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ROUTING AND SCHEDULING FOR MEDICATION DISTRIBUTION PLANS

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This paper presents a two-stage approach for solving the medication distribution problem. The problem addresses a critical issue in emergency preparedness. Public health officials must plan the logistics for distributing medication to points of dispensing (PODs), which will give medication to the public in case of a bioterrorist attack such as anthrax. We consider the problem at the state and local levels. Our approach separates the problem into two subproblems: (1) the “routing problem” assigns PODs to vehicles and creates routes for each vehicle, and (2) the “scheduling problem” determines when the vehicles should start these routes and how much material should be delivered on each trip. This paper presents the results of using this approach to construct solutions for a realistic three-county scenario. The results show that the routing and scheduling decisions greatly affect the quality of the solution.

1. Introduction

Improving emergency preparedness requires planning responses to bioterrorist attacks. In the case of a large scale bioterrorist event, such as the release of anthrax, public health officials may decide that mass dispensing of medication is needed. According to the Centers for Disease Control and Prevention, large cities and metropolitan areas need to dispense antibiotics to their entire identified population within 48 hours of the decision to do so (CDC, 2008). Federal funding is supporting efforts by cities in every state to create effective plans. These plans call for opening points of dispensing (PODs) to give prophylactic medication to persons who are currently healthy but may have been exposed to a pathogen. PODs may be setup in schools, recreation centers, churches, and other non-medical facilities. Other modes of dispensing medication are being considered, but PODs are the primary focus of planning activities.

The proposed research is motivated by work with county public health departments in the state of Maryland who must plan the logistics for distributing medication to the PODs from a central location. We consider the problem at the state and local levels (not the national level). After the decision for mass dispensing is made, county public health departments will begin preparing for opening multiple PODs simultaneously at a designated time. The state will request medication from the federal government, who will deliver an initial but limited supply of medication to a state receipt, storage, and stage (RSS) facility (which we call the “depot”).

Contractors will deliver more medication to the depot, but the state will begin shipping medication from the depot to the PODs before everything arrives from the contractors.

Some counties in a state may choose to operate a local distribution center (LDC), which receives medication from the depot and operates as a cross-docking facility. Personnel at the LDC load trucks that deliver the medication to the PODs in that county. LDCs are viewed as desirable because a county can employ drivers and transportation managers who are familiar with the county and can adjust the distribution of medication based on local needs and preferences.

Poor medication distribution plans will delay the time that some PODs receive medication. This can delay the opening of these PODs, and some residents may not get their medication in a timely manner, which increases their risk of death or illness. Clearly, there are many uncertainties in medication distribution, including the timing of shipments to the depot, the time needed to load and unload trucks, travel times, and the demand for medication at each POD. For this reason, planners need a robust plan. In particular, it is better if the plan calls for delivering medication to PODs much earlier than it is needed. This improves the likelihood that the PODs will open on-time, will not run out of medication during operations, and will dispense medication to the largest number of people in a timely manner.

The operations of firefighters, emergency medical services, and police departments have motivated research into location models (e.g. Daskin and Stern 1981, Ball and Lin 1993, Ceyhun et al. 2007) and dynamic vehicle routing models (Sivanandan et al. 1988, Weintraub et al. 1999, Haghani et al. 2004). However, these models are not relevant to the medication distribution problem.

The problem of routing a variety of vehicles to deliver medication to the PODs within a short period of time, when not all medication is available initially, is more closely related to the inventory routing problem (IRP) and the production-distribution scheduling problem (PDSP). Still, these models are also not directly relevant. In a deterministic IRP, the demand at each site is known (see survey papers by Dror et al. 1985, Campbell et al. 1998, Baita et al. 1998, and Moin and Salhi 2007). In a stochastic IRP, the demand at each site is a random variable (see, e.g. Trudeau and Dror 1992, Bard et al. 1998, Kleywegt et al. 2002).

In a PDSP, there exists a set of jobs that need to be processed by a resource and then delivered to the customers who requested them. Chen (2008) provides a recent survey. Some

PDSPs have a single customer (e.g. Herrmann and Lee 1993, Chen 1996, Lee and Chen 2001, Chang and Lee 2004, Chen and Pundoor 2006), while others have multiple customer sites (e.g. Van Buer et al. 1999, Hall and Potts 2003, Chen and Vairaktarakis 2005, Wang et al. 2005, Stecke and Zhao 2007, Geismar et al. 2008). In some versions of the problem, a job can be split into multiple subjobs that are delivered separately, in which case multiple deliveries to the same customer are required (Dror and Trudeau 1989, Chen and Pundoor 2005).

