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A Temporo-Spatial Stochastic Model for Optimal Positioning of Humanitarian Inventories for Disaster Relief Management

V. S. S. Yadavalli[1,*], *E. van Wyk*[1] *and S. Udayabaskaran*[2]

[1] Department of Industrial and System Engineering, University of Pretoria, Pretoria 0002, South Africa
[2] Department of Mathematics, Vel Tech Dr RR & Dr SR Technical University, Chennai 600 062, India

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Abstract: A temporo-spatial stochastic model is formulated for analysing the problem of positioning of humanitarian relief centres for optimum disaster-relief management. Disasters occur in a line segment region of the real line according to a Poisson process. Two relief centres are positioned at two different points of the line segment for providing humanitarian relief to the disaster sites. The stationary mean rate of relief rendered by the two inventories is obtained. By optimizing the mean rate, the optimum positions of the two relief centres are obtained.

Keywords: Humanitarian Inventory, Disaster relief, Temporo-spatial model, Stationary mean rate of relief, Optimal positioning

1 Introduction

Considerable literature has addressed the operational management of disaster relief organizations. The review of White et al. [1] provides the importance of Operations Research techniques in analysing some crucial problems such as disaster management in developing countries. Much of this deals with the social and organizational implications of responding to disasters in many parts of the world, including countries with poor infrastructure that may be involved in hostilities. Researchers had paid their attention towards the study of optimal management of sociological problems such as reduction of roadway congestion, effective utilization of ambulance service for medical relief, optimal positioning of humanitarian inventories for disaster management and so on. Toregas et al. [2] have solved a covering problem related to the location of emergency relief facilities viewed as the potential facility points within a specified time or distance of each demand point. White and Case [3] have solved a covering problem in which the objective is to locate p service facilities that could cover the maximum number of demand areas. Larson and Odoni [4] have published their treatise on urban operations research including logistical and transportation planning methods. Berman et al. [5] have considered a network location with mobile and congested facilities and analysed four facility location problems which are motivated by urban service applications. Zografos et al. [6] have formulated an analytical framework for the minimization of freeway incident delays through the optimum deployment of traffic flow restoration units. Their framework determines the number of required traffic flow restoration units and their service territories. Durett and Levin [7] have developed stochastic spatial models in order to provide a users guide to ecological applications. Shiode and Drezner [8] have analysed a competitive facility location problem on a tree network with stochastic weights. Bryson et al. [9] have developed a Disaster Recovery Plan (DRP) model for organizational preparedness. The mathematical model maximizes the total value of coverage when a disaster occurs. The authors motivate that the research is a forward step in providing MS/OR literature for disaster relief. Brotcorne et al. [10] have investigated the problem of identifying appropriate locations and positions of disaster relief measures. Barbarosoglu and Arda [11] have developed a two-stage stochastic programming model to plan the transportation of vital first-aid supplies to disaster-affected areas. The

