Emergency Supply Planning

CREATE Report
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Executive Summary

In order to effectively respond to a large-scale emergency such as a bio-terrorist attack, plans for the wide-scale distribution of medical supplies must be developed. For example, to address emergencies of infectious diseases, the Federal government's Strategic National Stockpile contains 300 million doses of smallpox vaccines and enough antibiotic to treat 20 million people for anthrax. In the event of an emergency, these vaccines would be delivered in push packages of emergency supplies to the Emergency Staging Area (ESA). This work cover models that can be used to aid emergency responders in selecting (1) appropriate staging areas, and (2) suitable routes to distribute the vaccinations to the staging areas.

We formulated the problem of selecting the staging areas as a facility location problem and the problem of disbursing supplies as a vehicle routing problem (VRP). The differences between the models developed in this research and the available models in the existing literature lie in that the developed models take into account the unique characteristics of large-scale emergencies (e.g., overwhelming demand, high degree of uncertainties of travel time and demand requirements, and low probability of occurrence) and hence could better mitigate the impact of the emergencies.

The developed models have been tested on hypothetical large-scale emergency scenarios. The facility location and vehicle routing problems are respectively formulated and solved. It is shown that the proposed models obtain solutions that provide better coverage than solutions generated by traditional models in the literature. We have made progress toward integrating these models in a GIS planning tool.

The benefits of modeling and solving the facility location and vehicle routing problems are two-fold. First, from a planning perspective, the models and solutions can aid planners to optimally determine the facility locations and vehicle routes and thus maximize the efficiency and effectiveness of the medical supply chain system as a whole. Second, these plans can become well tested operating policies, which, during an emergency, could be integrated with real-time information to generate the most suitable operation procedures for the specific emergency that has occurred.

1 Introduction and Background

Large-scale emergencies such as natural disasters (e.g. earthquake) and terrorist attacks (e.g. Sept 11) result in substantial causalities and property damages, which overwhelms local emergency responders. Careful and systematic pre-planning as well as efficient and professional execution to respond to a large-scale emergency can save many lives. A key ingredient in an effective response to an emergency is the prompt availability of necessary medical supplies, such as vaccines in response to a bio-terrorism attack. In this work, we investigated the following two interrelated questions:

- Where to locate the facilities (staging areas) for receipt of the medical supplies from the SNS in support of rapid distribution, and
- How to route vehicles to disburse supplies to the facilities once an emergency has occurred?

Operations research models play an important role in addressing these logistical problems for distribution systems. At the heart of both questions there is a transportation network to distribute the medical supplies. The question of where to place warehouses/inventories is essentially a facility location problem within this supply network, while the disbursement of supplies can be posed as a vehicle routing problem (VRP) on this network. The benefits of modeling and solving the facility location and vehicle routing problems are two-fold. First, from a planning perspective, the models and solutions can aid planners to optimally determine the facility locations and vehicle routes and thus maximize the efficiency and effectiveness of the medical supply chain system as a whole. Second, these plans can become well tested operating policies, which can further improve performance. Clearly, the plans need to be flexible enough to accommodate contingencies of daily operations. For the plans to be robust, they must take into consideration the stochastic nature of the problem such as uncertain demand, traffic conditions, etc.

2 Technical Approaches

The deployment of medical facility sites (staging areas) in response to a large-scale emergency must account for massive service requirements. In most traditional facility location problems, each individual demand point is covered only by one facility given the fact that demand does not appear in large amounts. Hence, our approach is to develop a redundant and dispersed facility placement strategy so that more medical supplies could be mobilized to service different demand points to reduce mortality and morbidity.

Another important aspect of the facility locations for a large-scale emergency is the fact that given the occurrence of the emergency at an area, the resources of a number of facilities will be applied to quell the impact of the emergency, not only those located closest to the emergency site. This implies that there are different types of coverage, or quality of coverage, which can be classified in terms of the distance (time) between facilities and demand points. Thus, a facility that is close to a demand point provides a better quality of coverage to that demand point than a facility located far from that demand point. When planning the emergency medical services, it is important to consider adequate staging areas of various qualities for each demand point.

Furthermore, potential demand areas for medical services need to be categorized in a different way than other regular emergencies. Each demand area has distinct attributes, such as population density, economic importance, geographical feature, weather pattern, etc. Therefore, our facility location models allows for different requirements of facility quantity and quality for each demand point so that all demand points can be serviced in a balanced and optimal manner.