This paper addresses the single-product, deterministic problem. Inventory is treated as a continuous variable, but the number of pallets must be an integer. We measure the medication with the number of regimens. In mass dispensing, each person will get one predetermined regimen, which is a bottle with a specific number of pills. All PODs have the same hours of operation, and loading and unloading times are independent of the quantity. We are ignoring other resources such as the loading docks at the depot, the available drivers, and the number of available pallets.

The paper formulates two versions of the problem (with and without LDCs), presents a two-stage approach for constructing solutions, and discusses the results of applying this approach to a realistic three-county scenario.

2. Problem Formulation: Depot-to-PODs

Without loss of generality we let time $t = 0$ correspond to the first instant that the depot has medication. PODs will begin operating at time $t = T_1$ and continue to operate until time $t = T_2$. In practice, these times may be on the order of 12 to 36 hours.

There are n PODs (sites). Each site ($k = 1, \dots, n$) has a dispensing rate of L_i regimens per time unit. This is the rate at which the site consumes medication. The site needs a total of $(T_2 - T_1)L_i$ regimens.

There is a depot ($k = 0$) that has a supply of medications. Let $I(t)$ be the cumulative amount of medication delivered to the depot at time t . $I(t)$ is a discontinuous, non-decreasing function due to the batch deliveries that are made there.

For example, suppose that the depot will receive 100,000 regimens at $t = 0$, 125,000 regimens at $t = 4$ hours, and 135,000 regimens at $t = 8$ hours. Then, Figure 1 shows the graph of $I(t)$ over time.

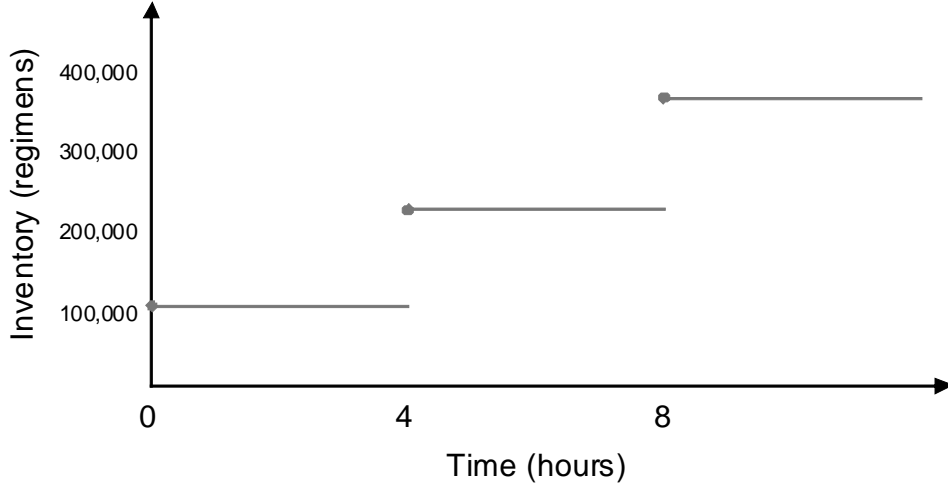


Figure 1. Cumulative deliveries $I(t)$ over time for example.

The time spent at site i (to load or unload a vehicle) is p_i for $i = 0, \dots, n$. The time to go from site i to site j is c_{ij} . There are V vehicles. Vehicle v has a capacity of C_v pallets of material. At each site, a vehicle will deliver one or more pallets. A pallet can hold at most P regimens.

A feasible solution specifies one or more routes for each vehicle. Let r_v be the number of routes that vehicle v makes. Let the sequence $\sigma_{vj} = \{i_1, \dots, i_{m(vj)}\}$ be the j -th route for vehicle v , where $m(vj)$ is the number of sites on the route. Let t_{vj} be the start time at which the vehicle begins loading at the depot. Let w_{vjk} be the duration between the start of the route and the time that the delivery at site k is complete. Let y_{vj} be the total duration of the route. When the vehicle returns to the depot, it may be used for another route. Let q_{vjk} be the quantity delivered to each site $k \in \sigma_{vj}$. The quantity q_{vjk} uses p_{vjk} pallets (recall that p_{vjk} must be an integer).

