common queue to receive service. Alternative layouts that explore these tradeoffs are examined discussed further in Sect. 2.4.

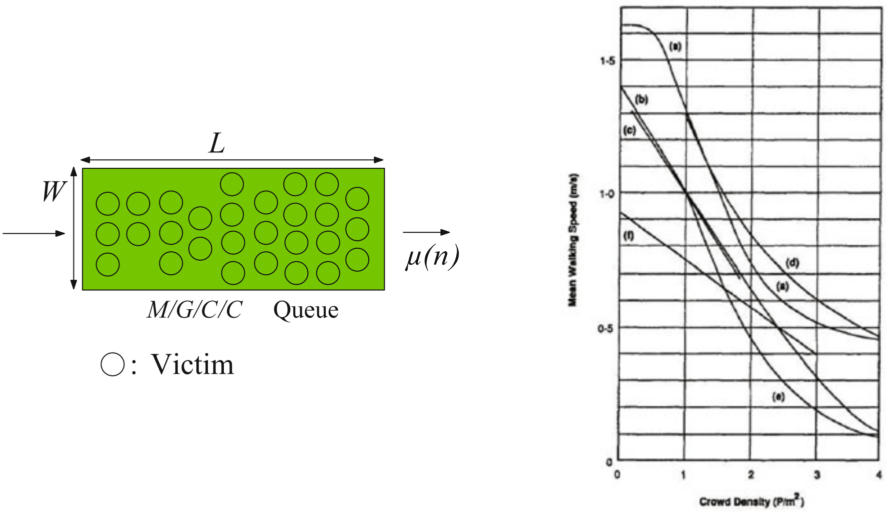
The queuing delays at the relief center depend on several factors including (i) the number of items distributed at each pod, (ii) the routing of the victims in the layout, (iii) the dimensions (length and width) of the walkways, (iv) arrival rate of victims, and (v) service times at each distribution 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 determines its 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 $\overrightarrow{ab}$) is denoted 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.

In Fig. 2.3b, 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, or 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_0. 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 $\frac{\lambda_0}{15}$. Under these assumptions, the queuing network shown in Fig. 2.3b is analyzed to determine performance measures such as expected waiting 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. The details are described in Sect. 2.3.1 and 2.3.2 respectively. Subsequently, using routing information of each class of victims, expected waiting times for each class of victim is obtained. The details are described in Sect. 2.3.3. Finally, based on the performance measures, the efficiency of this layout as well as the quality of service received by the victims at this relief center are investigated through numerical experiments in Sect. 2.5.

2.3.1 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 delays 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 victims 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, 1976 and is shown in Fig. 2.4. 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 Fig. 2.4 represents an empirical study referenced by Tregenza (1976).

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 $M/G/C/C$ model of the walkway denotes 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 (1976), the pedestrian traveling speed $V(n)$ decreases exponentially with the increase in the number of victims, n and



Pedestrian traffic flows vs. crowd density

Fig. 2.4 *M/G/C/C* model of the walkways (*left*) and empirical pedestrian speed-density curves (*right*). (Adapted from Smith (2010))

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 Cheah and Smith (1994) and Smith (1994), the traveling speed $V(n)$ when there are n victims on the walkway is given by

$$V(n) = Aexp\left[-\left(\frac{n-1}{\beta}\right)^{\gamma}\right] \tag{2.1}$$

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

$$\mu(n) = \frac{nV(n)}{L} \tag{2.2}$$

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

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

$$P_i(n) = \frac{[\lambda_i E(S)]^n / n! f(n) \ldots f(2) f(1)}{1 + \sum_{i=1}^{C} [\lambda_i E(S)]^i / i! f(i) \ldots f(2) f(1)} \quad \text{for} \quad i = 1, \ldots, 12 \tag{2.3}$$

and the expected waiting time of a victim on the walkway (W_i) is given by

$$W_i = \frac{\sum_{n=1}^{C} n P_i(n)}{\sum_{n=1}^{C} P_i(n)\mu_i(n)} \quad \text{for} \quad i = 1, \ldots, 12 \tag{2.4}$$

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

The $M/G/C/C$ queuing model for congested walkways has been used to model the critical impact of crowd density effect in a variety of settings. Smith and Towsley (1981) use $M/G/C/C$ in closed queuing network models for evacuation from high-rise buildings, while Smith (1994) use state dependent $M/G/C/C$ queues to model traffic congestion in highway networks. In that work, the state dependent $M/G/C/C$ queues model the reduced speeds in highways during rush hour traffic. State dependent $M/G/C/C$ queues have also been used to model variable conveyor speeds in material handling systems by Smith (2010). In their model, conveyor speeds decrease as the load (often bulk material such as coal, ore) on the conveyor increases. Therefore, we believe that state dependent $M/G/C/C$ queues form an appropriate building block to model pedestrian congestion and crowd density affects at disaster relief centers.

2.3.2 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 $i = 13, 14, 15, 16$. 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 these distribution pods are 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_i^{-1}. Note that μ_i^{-1} is assumed to be independent of the number of items requested by the victim (This assumption is relaxed in a later section). 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 Eq. 2.5 and 2.6 respectively (Gross et al. 2008).

$$P_i(n) = \frac{(1-\rho_i)\rho_i^n}{1-\rho^{N+1}} \quad \text{for} \quad n = 0,1,\ldots,K;\ i = 13, 14, 15, 16 \tag{2.5}$$

$$W_i = \frac{1-\rho_i^K - K\rho_i^K(1-\rho_i)}{\mu_i(1-\rho_i)(1-\rho_i^K)} \quad \text{for} \quad i = 13, 14, 15, 16 \tag{2.6}$$

where $\rho_i \left(= \frac{\lambda_i}{\mu_i}\right)$ denotes the utilization of pod i. Using the expressions for the mean waiting times at each walkway and at each distribution pod, in the next section, Springer

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