Our general facility location model can be cast as a covering model, a *P*-median model or a *P*-center model, each suited for different needs in a large-scale emergency. The covering model aims to maximize the sufficiently covered population who can receive medical services in a required time (distance) limit. This model is suitable in emergencies such as dirty bomb attacks or chemical incidents, in which instantaneous medical supplies are needed to service the affected areas. The *P*-median model aims to optimize the overall performance of the facilities by minimizing the total distance from the facilities to the demand points. It is more applicable to emergencies such as smallpox emergencies, in which a blanket coverage (e.g. mass vaccination) to all the population in an area is necessary. The *P*-center model aims to optimize the worst case performance of the facilities by minimizing the maximal distance from each demand point to its servicing facilities. It is suitable for locating the medical supplies for first responders so that they can be treated by the supplies within a maximum time limit. Our modeling framework also allows for the development of a model that is a combination of the covering model, P-median model, or a P-center model. For example, we have developed a P-median model with a coverage constraint to model an anthrax bio-terrorist attack scenario.

The primary goal of vehicle routing during a large-scale emergency is to deliver the medical supplies to the affected areas as soon as possible to save lives. Therefore, in this work we formulated the vehicle routing problem with an objective of minimizing the unmet demands for the medical services at all the demand points. Since the delivery of supplies to the populations within a time-limit will make an appreciable health difference, we associated a time window with each demand, which can be further divided into two types: soft and hard time-windows. The soft time-windows allow for late deliveries incurring in a penalty. The hard time-windows are used to model situations in which a late delivery directly leads to loss of life.

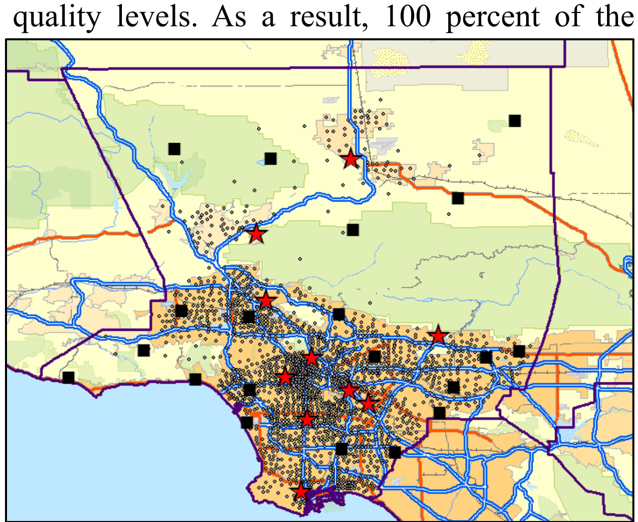
We addressed the randomness in the vehicle routing problem such as uncertain demand requirements and travel times by defining a probability distribution and a mean value to these parameters. Hence, the vehicle routing problem is formulated as a chance constrained model which guarantees that the time and demand constraints are not violated within a prescribed probability. Moreover, because of the massive service requirements, the demand at a location is not necessarily satisfied by a single truckload. As such, the vehicle routing problem allows for split delivery (i.e., a point can be visited more than once if the demand exceeds the load capacity of available vehicles) to the demand points from multiple depots.

3 Results and Analyses

The developed facility location and vehicle routing models have been formulated for a hypothetical anthrax bio-terrorist attack emergency in the Los Angeles County Area. The models determine the problems of where to locate the staging areas to receive the national stockpile and how to route the vehicles to distribute the medical supplies. The impact of an anthrax attack on the population can be tremendous. First, thousands of people could be directly infected by the disease at the incident site. Second, the affected area could quickly spread from the original incident site to a much larger region by the movement of the infected but unaware people because the anthrax attack is usually covert and the appearance of the disease symptom may lag the attack from hours to days. Third, after an anthrax disease emergency becomes known in public, people may panic and become scared. They may request medical treatment or vaccination even if they are not actually infected or not in a high-risk situation.

There are 2054 census tracts and 9.5 million people in Los Angeles County. We used the centroid of each census tract as a demand point to represent the aggregated population in this tract. Thus we obtained 2054 discrete demand points that have different population densities. To determine the staging areas that can be used to receive, re-package, and distribute the medical supplies from the national stockpile to the demand points, we identified 30 eligible facility sites. For the facility location problem, we assumed that the resource limitation allows only 10 eligible facility sites to be selected to service the demand points. The facilities are required to service the demand points at two quality levels, which are respectively defined as 35 miles and 60 miles. For the vehicle routing problems, we used a hard time-window of 12 hours to deliver the medical supplies from a central depot to the 10 selected facilities. The demand amount and travel times are assumed to have an exponential distribution with standard deviations to be 20 percent of the mean values.

Based on the input parameters defined above, we used the *P*-median model to solve the facility location problem. The solution is depicted in Figure 1 (The stars represent the selected facilities). In this solution, each demand point is covered by a required quantity of facilities at both quality levels. As a result, 100 percent of the population can be



sufficiently serviced/protected by the facilities in an efficient manner. The average distance from the demand points to their servicing facilities at quality level 1 is 25.8 miles; and the average distance at quality level 2 is 50.2 miles. Since the total distance between the demand points and the facilities has been minimized (as defined by the objective function), the effectiveness of facility service performance is optimized.