Certain constraints must be satisfied for the solution to be feasible.

The quantity shipped from the depot cannot exceed the amount delivered to the depot.

$$\sum_{(a,b): t_{ab} \leq t_{vj}} \sum_{k \in \sigma_{ab}} q_{abk} \leq I(t_{vj}) \quad v = 1, \dots, V; j = 1, \dots, r_v$$

A vehicle cannot begin a new route until it returns to the depot.

$$t_{vj} \geq t_{v,j-1} + y_{v,j-1} \quad v = 1, \dots, V; j = 2, \dots, r_v$$

All quantities are non-negative, and pallets have a fixed capacity, so $0 \leq q_{vjk} \leq Pp_{vjk}$ for all $v = 1, \dots, V$; $j = 1, \dots, r_v$; and $k \in \sigma_{vj}$. Note that $q_{vjk} = 0$ if and only if $k \notin \sigma_{vj}$.

Each vehicle has a fixed capacity for pallets: so $\sum_{k \in \sigma_{vj}} p_{vjk} \leq C_v$ for all $v = 1, \dots, V$; and $j = 1, \dots, r_v$.

All route start times are non-negative, so $t_{vj} \geq 0$ for all $v = 1, \dots, V$; and $j = 1, \dots, r_v$.

Each site must receive all needed medication.

$$\sum_{v=1}^V \sum_{j=1}^{r_v} q_{vjk} = (T_2 - T_1) L_k \quad k = 1, \dots, n$$

The problem is to find a feasible solution with the largest amount of minimum slack. Given a solution, evaluating its minimum slack requires measuring the slack of each route. For each site $k \in \sigma_{vj}$, let Q_k be the total quantity already delivered to that site on previous routes. Then, the expected time at which that site runs out of medication is $T_1 + Q_k / L_k$. This depends upon the set E_{vjk} of routes (a, b) such that $k \in \sigma_{ab}$ and $t_{ab} + w_{abk} \leq t_{vj} + w_{vjk}$. Note that E_{vjk} does not include the route (v, j) .

$$w_{vjk} = p_0 + c_{0i_1} + p_{i_1} + c_{i_1 i_2} + \dots + p_k$$

$$y_{vj} = p_0 + c_{0i_1} + p_{i_1} + c_{i_1 i_2} + \dots + p_{i_m(vj)} + c_{i_m(vj)0}$$

$$Q_k = \sum_{(a,b) \in E_{vjk}} q_{abk}$$

Let s_{vj} be the slack of route (v, j) . That is, if the start of the route were delayed more than s_{vj} time units and no more medication were delivered to the sites $k \in \sigma_{vj}$, at least one of these sites would run out of medication. The minimum slack S of a solution is the minimum slack over all vehicles and routes.

$$s_{vj} = \min_{k \in \sigma_{vj}} \left\{ T_1 + Q_k / L_k - (t_{vj} + w_{vjk}) \right\}$$

$$S = \min_{v=1, \dots, V; j=1, \dots, r_v} \left\{ s_{vj} \right\}$$

3. Example

Consider a two-site, one-vehicle problem instance. $T_1 = 24$ hours, $T_2 = 48$ hours. $L_1 = 10,000$ regimens per hour, and $L_2 = 5,000$ regimens per hour. $P = 10,000$ regimens per pallet. $C_1 = 10$ pallets. $p_0 = p_1 = p_2 = 15$ minutes. The travel times (in minutes) are given in Table 1. The depot will receive 100,000 regimens at $t = 0$, 125,000 regimens at $t = 4$ hours, and 135,000 regimens at $t = 8$ hours.

Table 1. Travel times (in minutes) for example.

From \ To	Depot	Site 1	Site 2
Depot	-	10	30
Site 1	10	-	25
Site 2	30	25	-

Table 2 describes a feasible solution in which the vehicle travels the same sequence for five routes: $\sigma_{1j} = \{1, 2\}$ for $j = 1, \dots, 5$. Then, $w_{1j1} = 15 + 10 + 15 = 40$ minutes, and $w_{1j2} = 40 + 25 + 15 = 80$ minutes. The total route duration is $y_{1j} = 80 + 30 = 110$ minutes. Table 3 shows the slack calculations. In this simple example, the minimum slack is 1360 minutes (22.67 hours), which is quite large. Figure 2 shows the deliveries and dispensing at site 1. The dashed red lines show the slack (at site 1) for each delivery.