* Corresponding author e-mail: sarma.yadavalli@up.ac.za

authors reveal the value of information when uncertainty exists by using a multi-commodity, multi-modal network flow formulation for flow of material. Ozdamar et al. [12] have analysed emergency logistics planning in natural disasters where it originates from military logistics and covers the distribution of emergency supplies to the affected areas immediately after the disaster to meet immediate needs and to ease the local tensions. Sherali et al. [13] have provided optimized schedules for allocating emergency response resources to minimize risk under equity considerations. Akella et al. [14] have analysed a problem related to base station location and channel allocation in a cellular network with emergency coverage requirements. Altay and Green [15] have provided a literature survey to identify potential research directions in disaster operations. The survey includes literature from 1984 to 2004 and is categorised according to mitigation, preparedness, response and recovery. The authors encourage this survey as a starting point for further research using OR methods for disaster management. Yin [16] have proposed a min-max bi-level programming model and investigated how to allocate tow trucks among patrol beats to maximize the effectiveness of the freeway service patrols services. Chang et al. [17] have studied the problem of locating and distributing relief supplies to victims of disasters and obtain some optimal decisions for effective relief operations. The problem of locating the emergency inventories has also been studied by Jia et al. [18]. Sheu [19] has presented a hybrid fuzzy clustering-optimization approach to the operation of emergency logistics co-distribution responding to the urgent relief demands in the crucial rescue period. Using a risk-based urban structural analysis, Yi and Ozdamar [20] have formulated and analysed an integrated location-distribution model for coordinating logistics support and evacuation operations in disaster response activities. The model provides fast relief access to affected areas and establishes the location of temporary emergency units in appropriate sites. Taking into account the fact that fluctuating demands occur at the disaster sites, Rajagopal et al. [21] have studied the problem of locating the minimum amount of relief measures to be kept at the humanitarian inventories. Iannoni et al. [22] have analyzed Emergency Medical Systems on highways by proposing a hypercube queueing model embedded into a genetic algorithm. Pal and Bose [23] have devised an optimization based approach to find the best locations of incidence response depots and assign response vehicles to these depots so that roadway incidents can be cleared efficiently at a minimum cost. Lodree and Taskin [24] have addressed a stochastic inventory control problem by using an optimal stopping problem with Bayesian updates. The model however only considers two demand classes per hurricane disaster. White et al. [1] have conducted a review of the overall picture of OR in developing countries which initiates further contribution towards poverty in developing countries. More recent literature on OR in disaster relief has been addressed the development of equations for determining optimal stocking quantities [25]. The equations are utilised to derive total costs when delivering to a demand point from a supply point. Some contributions relating to Optimal positioning of humanitarian inventories for disaster Relief Management are summarized in Table 1. Most of the relief processes involve uncertainties related to time of occurrence, type, location, and quantity of demands. Accordingly, it is considered worthwhile to consider marked stochastic point processes (see [26]) as models in analysing the problem of locating humanitarian inventories for disaster relief management.

Table 1: State-of-art.

Authors	Year	Contributions
Toregas et al.	1971	Solved a covering problem related to the location of emergency relief facilities.
White and Case	1974	Solved a covering problem in which the objective is to locate p service facilities that could cover the maximum number of demand areas.
Berman et al.	1981	Considered a network location with mobile and congested facilities and analysed four facility location problems which are motivated by urban service applications.
Brotcorne et al.	2003	Investigated the problem of identifying appropriate locations and positions of disaster relief measures.
Sherali et al.	2004	Provided optimized schedules for allocating emergency response resources to minimize risk under equity considerations.
Yi and Ozdamar	2006	Analysed an integrated location-distribution model for coordinating logistics support and evacuation operations in disaster response activities.
Chang et al.	2007	Studied the problem of locating and distributing relief supplies to victims of disasters.
Rajagopal et al.	2008	Studied the problem of locating the minimum amount of relief measures to be kept at humanitarian inventories.
Pal and Bose	2009	Devised an optimization based approach to find the best locations of incidence response depots and assign response vehicles to these depots so that roadway incidents can be cleared efficiently at a minimum cost.

The plan of the paper is as follows: In Section 2, we propose a very general temporo-spatial model for the optimum positioning of humanitarian inventories for the relief management of disasters. Section 3 analyses in detail a simple one dimensional spatial model in which the disasters occur randomly as a stochastic point process in the segment $[0,L]$ of the real line. The assumption is also made that the disasters are independent of each other. A conclusion is given in section 5.

2 A 2-dimensional Temporo-spatial model for disaster relief

Following [4], we consider a rectangular geographical region D where disasters occur according to a Poisson process in time at a rate of λ per unit of time. We choose the Cartesian frame ($x-$axis and $y-$axis) coinciding with two adjacent sides of D to represent analytically the points of the region D. Let there be two humanitarian inventories $HI1$ and $HI2$ positioned at the points (l_{11},l_{12}) and (l_{21},l_{22}) respectively in D. In [4], they have chosen a single facility situated at the point of intersection of the diagonals of D. For simplicity, we assume that the two inventories are positioned on the main diagonal of D passing through the origin such that

$$l_{11}{}^2+l_{12}{}^2<l_{21}{}^2+l_{22}{}^2.$$

These inventories are intended to provide relief instantaneously at the disaster site. Due to logistic problems, the intended relief may or may not be realized at the disaster site. We now proceed to quantify the total relief rendered by the two inventories for all the disasters which have occurred up to time t. Based upon the quantity, we shall obtain the optimal positions of the humanitarian inventories in D. To achieve this, we define the following: Given that a disaster occurs in D, it occurs in the infinitesimal rectangle $(x,x+dx)\times(y,y+dy)$ in D with probability $f(x,y)dxdy$. Evidently, $\lambda f(x,y)dxdydt$ is the probability that a disaster occurs in the location $(x,x+dx)\times(y,y+dy)$ and in the time interval $(t,t+dt)$. We define that the probability that the relief from the site $(l_{i1},l_{i2}), i=1,2$ is realized at the spot (x,y) of the disaster is given by

