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The Medication Distribution Problem

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Table of Contents

Introduction 3

Problem Formulation with no LDCs 4

Problem Formulation with LDCs 6

Heuristics 7

Solving Heuristics 9

LDC Considerations 9

Heuristics Summary 10

Delivery Volume Improvement 11

Problem Formulation: Delivery Volume Improvement 11

Delivery Volume Improvement Summary 12

Comparing Heuristics to Delivery Volume Improvement 13

Conclusions 14

Appendix 15

Appendix A: Sample Heuristics Spreadsheet (No LDC, Single Wave) 15

Appendix B: Sample Volume Improvement Spreadsheet (No LDC, Single Wave) 16

Appendix C: Minimum Slacks of Heuristics vs. Volume Improvement 17

The Medication Distribution Problem

Introduction

In a case of a bioterrorism attack, public health officials need to be prepared so the country, state, and counties are able to respond to any threat. The medication distribution problem specifically focuses on the state and local government levels of medication distribution to the points of dispensing (PODs). If health officials decide that mass dispensing of medication is needed, the PODs will be prepared as locations to administer the medication to the public. The state will then request medication from the federal government to be delivered to a state depot, where the medications will be stored until it is delivered to the PODs. The federal government will make multiple shipments, or waves, of medication to the depot. Likewise multiple shipments of medication will be made from the depot to the PODs.

The health officials have two strategic alternatives in order to ensure timely deliveries are made to the PODs.

1. *Using an LDC.* A county may choose to operate a local distribution center (LDC) which receives medications from the depot. The LDC then distributes the materials to the PODs within the LDC's jurisdiction.
2. *Not using an LDC.* The second strategic alternative for the counties is to forgo having an LDC so that the medication will be delivered from the depot directly to the PODs.

Variable aspects of the problem include the routes used by the trucks to deliver the medication, the travel time of the trucks (travel time to the PODs and time to finish a route), time to load and unload the trucks, and the demand of medication per each POD. The best solution is determined by maximizing the probability that the PODs open on-time and do not run out of medication during operation.

Assuming truck routes have already been determined, this paper addresses the scheduling aspect of mass medication distribution. The focus will be optimizing the schedules—deciding when a POD will receive a delivery and the amount of medication sent to the PODs during each delivery.

Problem Formulation with no LDCs

This paper addresses the single-product, deterministic problem. In order to solve this problem a few key assumptions are made:

- Inventory is treated as a continuous variable, but the number of pallets must remain an integer.
- Medication is measured in regimens and each person will receive one regimen, which may be a bottle or a specific number of pills.
- All PODs have the same hours of operation.
- Loading and unloading times are independent of the quantity.
- Resource constraints such as the loading docks at the depot, the available drivers, and the number of available pallets are ignored for the time being.
- The materials will be delivered to the depot in a number of waves.
- The no LDC solution documented in this paper incorporates three counties A, B, and C.

Time t=0 corresponds to the time when a depot receives its first wave of medications. PODs will begin dispensing medication at time $t=T_1$ and continue to operate until time $t=T_2$. In a real case scenario T_1 typically starts 12-36 hours after the first wave of materials arrives at the depot.

There are n PODs (k = 1… n) and each POD dispenses regimens at a rate of L_k per time unit, usually hours. There is also a depot that has a continuous supply of medication. I(t) is the cumulative amount of medication delivered to the depot at time t. I(t) is a discontinuous, non-decreasing function due to wave of deliveries that are made there.

A feasible solution designates a truck to a particular route. Let j denote the *j*-th route for each truck v, so that each route has a start time t_{vj} at which the vehicle begins loading at the depot, a sequence σ_{vj} of PODs, and a quantity q_{vjk} to deliver at each POD $k \in \sigma_{vj}$. Please note that the routes used in solving this problem were predetermined using Tour Solver.

The goal of the problem is to find a feasible solution with the largest amount of minimum slack. To do this, we must measure the slack of a route. Let the sequence sigma $\sigma_{vj} = \left\{i_1, \ldots, i_{m(vj)}\right\}$ be the *j*-th route for vehicle *v*, where *m*(*vj*) is the number of PODs on the route. Let w_{vjk} be the duration between the start of the route and the time that the delivery at POD *k* is complete.