Table 2. Feasible solution for example. All times in minutes.

Route	t_{1j}	q_{1j1}	p_{1j1}	q_{1j2}	p_{1j2}
1	0	70,000	7	30,000	3
2	240	70,000	7	30,000	3
3	345	10,000	1	15,000	2
4	480	70,000	7	30,000	3
5	585	20,000	2	15,000	2

Table 3. Slack calculations for example. All times in minutes.

Route j	Site 1			Site 2			Route slack
	Q_1	Run out time	Slack for site	Q_2	Run out time	Slack for site	
1	0	1440	1400	0	1440	1360	1360
2	70,000	1860	1580	30,000	1800	1480	1480
3	140,000	2280	1895	60,000	2160	1735	1735
4	150,000	2340	1820	75,000	2340	1780	1780
5	220,000	2760	2135	105,000	2700	2035	2035

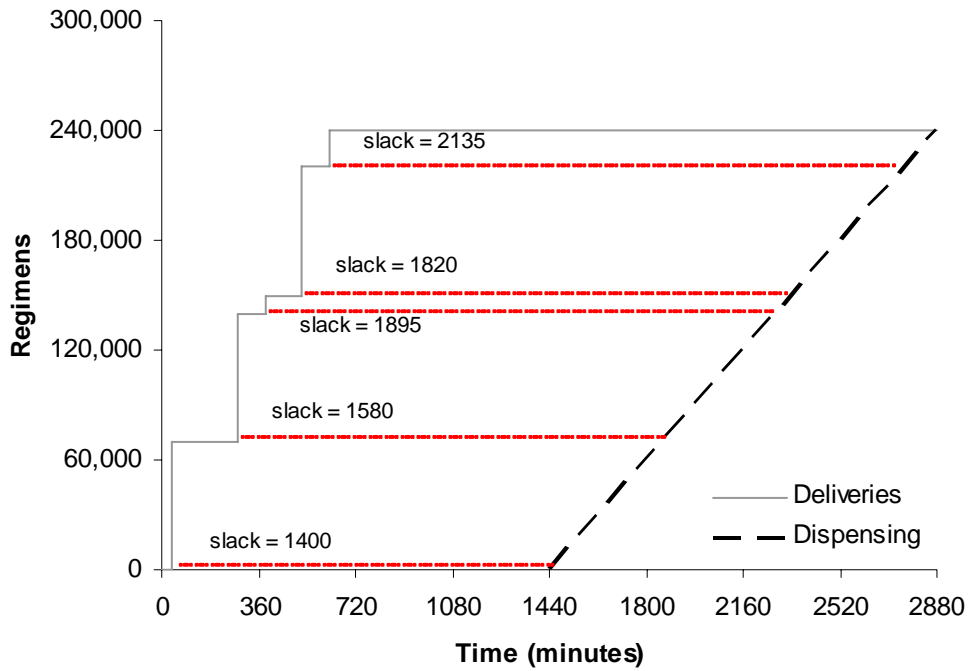


Figure 2. Cumulative deliveries and dispensing at site 1 for example. The red dashed lines show the slack at this site for each route.

4. Problem Formulation: Depot-to-LDCs-to-PODs

We formulate the problem with local distribution centers (LDCs) as follows. We assume that the locations of all LDCs and the division of sites into jurisdictions are given.

There are $M \geq 1$ jurisdictions that will operate LDCs. Let D_m be the set of sites in jurisdiction m that will be served by LDC m . D_0 is the set of sites that will continue to be served by the state depot. Let L be the set of M LDCs.

Let $I_0(t)$ be the cumulative deliveries to the depot, which is given. Let $I_m(t)$ be the cumulative deliveries to LDC m , which is determined by the routes.

There are $M + 1$ sets of vehicles. V_0 is the set of vehicles that operate from the depot, and V_m is the set of vehicles that operate from LDC m . Let $V = \bigcup_{m=0}^M V_m$ be the entire set of vehicles. A vehicle operating from LDC m serves only sites in D_m . Vehicles operating from the depot serve the LDCs in set L and the sites in D_0 .