$$e^{-\alpha(|x-l_{i1}|+|y-l_{i2}|)}, i=1,2. \tag{1}$$

If a disaster occurs at the spot (x,y) in D and if the relief from the $i-$th inventory is realized at the disaster site, then it is assumed that $h(|l_{i1}-x|+|l_{i2}-y|)$ is the amount of relief realized at (x,y). Then the amount of relief rendered by the two inventories up to time t is given by

$$R\ (l_{11},l_{12},l_{21},l_{22},t)=$$
$$\lambda\sum_{i=1}^{2}\int_0^t\int_D f(x,y)h(|l_{i1}-x|+|l_{i2}-y|)e^{-\alpha(|x-l_{i1}|+|y-l_{i2}|)}dxdydt. \tag{2}$$

Using the optimization procedure, we can obtain the optimal values of $l_{11},l_{12},l_{21},l_{22}$ such that $R(l_{11},l_{12},l_{21},l_{22},t)$ takes the maximum value. Further the relief operation initiated from an inventory to reach the disaster site takes a random time and it encounters with a random of interruptions on its way to the disaster site. The affects of interruptions on the service time distribution have been studied by several researchers (see, for example, [27, 28, 29]). Gendreau et al. [30] have provided the scientific literature on stochastic vehicle routing problems. Using the theory of stochastic point processes, we attempt to obtain the expected time taken by a vehicle from the start to the finish in a stochastic vehicle routing problem. Suppose that $\tilde{T}$ represents the total duration occupied by a relief operation from the start to the finish including the interruption times. Let T be the time taken by the relief operation from the start to the finish without interruptions. Suppose that $\phi(\theta)$ be the Laplace transform of the probability density function $b(y)$ of T. Let I denote the number of interruptions during the relief operation from the start to the finish. Gaver [31] has observed that I depends only on T. We assume that the interruptions arrive according to a Poisson process with rate γ. We also assume that the interruption times are independent and identically distributed random variables $\eta_1,\eta_2,\cdots$ having the probability density function $t(y)$. Then, by using the theory of stochastic point processes, we get as in [28, 29],

$$\begin{aligned} E\left[e^{-\xi\tilde{T}}\right] &= \int_0^\infty b(u)e^{-[\gamma\{1-\beta(\xi)\}+\xi]u}du \\ &= \phi(\gamma\{1-\beta(\xi)\}+\xi), \end{aligned} \tag{3}$$

where

$$\beta(\xi)=E\left[e^{-\xi\eta_j}\right]=\int_0^\infty e^{-\xi y}t(y)dy.$$

Differentiating the equation (3) with respect to ξ and then setting $\xi=0$, we get the expected time for the relief measure to reach the destination from the inventory as given by

$$E[\tilde{T}]=E[T][1+\gamma E(\eta_j)]. \tag{4}$$

In the next section, we consider the one-dimensional version of the above general model and obtain the optimal positions of $HI1$ and $HI2$.

3 Analysis of a 1-dimensional Temporo-spatial model for disaster relief

Let $N(t)$ be the total number of disasters that have occurred up to the time t in the region $[0,L]$. We assume that the disasters occur according to a Poisson process with rate λ and the disasters are independent of the locations in the interval $[0,L]$. Further, we assume that, if a disaster occurs, then the probability that the disaster occurs in the region $(x,x+dx)$ is $f(x)dx$. Evidently, $\lambda f(x)dxdt$ is the probability that a disaster occurs in the location $(x,x+dx)$ and in the time interval $(t,t+dt)$. Let there be two humanitarian inventories situated in the region $[0,L]$. Let l_1 and l_2 be the locations of the inventories in the interval$[0,L]$. For avoiding ambiguity, we assume that $0 \leq l_1 < l_2 \leq L$. Let the probability that the relief from the site l_i is not realized at the spot x of the disaster be given by

$$1 - e^{-\alpha|x-l_i|}, i = 1,2. \tag{5}$$

If a disaster occurs at the spot x and if the relief from the $i-$th inventory is realized at the disaster site, then it is assumed that $h(|l_i - x|)$ is the amount of relief realized at x. Then the amount of relief rendered by the two inventories up to time t is given by

$$R(l_1,l_2,t) = \lambda \sum_{i=1}^{2} \int_0^t \int_0^L f(x)h(|x-l_i|)e^{-\alpha|x-l_i|}dxdt. \tag{6}$$