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

Let y_{vj} be the total duration of the route. The quantity q_{vjk} delivered to POD *k* on this route uses p_{vjk}. For each POD $k \in \sigma_{vj}$, let Q_k be the total quantity already delivered to that POD on previous routes.

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

$$y_{vj} = p_0 + c_{0i_1} + p_{i_1} + c_{i_1 i_2} + \cdots + p_{i_{m(vj)}} + c_{i_{m(vj)}0}$$

Then, the expected time at which that POD runs out of medication is $T_1 + Q_k / L_k$.

Let s_{vj} be the slack of this route. That is, if the start of the route were delayed more than s_{vj} time units, then some POD $k \in \sigma_{vj}$ would run out of medication. The minimum slack *s* of a solution is the minimum slack over all trucks, routes, and PODs.

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

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

Certain constraints must be satisfied for the solution to be feasible. It is assumed that all routes should have positive slack. The quantity shipped from the depot cannot exceed the amount delivered to the depot.

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

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

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

All quantities are non-negative, and pallets have a fixed capacity, so $0 \le q_{vjk} \le P p_{vjk}$ for all $v = 1,\ldots,V$; $j = 1,\ldots,r_v$; 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 $\sum_{k \in \sigma_{vj}} p_{vjk} \le C_v$ for all $v = 1,\dots,V$; and $j = 1,\dots,r_v$. All route start times are non-negative, so $t_{vj} \ge 0$ for all $v = 1,\dots,V$; and $j = 1,\dots,r_v$. Finally each POD must receive all needed medication.

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

Problem Formulation with LDCs

Formulating the problem with an LDC is in many ways similar to the previously formulated problem with no LDC with a few additional assumptions:

- It is assumed that the locations of all LDCs and the division of PODs into jurisdictions are given.
- There are $M \ge 1$ jurisdictions that will operate LDCs. Let D_m be the set of PODs in jurisdiction *m* that will be served by LDC *m*. D_0 is the set of PODs that will continue to be served by the state depot. Let L be the set of *M* LDCs.
- 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 PODs in D_m.
- The LDC solution documented in this paper has only County B with an LDC out of all three Counties (A, B, and C).

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.

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.

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 PODs 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 PODs in D_0. For vehicles operating from LDC *m*, all of the stops are PODs in D_m. If stop $k \in \sigma_{vj}$ is a dispensing POD (not an LDC), then we can calculate Q_k as described above.

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

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.

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

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

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

Heuristics

The first step in solving the clinic dispensing problem was to develop sturdy heuristics based on the single wave, double wave, and all at once routes generated by Tour Solver. The purpose of these heuristics was not to optimize the solution per se, but offer a simpler method compared to optimization to obtain a reasonable solution. For instance, the heuristics assumed that if a delivery is made to two PODs with the same demand, then both of these PODs will receive the same amount of medications for that wave regardless of route length. A total of six heuristics were developed based off of the Tour Solver routes.