As before, a feasible solution specifies one or more routes for each vehicle, and each route has a start time t_{vj} , a sequence σ_{vj} of stops, and a quantity q_{vjk} to deliver at each stop.

In addition to the constraints mentioned before, some additional constraints must be satisfied for the solution to be feasible.

The cumulative quantity delivered to an LDC depends upon the routes that have stopped at the LDC. For an LDC m , Let the set $F_m(t)$ include the routes (a, b) such that $a \in V_0$, $m \in \sigma_{ab}$, and $t_{ab} + w_{abm} \leq t$.

$$I_m(t) = \sum_{(a,b) \in F_m(t)} q_{abm}$$

The quantity shipped from an LDC cannot exceed the amount delivered to the LDC.

$$\sum_{a \in V_m} \sum_{b: t_{ab} \leq t_{vj}} \sum_{k \in \sigma_{ab}} q_{abk} \leq I_m(t_{vj}) \quad m = 1, \dots, M; v \in V_m; j = 1, \dots, r_v$$

Each site must receive all needed medication from the corresponding location.

$$\sum_{v \in V_m} \sum_{j=1}^{r_v} q_{vjk} = (T_2 - T_1) L_k \quad m = 0, \dots, M; k \in D_m$$

Given a solution, we evaluate its minimum slack as follows. To do this, we must measure the slack of any route that includes one or more sites in D_0 , D_1 , ..., or D_M . For vehicles in V_0 (those operating from the depot), none, some, or all of the stops may be LDCs; stops that are not LDCs are sites in D_0 . For vehicles operating from LDC m , all of the stops are sites in D_m . If stop $k \in \sigma_{vj}$ is a dispensing site (not an LDC), then we can calculate Q_k as described above.

$$s_{vj} = \min_{k \in \sigma_{vj} \setminus L} \left\{ T_1 + Q_k / L_k - (t_{vj} + w_{vjk}) \right\}$$

If all of the stops in the route are LDCs (i.e., $\sigma_{vj} \setminus L = \emptyset$), then the slack is undefined.

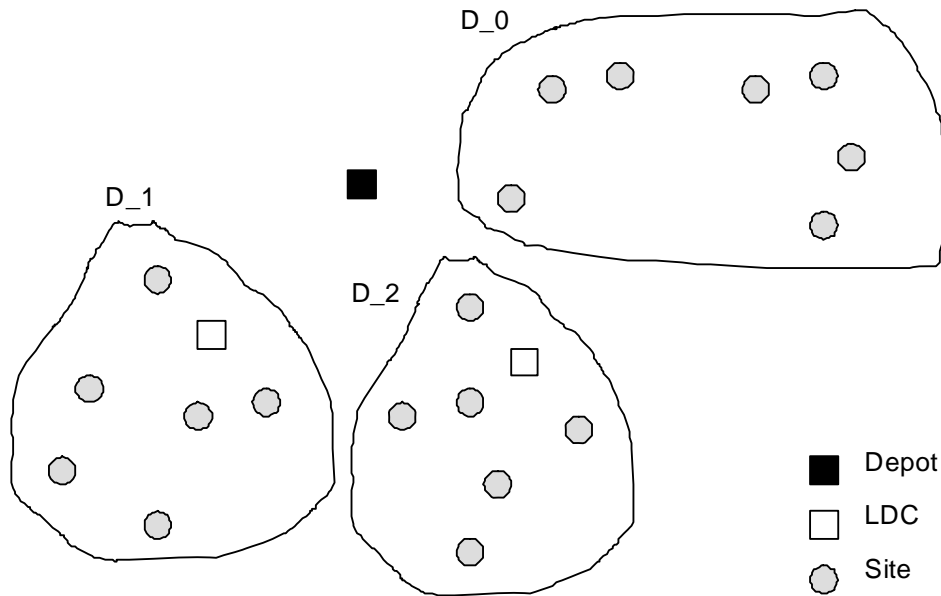


Figure 3. Depots serve the LDCs and the sites in D_0 .
Each LDC serves the sites in its jurisdiction.

5. Solution Approach

Our two-stage solution approach separates the Depot-to-POD problem into two subproblems: (1) the “routing problem” assigns PODs (sites) to vehicles and creates routes for each vehicle, and (2) the “scheduling problem” determines when the vehicles should start these routes and how much material should be delivered to each site on each trip.