The density function $f(x)$ can be chosen suitably. For simplicity, we choose

$$f(x) = \frac{6x(L-x)}{L^3}. \tag{7}$$

The function $h(|x-l_i|)$ is chosen as follows:

$$h(|x-l_i|) = \cos\frac{\pi|x-l_i|}{2L}. \tag{8}$$

The above assumptions are justifiable from the fact that the relief distributions at the very beginning can be skewed and high. We have taken that the amount of relief will be more very close to the point of inventory location and less very far away from the point of inventory location. Then we obtain

$$R\ (l_1,l_2,t) = \lambda \sum_{i=1}^{2} \int_0^t \int_0^L \frac{6x(L-x)}{L^3} \cos\frac{\pi|x-l_i|}{2L} e^{-\alpha|x-l_i|}dxdt. \tag{9}$$

From the equation (9), we get

$$R(l_1,l_2,t) = \frac{6\lambda t}{L^3} \sum_{i=1}^{2} \int_0^L x(L-x)\cos\frac{\pi|x-l_i|}{2L} e^{-\alpha|x-l_i|}dx. \tag{10}$$

The mean-rate of relief provided by the two inventories is given by

$$\begin{aligned} R(l_1,l_2) &= \lim_{t\to\infty} \frac{R(l_1,l_2,t)}{t} \\ &= \frac{6\lambda}{L^3} \sum_{i=1}^{2} \int_0^L x(L-x)\cos\frac{\pi|x-l_i|}{2L} e^{-\alpha|x-l_i|}dx \end{aligned} \tag{11}$$

Using the formula

$$\begin{aligned} &\int (px^2+qx+r)e^{ax}\cos bx dx \\ &= e^{ax}\Bigg[(px^2+qx+r)\left(\frac{a\cos bx + b\sin bx}{a^2+b^2}\right) \\ &- (2px+q)\left(\frac{(a^2-b^2)\cos bx + 2ab\sin bx}{(a^2+b^2)^2}\right) \\ &+\ 2p\left(\frac{(a^3-3ab^2)\cos bx + (3a^2b-b^3)\sin bx}{(a^2+b^2)^3}\right)\Bigg], \end{aligned} \tag{12}$$

the equation (11) gives

$$\begin{aligned} &R\ (l_1,l_2) = \\ &\frac{6\lambda}{L^3}\sum_{i=1}^{2}\Bigg[\frac{2(L-l_i)l_i\alpha}{\alpha^2+\frac{\pi^2}{4L^2}} - \frac{4\left(\alpha^3-\frac{3\alpha\pi^2}{4L^2}\right)}{\left(\alpha^2+\frac{\pi^2}{4L^2}\right)^3} \\ &+ \frac{Le^{-\alpha l_i}}{\left(\alpha^2+\frac{\pi^2}{4L^2}\right)^2}\left\{\left(\alpha^2-\frac{\pi^2}{4L^2}\right)\cos\frac{\pi l_i}{2L} - \frac{\alpha\pi}{L}\sin\frac{\pi l_i}{2L}\right\} \\ &+ \frac{2e^{-\alpha l_i}}{\left(\alpha^2+\frac{\pi^2}{4L^2}\right)^3}\left\{\left(\alpha^3-\frac{3\alpha\pi^2}{4L^2}\right)\cos\frac{\pi l_i}{2L} - \left(\frac{3\alpha^2\pi}{2L}-\frac{\pi^3}{8L^3}\right)\sin\frac{\pi l_i}{2L}\right\} \\ &+ \frac{Le^{-\alpha(L-l_i)}}{\left(\alpha^2+\frac{\pi^2}{4L^2}\right)^2}\left\{\left(\alpha^2-\frac{\pi^2}{4L^2}\right)\sin\frac{\pi l_i}{2L} - \frac{\alpha\pi}{L}\cos\frac{\pi l_i}{2L}\right\} \\ &+ \frac{2e^{-\alpha(L-l_i)}}{\left(\alpha^2+\frac{\pi^2}{4L^2}\right)^3}\left\{\left(\alpha^3-\frac{3\alpha\pi^2}{4L^2}\right)\sin\frac{\pi l_i}{2L} - \left(\frac{3\alpha^2\pi}{2L}-\frac{\pi^3}{8L^3}\right)\cos\frac{\pi l_i}{2L}\right\}\Bigg]. \end{aligned} \tag{13}$$

