Emergency Supply Planning

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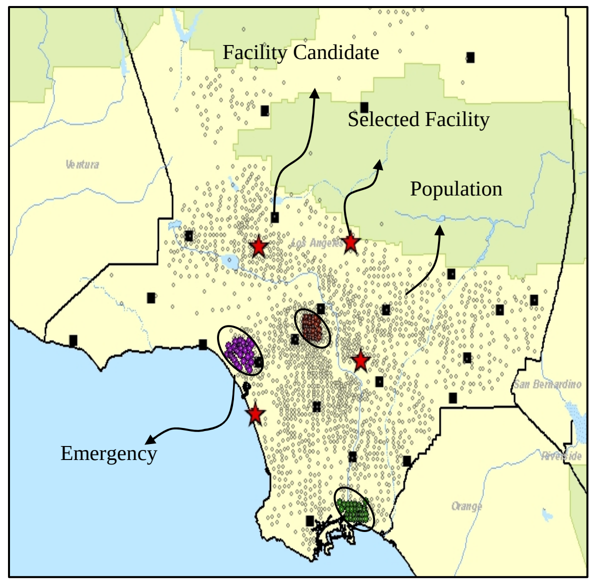
1. Overview



Rapid and efficient wide-scale distribution of medical supplies plays a critical role in assuring the effectiveness in managing the risks of large-scale emergencies such as bio-terrorism. Important issues in the design of such an efficient distribution network involve deciding where to place the warehouse/inventories, how to route distribution vehicles and how to manage these inventories. Solving appropriate facility location, vehicle routing and inventory management problems in a coordinated manner can ensure the design of a logistic network capable of efficient wide-scale distribution of medical supplies to respond to a large-scale emergency.

In this work, we develop models and solution approaches to solve facility location and vehicle routing problems as well as a conceptual model for efficient inventory management in the context of the response to a large-scale emergency. By directly taking into account some of the unique requirements of large scale emergencies, we show that our models provide better backup coverage than existing models of emergency response planning for a number of scenarios representing a bio-terrorist attack in Los Angeles County.

Although the emphasis of this report is on research completed during the third year, we summarize the work finished in all three years for completeness where appropriate.

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 integrated these models in a GIS planning tool. We have also collaborated with Los Angeles County, Department of Health to investigate the efficient strategies and best practices in identifying potential points of dispensing (PODs) sites.

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

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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.

2. Research Accomplishments

To manage the risks of large-scale emergencies such as bio-terrorism and mitigate their impacts to the population, efficient strategies for distribution of large amount of medical supplies must be developed.

This work covers models that can be used to:

- aid emergency responders in selecting appropriate points of dispensing (PODs)
- aid emergency responders in selecting suitable routes to distribute the vaccinations to PODs
- improve the management of medical supply inventories to reduce cost of maintaining a stockpile.

To manage the risks and consequences of large-scale emergencies, such as a bio-terrorism attack and mitigate their impacts to the population, wide-scale distribution of medical supplies must be developed. For example, to address emergencies of infectious diseases, the Federal Government's Strategic National Stockpile (SNS) contains 300 million doses of smallpox vaccines and enough antibiotic to treat 20 million people for anthrax. These medical stockpiles include both the supplies from the federal government and the managed inventories from the vendors. In the event of an emergency, these vaccines would be delivered in push packages of emergency supplies to the Emergency Staging Area (ESA) to be distributed from there to the population through various points of dispensing (PODs).

We formulated the problem of selecting the staging areas as a facility location problem, the problem of disbursing supplies as a vehicle routing problem (VRP), and the problem of managing medical supplies as an inventory economical manufacturing quantity (EMQ) model. These problems are inter-connected and they are integrated to provide a complete medical supply management solution to large-scale emergencies. 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 and manage the large-amount of medical stockpiles.