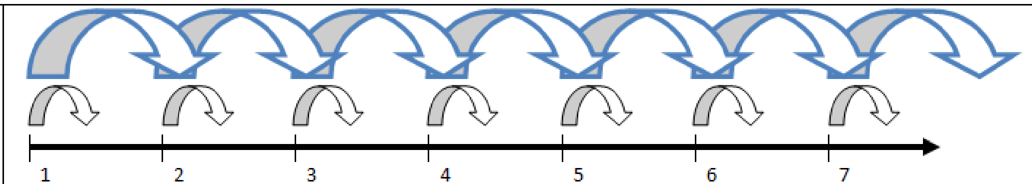
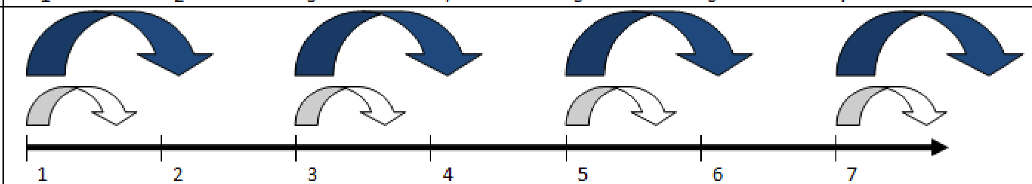
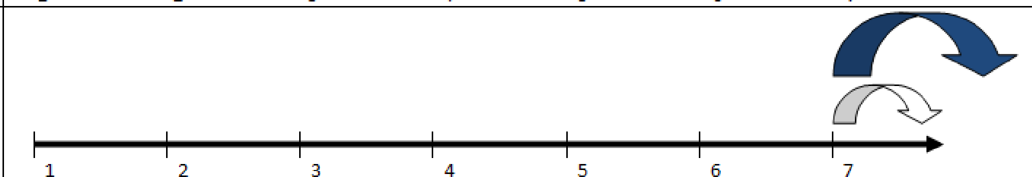
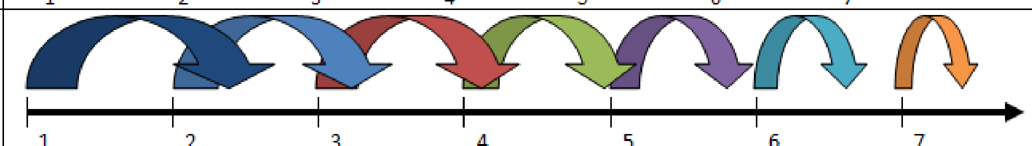
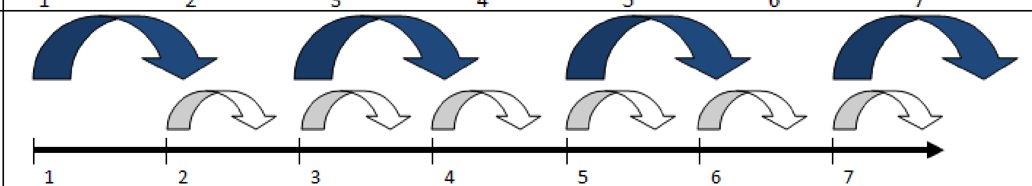
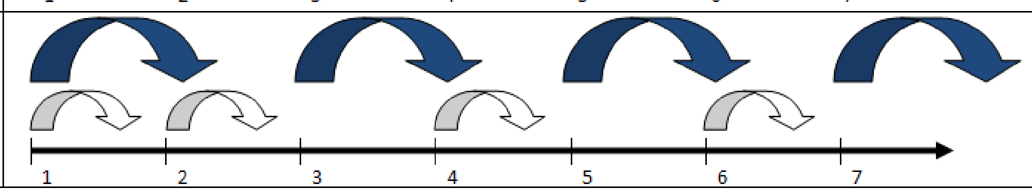
Pure Single	
Pure Double	
All at Once	
Modified all at Once	
Hybrid Double	
Modified Double	

Table 1: Heuristics Illustrations

1. *Pure single wave*. Table 1 shows the deliveries being made from the depot over time. The numbers represent each wave and the corresponding time these waves arrive to the depot. The first heuristic ensures that all routes are utilized for all the waves so that all the PODs receive shipments for each wave. The white arrows represent the shorter routes which make it back in to the depot in time to receive the next wave of materials to deliver. The blue arrows represent the longer routes which make it back to the depot after the next wave of materials has arrived. As a result these routes do not start on time at the beginning of each wave.
2. *Pure double wave*. Deliveries are made to the PODs every other wave. Essentially two wave's worth of materials is made to the depot before shipment out to the PODs with exception of the first wave.

3. *All at once*. A single delivery is made to the PODs after all the medication is received at the depot. This single delivery satisfies the POD's entire demand of regimens. This heuristic is clearly not the optimal, but is used nonetheless to find the worst case scenario of the problem.
4. *Modified all at once.* Similar to the all at once delivery method, the modified all at once delivery method put priority on routes that take more time to complete. As a result the PODs in the longer routes get their entire demand satisfied first. The maximum number of regimens will be delivered while ensuring routes are not split among multiple waves.
5. *Double hybrid.* In the double hybrid wave delivery method, only PODs in the routes that will not start on time from the second wave onward will be given shipments for the first wave. Afterwards these PODs will receive shipments from the depot every other wave similar to a double wave. The PODs in the shorter routes will receive shipments from the depot every wave excluding the first wave.
6. *Double modified.* Similar to the hybrid double wave, the double modified wave separates the routes into long and short routes which can make it back to the POD in time. For the first wave all PODs receive materials. However since the shorter routes make it back to the depot for the second wave, the PODs in these routes receive materials again in the second wave. Afterward the PODs in the shorter routes receive materials every other wave. The PODs in the longer routes receive a shipment from the depot every other wave starting from the first wave.