In this approach, each available vehicle will have exactly one route. A vehicle may perform that route more than once with different delivery quantities each time.

5.1. The Routing Problem

The routing problem is a capacitated vehicle routing problem (CVRP), which has been studied extensively (see, for example, Toth and Vigo, 1998). Each site has a quantity that needs to be delivered, and each vehicle has a capacity that limits how much it can take from the depot on its route.

The objective of our CVRP is to find a minimum cost solution so that the duration of every route is not greater than a given route duration bound. The cost of a solution depends upon the total travel time plus penalties for routes that exceed the route duration bound.

As discussed below, we will change the delivery quantities and the route duration bound in order to generate different sets of routes.

5.2. The Scheduling Problem

Given a set of routes, the scheduling problem determines how many times each vehicle should perform its route, when it should leave the depot, and how much should be delivered to each site on its route. The objective is to maximize the minimum slack of a solution.

To solve this problem, we developed a variety of heuristic techniques to construct a feasible solution. Note, however, that these scheduling heuristics are much different from dispatching, which maintains a queue of vehicle waiting to start their routes, uses simple policies to prioritize the vehicles in the queue, and starts the highest priority vehicle as soon as sufficient material is available at the depot. Previous studies have shown that such dispatching is highly myopic and cannot generate high-quality solutions because it ignores the pattern of deliveries to the depot.

Determining route start times depends upon the duration of its route and the time between deliveries to the depot (the “waves”). Typically, each wave should be followed by vehicles leaving the depot to take the newly-arrived material from the depot to the sites. However, if the route duration is long, the vehicle may not be finished with its route when the next wave arrives at the depot.

The general outline of the scheduling heuristic is to partition the vehicles into distinct subsets and then to determine the waves after which each subset of vehicles should perform their routes. (For example, some vehicles will perform their routes after every wave.) Also, in general, the delivery quantities to the sites are proportional to the demand at the sites. That is, if one site has a demand that is two times another site’s demand, the quantity delivered to the first

site will be two times the quantity delivered to the second site. Typically, the total quantity available in the wave will be delivered by vehicles immediately following that wave.

5.3. Delivery Volume Improvement

After some experimentation with these heuristics, we discovered that carefully manipulating the delivery quantities can increase minimum slack significantly.

For example, let us revise the example considered earlier as follows. Now, there are five waves, each three hours apart. The first wave delivers only 30,000 regimens to the depot. The other four waves each deliver 82,500 regimens to the depot. Table 4 shows the delivery quantities and slack of a simple schedule in which the vehicle performs its route after every wave, and the delivery quantities are proportional to the site demands. Note that the minimum slack occurs on route 2 at site 2.

Adjusting the delivery quantities in the first route modifies the slack at each site in route 2. By delivering more to site 2 (and less to site 1), we increase the slack at site 2 (and decrease the slack at site 1). The best we can do is to make them equal. Table 5 shows the modified delivery quantities and slack.

The delivery volume improvement algorithm uses the following variables:

- Let T_1 be the start of dispensing.
- Let K be the target slack for wave N .
- Let C_j be the time that POD j will receive a delivery in wave N .
- Let Q_1, \dots, Q_{N-1} be the amount delivered in waves 1 to $N-1$. Note that Q_1, \dots, Q_{N-2} are known

Finding Q_{N-1} is the goal. Let L_j be the dispensing rate for POD j . We determine Q_{N-1} as follows:

$$T_1 + \frac{Q_1 + \dots + Q_{N-2} + Q_{N-1}}{L_j} - C_j = K$$

$$\text{Then } Q_{N-1} = (K + C_j - T_1)L_j - (Q_1 + \dots + Q_{N-2}) \text{ for POD } j.$$

The best solution will occur by picking K as large as possible so that inventory and vehicle capacity constraints are satisfied.

Table 4. Delivery quantities and slack before delivery volume improvement.

Route j	Site 1		Site 2	
	$q_{1,j1}$	Slack for site	$q_{1,j2}$	Slack for site
1	20,000	1400	10,000	1360
2	55,000	1340	27,500	1300
3	55,000	1490	27,500	1450
4	55,000	1640	27,500	1600
5	55,000	1790	27,500	1750

Table 5. Delivery quantities and slack after delivery volume improvement.