<u>Facility Location Model</u>

For the PODs facility location problem, a general uncapacitated facility location model has been formulated. This model addresses the uncertainty present in large scale emergencies requiring the location solution to provide multiple quantity and quality of coverage. This redundancy leads to solutions that can better respond to variations in demand and/or distance levels. It 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. Furthermore, since there can be different scenarios during large-scale emergencies, a regret model is also proposed to address the stochasticity in the emergencies and it can be used to find a globally optimal solution across scenarios.

Different solution approaches (e.g. a GA, a Lagrangean Relaxation heuristic, and a Locate-Allocate heuristic) have been developed to solve these uncapacitated facility location problems. A detailed computational study is made to evaluate the performance of these solution approaches. The results imply a good capability of the model in improving the population coverage and reducing life-loss during large-scale emergencies. We find that the Genetic Algorithm heuristic was more appropriate to solve the location problems with small sizes, for which it was able to generate better solutions within reasonable computational times; The Lagrangean Relaxation and the Locate-Allocate heuristics were more preferable for larger problems since they could generate better or comparable solutions with less computational times.

As an extension to the uncapacitated facility location problem, we have also considered the constraints of the PODs such as physical space or available personnel, and hence formulated a capacitated facility location problem. A Locate-Allocate heuristic is applied to solve this problem. It decomposes the facility location problem into two Integer Programming problems and solves them iteratively. One problem decides the location of facilities for fixed demand loads; the other allocates demand loads to fixed facilities.

Vehicle Routing Model

In a large scale emergency setting, a vehicle routing/dispatching model provides a method to plan for the first responder's reaction to the emergency, and in the event an emergency occurs, a methodology to quickly adjust the dispatching policy to provide an efficient response. In a large scale emergency, we consider that the objective of the routing problem is to minimize the unsatisfied demand that can occur because resources and first responders are overwhelmed. Unmet demand is an overriding objective in an emergency situation since it can result in loss of life, which outweighs traditional VRP objectives. An additional important aspect in meeting the demand in a large-scale emergency is the response time. Since the administration of the medication to the population within a time-frame makes an appreciable health difference in a large-scale emergency, it is important to associate each demand with a time window, to address situations in which a late delivery directly leads to loss of life, such as in an anthrax attack.

We represented the randomness in the vehicle routing problem such as uncertain demand requirements and travel times assuming a known probability distribution. Hence, the vehicle routing problem is formulated as a chance constrained model which guarantees that the time and demand constraints are not violated more than 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.

We decompose our problem into a two-stage problem. In the first planning stage, we formulate the problem into a mixed integer programming (MIP) model well in advance of any possible emergency to generate pre-planned routes, which can be used for mock trial runs and training purposes. A chance-constrained model is applied to handle the uncertainty. In the second operational stage, at the time of the emergency when more information is revealed, we need to quickly respond to the event and generate the delivery requirements with the planned routes as well as making adjustments on the routes if necessary. We refer to the second stage model as the recourse strategy. We propose 3 different recourse strategies: adjust the quantity in each vehicle (LP recourse strategy); adjust quantity and skip customers (Knapsack recourse strategy) and complete reroute (re-planning strategy). We propose a tabu heuristic for the planning stage model and an approximation heuristic for the knapsack recourse strategy. It is demonstrated by numerical experiments that the tabu search method is effective in minimizing the unmet demand, which is our primary concern in this model. In the planning stage, under moderate supply and deadline combination, the chance-constrained model outperforms a deterministic model according to the simulation results since it leads to more balanced routes with similar number of demand nodes. In the operational stage, the experiment reveals that the knapsack recourse strategy provides a nice trade-off between maintaining the familiarity of the preplanned routes and an efficient solution and quick solution times; hence it is the most efficient recourse strategy that uses the preplanned routes and the proposed knapsack approximation algorithm obtains solutions quickly.