Solving Heuristics

Using the routes generated by Tour Solver for each of the county's data, the solutions for the slack were solved using Microsoft Excel. The slack was solved for all combinations of strategic alternatives (LDC, no LDC), heuristics, and waves. For each combination of strategic alternatives and heuristics, the wave with the smallest slack was the overall solution for that combination. Samples of the work done in Excel can be found in Appendix A and B.

LDC Considerations

Since using an LDC required the LDC routes (determining when the LDC received the materials) and the County B routes (determining when County B PODs received the materials), the feasible combinations were only used to determine the slack. For instance the all at once, both pure and modified, were not considered because the slacks would be negative. Also when the LDC received its deliveries through any type of double wave, the subsequent deliveries made at the county level would be pure double waves so the materials are delivered as quickly to the PODs as possible. Finally the time it takes for the materials to arrive at the LDC needs to be taken into consideration when calculating the slack for County B. The considered LDC/County B combinations can be found in the first column of Table 2.

Heuristics Summary

LDC	Slack (min)
LDC Modified Double/ County B Pure Double	317
LDC Double Pure/ County B Pure Double	429
LDC Pure Single/ County B Hybrid Double	438
LDC Pure Single/ County B Modified Double	424
LDC Pure Single/ County B Pure Double	424
LDC Pure Single/ County B Pure Single	316

No LDC	Slack (min)
Modified all at once	-36
All at once	-298
Pure single	360
Pure double	510
Hybrid double	387
Modified double	510

Table 2: Minimum Heuristics Slacks

When using an LDC, the best method was to deliver the materials to the LDC using a single wave method and then from the LDC the materials would be delivered to County B's PODs using the hybrid double wave method. Since all the routes had only one POD, the single delivery method was optimal for deliveries to the LDC. Then at the County B level the hybrid modified method accounted for the fact that the majority of the routes took longer than the allotted two hours to get back to the depot.

When a county had no LDC, the all at once and the all at once modified were the worst delivery methods as both of these heuristics resulted in negative slack. The best method was the pure double and the modified double delivery method which resulted in the largest minimum slack. Both of these methods resulted in the same minimum slack because there is no difference between the pure double and modified double wave when the modified double wave have routes that start on time for each wave.

The results from the heuristics also showed that the slack for the first wave were similar when the same routes were used. This meant that all the heuristics using the double wave routes all had the same slack for the first wave because no prior deliveries had been made. As a result the worst slack corresponds with the longest route.

It was also found that the pure single delivery method was the best for shorter routes while the double strategies worked best for longer routes. Ideally if all trucks return on time to the depot to pick up the next wave of medication then the single route ensures that every POD receives materials for every wave. However if the trucks return after the start of the next wave, then the PODs will be delayed in receiving deliveries from the truck. Since the truck follows the same route for every wave, the affected PODs will be further delayed in receiving their required medication at the end of each wave. In this case the longer routes are better suited using double strategies which ensure that no delay occurs.

Overall the best alternative based on the heuristics is to forgo using an LDC and directly deliver regimens from the depot to the PODs using either the pure or modified double wave delivery methods. Using the best case scenario for both strategic alternatives shows that using no LDC results in a 67 minute larger slack.

Delivery Volume Improvement

Solving for the slack using the heuristics showed that the best solution is only as good as the worst slack. This concept is the basis for the delivery volume improvement where a target slack is set for all the PODs in each wave. By setting a target slack and using the slack equation to solve for the quantity delivered, the optimal delivery amount can be found for each POD depending on the wave.

Problem Formulation: Delivery Volume Improvement

The delivery volume improvement 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 $Q_1, \ldots, Q_{N-1}$ be the amount delivered in waves 1 to N-1. Note that $Q_1, \ldots, Q_{N-2}$ are known

Finding Q_{N-1} is the goal. Let L_j be the dispensing rate for POD j. We want Q_{N-1} such that:

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

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

The best solution will occur by picking a k as large as possible so that inventory and vehicle capacity constraints are satisfied. From the equation, the amount of regimens delivered from the previous wave, Q_{N-1} affects the subsequent wave's slack, k.

Using the data from heuristics as guide, the best alternatives underwent the delivery volume improvement. A target slack was set for each wave/alternative combination in order to find the amount that needed to be delivered to the PODs for that wave.