Route j	Site 1		Site 2	
	$q_{1,j1}$	Slack for site	$q_{1,j2}$	Slack for site
1	17,778	1400	12,222	1360
2	55,555	1326.7	26,945	1326.7
3	55,555	1480.0	26,945	1470.0
4	55,556	1633.3	26,944	1613.3
5	55,556	1786.7	26,944	1756.7

6. Results

We considered a realistic scenario with three counties in the state of Maryland (here we will call these counties A, B, and C). Medication arrives at the state RSS (depot) in seven shipments, two hours apart, which we call “waves,” with roughly the same amount of medication in each wave. County B plans to use an LDC, and the other two do not. A total of 189 PODs require medication. In the first scenario, the state vehicles distribute medication to the PODs in all three counties. In the second scenario, the state vehicles distribute medication to the PODs in Counties A and C and to the LDC in County B. County B uses its own vehicles to distribute medication from its LDC to its PODs.

To solve the routing problem, we used the TourSolver route optimization software (C2Logix, 2008). TourSolver solves capacitated vehicle routing problems. We created three sets of routes by varying the quantity delivered to each POD. In the first set, the route duration

limit was 2 hours, and the delivery quantity to each POD was a fraction of the largest wave (these we called the “single-wave routes”). (The fraction used equals the ratio of that POD’s L_i to the sum of all L_i .) In the second set, the route duration limit was 4 hours, and the delivery quantity to each POD was twice this amount (these we called the “double-wave routes”). In the third set, the route duration limit was 6 hours, and the delivery quantity to each POD was $L_i(T_2 - T_1)$, the entire amount that the POD requires (these we called the “all-at-once routes”).

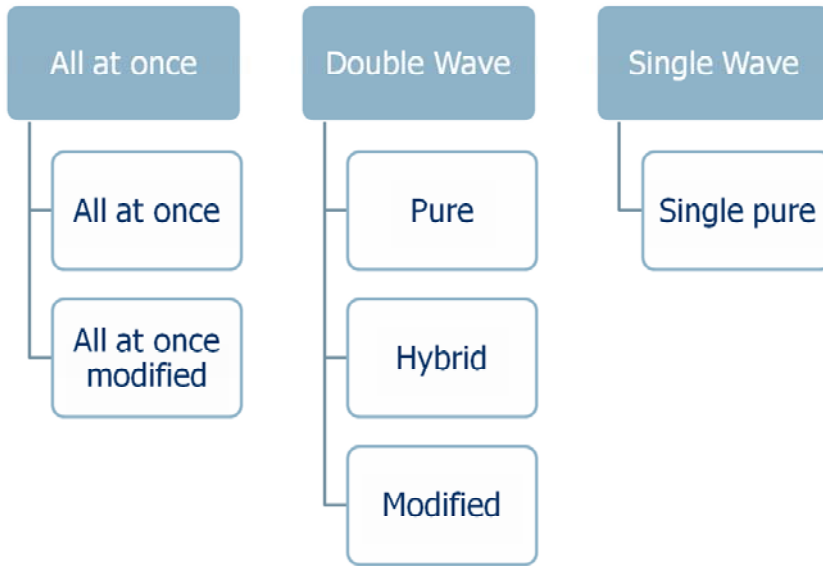


Figure 1. Routing and Scheduling Solutions.

We then solved the scheduling problem using the three sets of routes to generate six solutions (as shown in Figure 1). We used one vehicle for each route. (1) The *single pure* solution: Using the single-wave routes, each vehicle left the depot as soon as it could after each wave. The delivery quantity to each POD was a fraction of that wave. (2) The *double pure* solution: Using the double-wave routes, each vehicle left the depot after the first, third, fifth, and seventh waves. The first delivery quantity to each POD was a fraction of the first wave. Each remaining delivery quantity to a POD was a fraction of the last two waves. (3) The *double modified* solution: Using the double-wave routes, each vehicle left the depot after the first wave. Vehicles with shorter duration routes left the depot after the second, fourth, and sixth waves. Vehicles with longer duration routes left the depot after the first, third, fifth, and seventh waves. In all cases, the delivery quantities were the same as in Solution 2. (4) The *double hybrid* solution: The double-wave routes were split into two subsets: one with shorter duration routes (completed in less than 2 hours), and one with longer duration routes. Vehicles following longer routes left the depot after the first, third, fifth, and seventh waves. The first delivery quantity to