Figure 1. Solution to the Facility Location Problem

To compare our model with the traditional location models in the literature, we also solved the location problem using the traditional *P*-median model by assuming that only one facility is required for servicing each demand point. Then we applied the obtained solution by considering the multiple facility quantity and quality coverage requirement. The result shows that only 43 percent of the population can be covered by the facilities and the average distances at the quality level 1 and 2 are respectively 47.7 miles and 83.2 miles. These average distances are much larger than (and hence inferior to) the solution obtained from our model.

Based on the solution to the facility location problem, the vehicle routing problem is also solved based on the specified parameters. The result is compared with that of a traditional deterministic formulation to show the advantage of our chance-constraint model. We simulated 50 cases using the exponential distribution to represent travel time and demand, and for each simulated case we measured the unmet demand for both the vehicle routes generated by the deterministic and chance-constraint formulations. The comparison shows that out of the 50 test cases, the deterministic routes generate 18 unmet demand cases with an average unmet demand of 9.94 while the chance-constraint routes only generate 2 unmet demand cases with average unmet demand of 5.50. The chance-constraint routes outperform the deterministic ones because of the conservative nature of the chance-constraint model, which leads to balanced routes with similar number of demand points. The deterministic routes are more prone to have uneven number of nodes on different paths. We observed that this property makes the chance-constraint solution more robust and competitive than the deterministic one especially for the test cases that deviate far away from the mean value.

4 Conclusions and Recommendations

Facility location and vehicle routing are important issues in designing a medical supply distribution system, particularly for large-scale emergencies. This work presents tailored location and vehicle routing models to design rapid distribution systems of medical supplies in response to a large-scale emergency. An illustrative example of an anthrax emergency was discussed to show how the proposed models can be used to determine the facilities locations and vehicle routes for rapid medical supply distribution during an emergency.

In this work, we consider an emergency due to an anthrax attack as a representative large-scale emergency. We discuss the characteristics of large-scale emergencies and their requirements for the facility location and vehicle routing problems in the context of this particular emergency. However, other types of emergencies (e.g. chemical incident, dirty bomb attack, contagious disease outbreak, etc.) may involve different characteristics and thus will lead to different requirements on the problem formulations and solutions. For example, an emergency caused by a dirty bomb attack may impact not only the population, but also the medical supply facilities themselves. Therefore, reduced service capability of the facilities needs to be taken into account. A chemical incident may need instantaneous medical service to the infected people, and therefore medical supplies may need to be pre-positioned at a local level for immediate deployment. An open research question is how to develop an overall response plan that takes into consideration all the different possible scenarios. Is it more efficient and cost effective to develop a single strategy that is robust to the different possibilities or is it better to develop a separate plan for each possible emergency?

Another research direction is to develop efficient algorithms to solve the facility location and vehicle routing problems. To date, the formulated problems were of relatively small size (i.e. 30 eligible facility sites, 10 selected staging areas, 1 central depot) so the optimal solutions could be readily found using commercially available optimization software. However, for modeling more realistic and larger scenarios, the problem size of the models will increase significantly so that it becomes computationally prohibitive to obtain an optimal solution. Future research direction should also focus on developing efficient heuristics which can identify near optimal solutions to the large problems within a reasonable computational time.

5 Research Products

5.a Refereed Publications

"A Modeling Framework for Facility Location of Medical Services for Large-Scale Emergencies", under revision to *Special Issue of IIE Transactions on Homeland Security* (H. Jia, F. Ordóñez , and M. M. Dessouky)

“Stochastic Vehicle Routing Problem for Large-scale Emergencies”, submitted to *Computers and Operations Research* (Z. Shen, M. M. Dessouky, F. Ordóñez).

5.b Non-Refereed Publications

"Rapid Distribution of Medical Supplies," *Delay Management in Health Care Systems*, R. Hall (ed), Springer, 2006. (M. M. Dessouky, F. Ordóñez, H. Jia, Z. Shen)

5.c Other Technical Reports

5.d Software Tools

An ArcGIS-integrated facility location planning tool for large-scale emergencies (in development)

5.e Presentations

"A Modeling Framework for Facility Location of Medical Services for Large-Scale Emergencies", Presented at IFORS Hawaii conference, Jul 2005.

"A Modeling Framework for Facility Location of Medical Services for Large-Scale Emergencies", Presented at the INFORMS San Francisco conference, Nov. 2005.

6 Education and Outreach Products

Two PhD students are supported and actively participate in this research work. The project team is supporting another project "Transportation Plan for Strategic National Stockpile (SNS) – Deployment Within Los Angeles County" which is developing a detailed transportation plan for Los Angeles County for the deployment of medications to predefined staging areas.