Delivery Volume Improvement Summary

LDC	Slack (min)
LDC Modified Double/ County B Pure Double	459
LDC Double Pure/ County B Pure Double	459
LDC Pure Single/ County B Hybrid Double	454
LDC Pure Single/ County B Modified Double	454
LDC Pure Single/ County B Pure Double	454
LDC Pure Single/ County B Pure Single	469

No LDC	Slack (min)
Pure single	552
Pure double	540
Hybrid double	540
Modified double	540

Table 3: Minimum Delivery Volume Improvement Slacks

The results show that the minimum slacks for either strategic alternative are similar because the minimum slack occurred on the first wave. Little could be done to change the minimum slack since the routes were predetermined by Tour Solver. However the average minimum slacks excluding the first wave greatly increased from volume improvement.

When using the double wave methods, certain waves needed to have the same target slack. For example if a delivery is made at the end of wave 3, then the target slack of waves 2 and waves 3 needed to be the same. Since both waves receive the same amount of materials (total delivered from wave 1), setting the slacks equal to one another ensures that neither wave 2 nor wave 3 receives more materials than the other.

In all scenarios, each POD received different amounts of materials for the first wave. This attributed to when the truck arrives at the POD with a delivery. After the initial wave for the single wave methods, the quantities delivered to the PODs typically changed from wave to wave. However if two PODs have the same demand and both the POD's trucks returned to the depot or LDC before the start of the next wave, then amount delivered to these PODs for a single wave will be the same after the initial wave. Since all the trucks return in time when any type of double wave delivery method is used, the quantities delivered for a double wave stays the same for all PODs which share similar demands. This phenomenon occurs because after the first wave of deliveries, all the PODs have the same slack. In order to ensure that all PODs have the same slack for future waves, the same amount of medication will need to be delivered to the PODs for each wave.

When using the single wave method it was found that the PODs with the longer routes had their demand satisfied first. In many cases these PODs would receive their entire demand in just six waves instead of seven.

Overall the best method found using the delivery volume improvement showed once again using no LDC results in the largest slack. However instead of using a double wave method like the heuristics results indicate, the single wave method was the best.

Comparing Heuristics to Delivery Volume Improvement

Strategic Alternative	Heuristics Slack (min)	Delivery Volume Improvement Slack (min)	Difference
LDC	438	469	31
No LDC	510	552	42
LDC (no 1st wave)	510	691	181
No LDC (no 1st wave)	438	631	193

Table 4: Best Minimum Slacks

Finding the quantities to be delivered each wave using the delivery volume improvement method will result in greater slacks. Overall when all waves are considered the volume improvement method increases the slack by about 30-40 minutes when using the best case scenarios for heuristics and volume improvement. However this does not justify the extent to which volume improvement increases the slacks. When looking at the best case scenarios for heuristics and volume improvement the difference in slack is over 181 minutes, roughly three hours. A comparison of all the strategic alterative/delivery method can be found in Appendix C, Tables 5-8.