For obtaining the optimal positions of the relief centers, we apply the condition that the stationary mean rate of relief $R(l_1,l_2)$ is maximum. Accordingly, we get the necessary conditions:

$$\frac{\partial R(l_1,l_2)}{\partial l_1} = 0, \frac{\partial R(l_1,l_2)}{\partial l_2} = 0. \tag{14}$$

For further simplicity, we take

$$\frac{L-l_1}{l_1} = \frac{l_2}{L-l_2} = \theta, \tag{15}$$

where $\theta > 0$. Consequently, we get

$$l_1 = \frac{L}{1+\theta}, l_2 = \frac{L\theta}{1+\theta}. \tag{16}$$

The equation (13) gives $R(l_1,l_2)$ as a function of θ only. Hence the condition for optimality becomes

$$\frac{\partial R(l_1,l_2)}{\partial \theta} = 0. \tag{17}$$

4 Numerical Illustration

The equation (17) turns out to be a transcendental equation to solve for θ and hence we adopt a search technique to obtain the optimum value of θ. For this, we take the following values:

$$\lambda = 0.1, L = 100, \alpha = 1. \tag{18}$$

For θ ranging from 0.1 to 6.00, Table 2 provides the values of $R(l_1,l_2)$. We find from the above table that the relief is maximum when θ = 1.00. Using the equations (14), we get $l_1 = 50, l_2 = 50$. This means that the two inventories are to be positioned at the center of the line segment in order to derive the maximum stationary rate of relief. This agrees with the model of Larson and Odoni [4] where they have taken the Emergency Medical Facility at the center of the rectangular region. We have taken different values for λ and α and obtained the optimum $\theta = 1.0$. Instead of assuming the condition (15), we allow l_1 and l_2 to vary freely in $(0, L)$. We vary l_1 from 1 to 96 and obtain the optimum values of l_2 such that the value of $R(l_1, l_2)$ is maximum. We find that the optimum position of l_2 is $l_2 = 51$. Similarly, we vary l_2 from 1 to 96 and obtain the optimum values of l_1 such that the value of $R(l_1, l_2)$ is maximum. We find that the optimum position of l_1 is $l_1 = 51$. In other words, among the two inventories, one inventory should be positioned at the center of the line segment.

Table 2: Amount of relief for different θ.

θ	$R(l_1,l_2)$	θ	$R(l_1,l_2)$	θ	$R(l_1,l_2)$
0.1	0.0021202	2.1	0.0053805	4.1	0.0039194
0.2	0.0034697	2.2	0.0052922	4.2	0.0038641
0.3	0.0043965	2.3	0.0052048	4.3	0.0038102
0.4	0.0050340	2.4	0.0051187	4.4	0.0037577
0.5	0.0054692	2.5	0.0050340	4.5	0.0037066
0.6	0.0057608	2.6	0.0049508	4.6	0.0036568
0.7	0.0059489	2.7	0.0048694	4.7	0.0036082
0.8	0.0060617	2.8	0.0047898	4.8	0.0035609
0.9	0.0061191	2.9	0.0047120	4.9	0.0035147
1.0	0.0061357	3.0	0.0046361	5.0	0.0034697
1.1	0.0061221	3.1	0.0045621	5.1	0.0034258
1.2	0.0060862	3.2	0.0044899	5.2	0.0033830
1.3	0.0060337	3.3	0.0044196	5.3	0.0033413
1.4	0.0059691	3.4	0.0043511	5.4	0.0033005
1.5	0.0058958	3.5	0.0042843	5.5	0.0032607
1.6	0.0058163	3.6	0.0042194	5.6	0.0032219
1.7	0.0057325	3.7	0.0041561	5.7	0.0031839
1.8	0.0056461	3.8	0.0040946	5.8	0.0031469
1.9	0.0055580	3.9	0.0040346	5.9	0.0031107
2.0	0.0054692	4.0	0.0039763	6.0	0.0030753

Table 3: Amount of relief for varying l_1, l_2.