each POD was a fraction of the first wave. Each remaining delivery quantity to these PODs was one-third of the remaining amount needed. Vehicles following shorter routes left the depot after every wave after the first. The delivery quantity to each POD each time was one-sixth of the entire amount that the POD requires. (5) The *all-at-once* solution: Using the all-at-once routes, each vehicle left the depot after the seventh wave. The delivery quantity to each POD was the entire amount that the POD requires. (6) The *all-at-once modified* solution: The all-at-once routes were sorted into seven subsets so that the longest duration routes were in the first subset, and the shortest duration routes were in the seventh subset. One subset of vehicles left the depot after each wave (the longest duration routes left after the first wave, and the shortest duration routes left after the last wave). The number of vehicles in each subset was limited by the number of regimens in each wave (plus any regimens remaining from the previous wave but not distributed by the previous vehicles) so that each vehicle left with all of the regimens it needed to deliver. The delivery quantity to each POD was the entire amount that the POD requires.

Solutions using the all-at-once routes (Solutions 5 and 6) were very poor; some PODs did not receive medication before the designated start time because the last wave arrived so late (thus, the minimum slack was negative). The results showed that both Solution 2 and Solution 3 had the largest minimum slack (509 minutes), while Solutions 1 and 4 had a minimum slack between 350 and 400 minutes.

To improve the slack of these solutions, we adjusted the delivery quantities so that PODs that were visited later in a route received more material in the first delivery. This increased the time at which the POD would run out. The delivery volume improvement technique described in Section 5.3 set the delivery quantities of one “wave” so that the slacks at every POD during the next wave were the same. Using this technique dramatically increased the minimum slack of Solution 1 to 552 minutes. The minimum slack of Solutions 2, 3, and 4 increased to 540 minutes. This showed that the relative quality of the solutions changed after delivery volume improvement. However, the potential improvement of delivery volume improvement was limited because the minimum slack often occurred on the first delivery to a POD with the latest delivery time, which was determined by the routes generated by TourSolver.

We then repeated the above analysis on the Depot-to-LDC-to-POD problem, using the same types of routes and schedules. To do this, we had to create two different sets of routes (one for each “level”): one set that routes vehicles from the depot to the County B LDC and the PODs

in Counties A and C, and a second set that routes vehicles from the County B LDC to the PODs in County B. A solution to the complete problem combines solutions to both “levels” of the problem.

When using the LDC, the best solution delivered materials from the depot using a single pure schedule and then delivered materials from the LDC to County B’s PODs using the double hybrid schedule. Overall, this solution had a minimum slack of 438 minutes. After delivery volume improvement, the best solution delivered materials from the depot using a single pure schedule and then delivered materials from the LDC to County B’s PODs using a single pure schedule. Overall, this solution had a minimum slack of 469 minutes. Note that this combination had a minimum slack of 315 minutes before delivery volume improvement.

As discussed above, without the LDC, the best solutions used the double pure and double modified schedules, which had a minimum slack of 509 minutes. After delivery volume improvement, the minimum slack of both schedules increased to 540 minutes. However, the minimum slack of the single pure schedule increased from 360 to 552 minutes.

7. Summary and Conclusions

This paper introduced the medication distribution problem, an important part of planning the response to a bioterrorism attack, and presented a two-stage routing and scheduling approach for constructing solutions. Because a robust plan is desirable, our objective was to maximize the minimum slack of the solution. We also developed a delivery volume improvement technique for improving the slack of a solution. To demonstrate the approach, we applied it to a realistic scenario that included sites from three counties in the state of Maryland. In addition, we considered how using an LDC would affect the slack of the medication distribution plan.

The results show that, even if the routes are given, determining when vehicles should deliver and how much they deliver significantly affects the slack. Delivery volume improvement increased slack, dramatically in some cases. The extra hours of slack could be critical in an emergency. They show that a careful analysis of the scenario, considering solutions both with LDCs and without LDCs, is necessary to construct an effective medication distribution plan.

Future work is needed to automate the routing and scheduling approach to enable a decision support tool for public health emergency preparedness planners, to develop optimization techniques for finding even better solutions, and to test the approach on other scenarios.

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