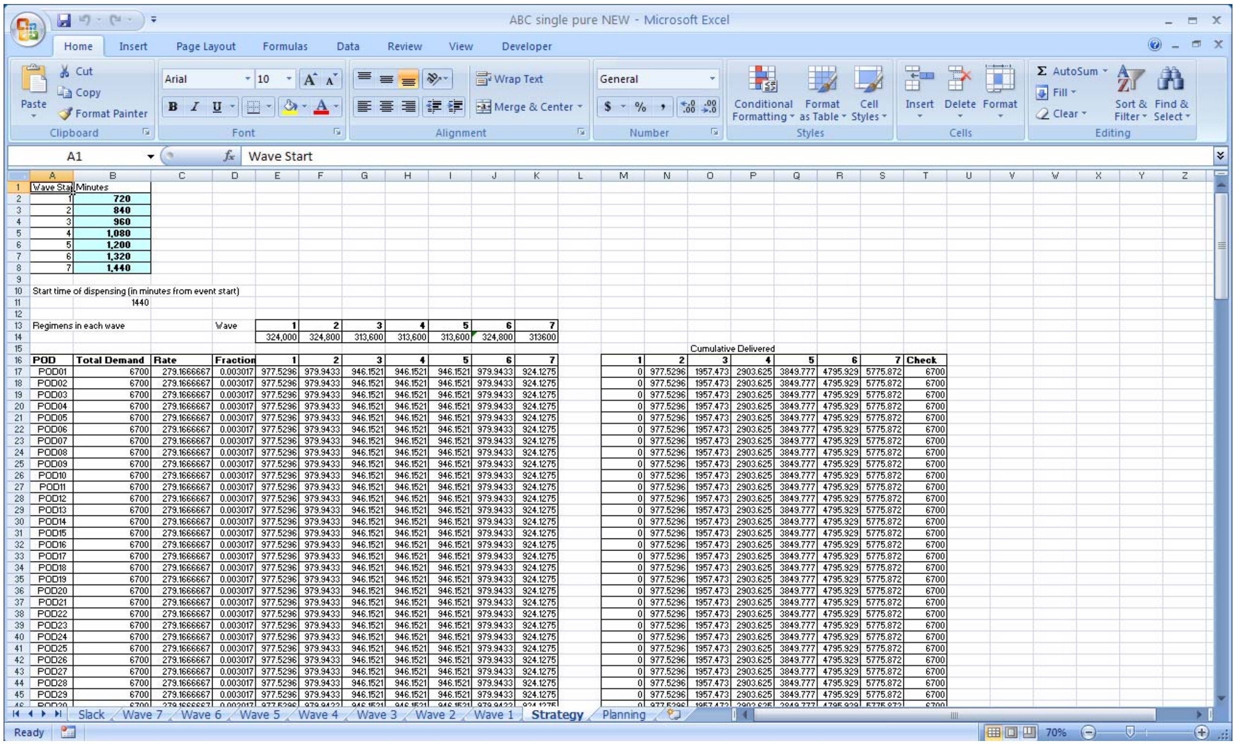
Conclusions

The analysis of different scheduling heuristics and delivery volume improvement techniques shows that, even if the routes are given, determining when vehicles should deliver and how much they deliver significantly affects the slack. Volume improvement resulted in greater slack and the difference from using heuristics ranged from 30 minutes to 5 hours. The overall best solution when using an LDC is to deliver the materials to the LDC using single wave deliveries and using single wave again at the County B level. When not using an LDC, the best slack occurs when any of the double wave delivery methods are used since the worst slack occurs during the first wave.

The best methods of delivery that health officials should consider would be to implement single waves. Using the single wave method allowed the volume to be improved according for all waves instead of every other wave like in a double wave scenario. In addition not implementing an LDC increased the slack for all scenarios. However in a real scenario other considerations need to be taken into consideration such as the number of docks available at one time and the increase in truck queue time if all materials at picked up at the depot. Consequently the state may be forced to employ LDCs in order to ensure the demand is met in a timely manner at the PODs. However if the state depot is located in a central location in the state, this may greatly increase the slack when using an LDC.

Appendix

Appendix A: Sample Heuristics Spreadsheet (No LDC, Single Wave)