λ	1.0	2.0	3.0	4.0	5.0
α	0.5	1.5	2.5	3.5	4.5
$R(l_1,l_2)$	0.16484	0.080337	0.072032	0.068576	0.066667

5 Conclusions

The paper makes an important contribution to the field of disaster relief management by providing a stochastic model for optimally determining the locations of emergency inventories for disasters. The work reported in the paper is timely and a good first step in the investigation of optimum positions for the emergency inventories. We have applied an innovative method of optimizing the stationary mean rate of relief rendered in obtaining the optimum locations of the inventories. Our work can be extended (as indicated in Section 2 of our paper) to analyse the geographic situations where several humanitarian inventories are involved and distance other than the euclidean distance are taken into account for the location of relief supplies. The advantage of the present formulation is the tractability and the assumption of the fact that the relief rendered depends on the distance of the disaster site from the location of the relief center. The disadvantage of the present formulation is that the relief rendered does not depend on the time of occurrence the disaster. We have taken different values for the parameters λ and α and obtained the same conclusion that the relief inventories should be positioned at the center of the region. We have used the stationary mean rate of relief rendered and avoided the time period. The stationary mean rate has been calculated exactly. However the optimality equation is transcendental and hence we have adopted a search technique.

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References

[1] L. White, H. Smith, and C. Currie. OR in developing countries: a review. *European Journal of Operational Research*, 208(1):1–11, 2011.

[2] C. Toregas, R. Swain, C. ReVelle, and L. Bergman. The location of emergency service facilities. *Operations Research*, 19(6):1363–1373, 1971.

[3] J.A. White and K.E. Case. On covering problems and the central facilities location problem. *Geographical Analysis*, 6(3):281–294, 1974.

[4] R.C. Larson and A.R. Odoni. *Urban Operations Research*. Number Monograph. 1981.

[5] O. Berman, R.C. Larson, and A.R. Odoni. Developments in network location with mobile and congested facilities. *European Journal of Operational Research*, 6(2):104–116, 1981.

[6] K.G. Zografos, T. Nathanail, and P. Michalopoulos. Analytical framework for minimizing freeway-incident response time. *Journal of Transportation Engineering*, 119(4):535–549, 1993.

[7] R. Durrett and S.A. Levin. Stochastic spatial models: a user's guide to ecological applications. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 343(1305): 329–350, 1994.

[8] S. Shiode and Z. Drezner. A competitive facility location problem on a tree network with stochastic