<u>Supply Chain Management Model</u>

The primary goal of the vendor stockpile inventory management is to ensure the maximal economical value of the stockpile inventory. The federal response to a bio-terrorist attack on the United States includes a combination of vaccines, prophylaxis, and medical supplies. Traditional pharmaceutical supply chains are not adequate to push a huge volume of medical supplies to the affected population. The majority of the medical supplies used would be from the Strategic National Stockpile (SNS), which is separated into ready to deploy push packages and a larger inventory managed by manufacturers, the Vendor Managed Inventories (VMIs). Under the current system, drugs are produced and stored in stockpiles by firms for the government to tap into in case of an emergency. These are the VMIs and firms are paid by the government for the production and storage of the drugs. For example, in a potential anthrax attack, the federal government aims to help 20 million people. This stockpile represents enough Cipro, a common antibiotic with 7 year lifespan that works against anthrax and other infections, to meet regular market demand for years. Considering the obvious fact that it is more efficient to sell some of the stockpile rather than holding it until it expires, current SNS policy allows firms sell the drugs to the private market (where Cipro works as handy antibiotics for non-anthrax related illnesses) when they are 6 months prior to expiration rather than let the drugs spoil. However, the size of the stockpile is large compared with the expected market demand which leads to waste. Given more time there is the opportunity to capture a significant amount of salvage value for the unsold stockpile. From the government's perspective, if it can negotiate the "prior rule" with the firm to have the VMIs to sell earlier, then the firm can re-coop more of the capital in the stockpile, hence charging less production and inventory holding cost per pill to the government. We propose a conceptual revenue model to depict the potential saving for the government and intend to find an "optimal prior rule". From the manufacture's perspective, if it can apply a more sophisticated inventory holding policy which allows the constant usage of the stockpile to meet the regular market demand and refill with new production at the same time to maintain the minimum stockpile requirement, then the firm can save on the total cost in maintaining the stockpile inventory, hence making it possible to further reduce the price charged to the government. We propose a conceptual inventory Economic Manufacturing Quantity (EMQ) model to address this issue and intend to find the "optimal order quantity (Q*)".

3. Applied Relevance

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 help determine where to locate the PODs to receive the medical supplies from SNS and how to route vehicles to distribute these 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. To determine the PODs 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. 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.

Based on the input settings 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. 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.

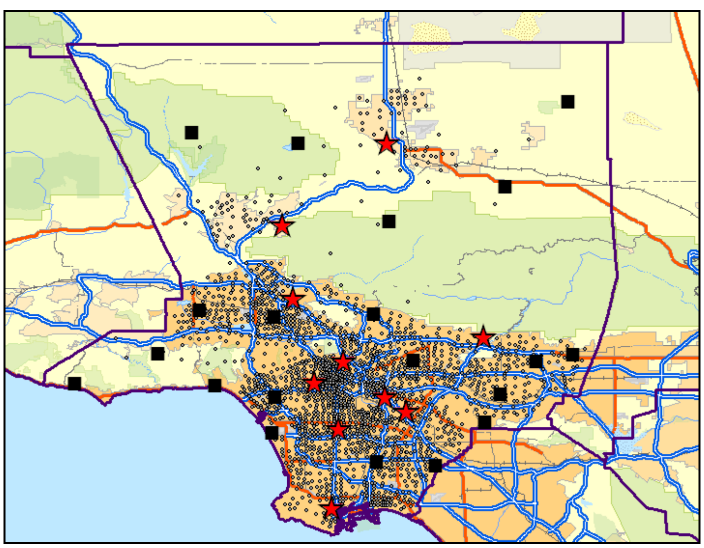

Figure 1. Solution to the Facility Location Problem

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 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.

This effort produced models and software tools usable for emergency response, recovery and planning. The prototype Facility and Router software is available for use by city and county emergency response planners, such as the Los Angeles County Department of Health, as part of the Risk Analysis Workbench (RAW). The facility and route selection is embedded with a GIS system, and includes the case study with LA county data.