weights. *European Journal of Operational Research*, 149(1):47–52, 2003.
[9] K.-M. Bryson, H. Millar, A. Joseph, and A. Mobolurin. Using formal MS/OR modeling to support disaster recovery planning. *European Journal of Operational Research*, 141(3): 679 – 688, 2002. ISSN 0377-2217. doi: http://dx.doi.org/10.1016/S0377-2217(01)00275-2.
[10] L. Brotcorne, G. Laporte, and F. Semet. Ambulance location and relocation models. *European Journal of Operational Research*, 147(3):451–463, 2003.
[11] G. Barbarosoğlu and Y. Arda. A two-stage stochastic programming framework for transportation planning in disaster response. *Journal of the Operational Research Society*, 55(1):43–53, 2004.
[12] L. Özdamar, E. Ekinci, and B. Küçükyazici. Emergency logistics planning in natural disasters. *Annals of Operations Research*, 129(1-4):217–245, 2004.
[13] H.D. Sherali, J. Desai, and T.S. Glickman. Allocating emergency response resources to minimize risk with equity considerations. *American Journal of Mathematical and Management Sciences*, 24(3-4): 367–410, 2004.
[14] M.R. Akella, R. Batta, E.M. Delmelle, P.A. Rogerson, A. Blatt, and G. Wilson. Base station location and channel allocation in a cellular network with emergency coverage requirements. *European Journal of Operational Research*, 164(2):301–323, 2005.
[15] N. Altay and W.G. Green. OR/MS research in disaster operations management. *European Journal of Operational Research*, 175(1):475–493, 2006.
[16] Y. Yin. Optimal fleet allocation of freeway service patrols. *Networks and Spatial Economics*, 6(3-4): 221–234, 2006.
[17] M.-S. Chang, Y.-L. Tseng, and J.-W. Chen. A scenario planning approach for the flood emergency logistics preparation problem under uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, 43(6):737–754, 2007.
[18] H. Jia, F. Ordóñez, and M. Dessouky. A modeling framework for facility location of medical services for large-scale emergencies. *IIE transactions*, 39(1):41–55, 2007.
[19] J.-B. Sheu. An emergency logistics distribution approach for quick response to urgent relief demand in disasters. *Transportation Research Part E: Logistics and Transportation Review*, 43(6):687–709, 2007.
[20] W. Yi and L. Özdamar. A dynamic logistics coordination model for evacuation and support in disaster response activities. *European Journal of Operational Research*, 179(3):1177–1193, 2007.
[21] H.K. Rajagopalan, C. Saydam, and J. Xiao. A multiperiod set covering location model for dynamic redeployment of ambulances. *Computers and Operations Research*, 35(3):814–826, 2008.
[22] A.P. Iannoni, R. Morabito, and C. Saydam. A hypercube queueing model embedded into a genetic algorithm for ambulance deployment on highways. *Annals of Operations Research*, 157(1):207–224, 2008.
[23] R. Pal and I. Bose. An optimization based approach for deployment of roadway incident response vehicles with reliability constraints. *European Journal of Operational Research*, 198(2):452–463, 2009.
[24] E.J. Lodree Jr and S. Taskin. Supply chain planning for hurricane response with wind speed information updates. *Computers & Operations Research*, 36(1): 2–15, 2009.
[25] A.M. Campbell and P.C. Jones. Prepositioning supplies in preparation for disasters. *European Journal of Operational Research*, 209(2):156–165, 2011.
[26] D. Vere-Jones. Some models and procedures for space-time point processes. *Environmental and Ecological Statistics*, 16(2):173–195, 2009.
[27] D. Fiems, T. Maertens, and H. Bruneel. Queueing systems with different types of server interruptions. *European Journal of Operational Research*, 188(3): 838–845, 2008.
[28] J.P.C. Blanc. Bad luck when joining the shortest queue. *European Journal of Operational Research*, 195(1):167–173, 2009.
[29] J.P.C. Blanc. M/G/1 queues with postponed interruptions. *International Scholarly Research Notices*, 2012, 2012. Article ID: 653167.
[30] M. Gendreau, G. Laporte, and R. Séguin. Stochastic vehicle routing. *European Journal of Operational Research*, 88(1):3–12, 1996.
[31] D.P. Gaver Jr. A waiting line with interrupted service, including priorities. *Journal of the Royal Statistical Society. Series B (Methodological)*, pages 73–90, 1962.

V. S. S. Yadavalli is a Professor of Industrial & Systems Engineering, University of Pretoria, South Africa. He obtained his PhD from Indian Institute of Technology, Chennai in 1983. He has published over 120 research papers in reliability theory, queueing theory, inventory theory, manpower planning models, etc, in a wide variety of journals including IEEE Transactions on Reliability, Asia-Pacific Journal of Operational Research, Stochastic Analysis and Applications, International Journal of Systems Science, International Journal of Production Economics, and Applied Mathematics and Computation.

E. van Wyk is a Masters of Engineering graduate at the University of Pretoria. Specializing in Industrial Engineering, she lectured at the University of Pretoria at the Industrial Engineering Department. She is now pursuing her career in Industry and is currently employed as a Process Engineer at Ovations. She is currently also in the process of completing her PhD in Industrial Engineering specifically focusing on disaster and risk management associated with the recovery of a disaster response network within a country.

S. Udayabaskaran, M.Sc., Ph.D. is presently working as Professor of Mathematics in Vel Tech Rangarajan Dr. Sagunthala R & D Institute of Science and Technology, Avadi, Chennai 600062, Tamilnadu, India. He obtained his M.Sc. and Ph.D. degrees in Mathematics both from Indian Institute of Technology, Madras, Chennai 600036, Tamilnadu, India. He has nearly 45 years of teaching and research experience. He has published over 30 research papers in international journals. His field of research includes Stochastic differential equations, Branching processes, Queueing theory, Inventory Theory and Stochastic finance.