Wave Start	Minutes
1	720
2	840
3	960
4	1,080
5	1,200
6	1,320
7	1,440

Start time of dispensing (in minutes from event start)
1440

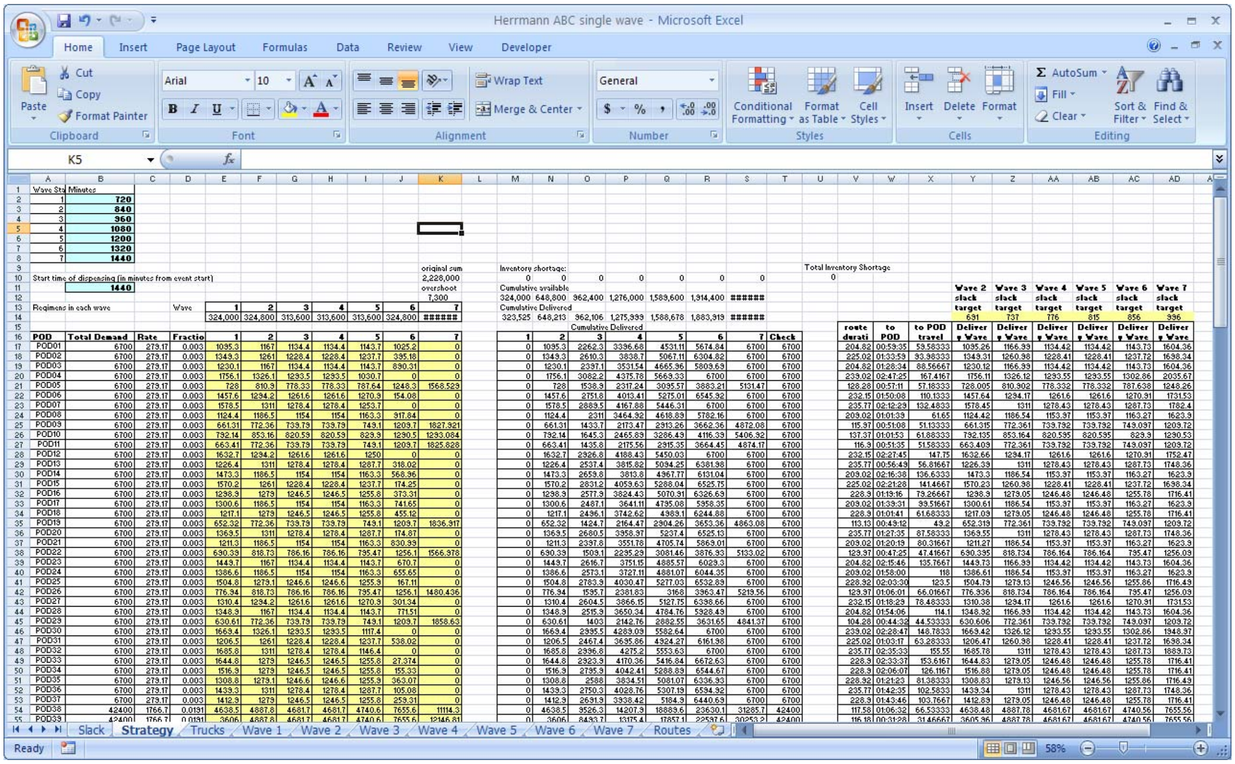
Regimens in each wave							
Wave	1	2	3	4	5	6	7
	324,000	324,800	313,600	313,600	313,600	324,800	313600

POD	Total Demand	Rate	Fraction	1	2	3	4	5	6	7
POD01	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD02	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD03	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD04	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD05	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD06	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD07	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD08	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD09	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD10	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD11	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD12	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD13	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD14	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD15	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD16	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD17	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD18	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD19	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD20	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD21	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD22	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD23	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD24	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD25	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD26	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD27	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD28	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275
POD29	6700	279.1666667	0.003017	977.5296	979.9433	946.1521	946.1521	946.1521	979.9433	924.1275

Cumulative Delivered

POD	1	2	3	4	5	6	7	Check
POD01	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD02	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD03	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD04	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD05	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD06	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD07	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD08	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD09	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD10	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD11	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD12	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD13	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD14	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD15	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD16	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD17	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD18	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD19	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD20	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD21	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD22	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD23	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD24	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD25	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD26	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD27	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD28	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700
POD29	0	977.5296	1957.473	2903.625	3849.777	4795.929	5775.872	6700

Appendix B: Sample Volume Improvement Spreadsheet (No LDC, Single Wave)



Appendix C: Minimum Slacks of Heuristics vs. Volume Improvement

	Heuristics	Optimization	Difference
LDC Modified Double/ County B Pure Double	317	459	142
LDC Double Pure/ County B Pure Double	428	459	31
LDC Pure Single/ County B Hybrid Double	437	454	12
LDC Pure Single/ County B Modified Double	423	454	26
LDC Pure Single/ County B Pure Double	423	454	26
LDC Pure Single/ County B Pure Single	315	469	148
Best Case	437	469	32

Table 5: Minimum Slack with LDC

	Heuristics	Optimization	Difference
Pure single	360	552	192
Pure double	509	540	31
Hybrid double	387	540	153
Modified double	509	540	31
Best case	509	552	43

Table 6: Minimum Slack with no LDC

	Heuristics	Optimization	Difference
LDC Modified Double/ County B Pure Double	317	578	261
LDC Double Pure/ County B Pure Double	428	541	113
LDC Pure Single/ County B Hybrid Double	437	532	90
LDC Pure Single/ County B Modified Double	425	541	113
LDC Pure Single/ County B Pure Double	425	533	105
LDC Pure Single/ County B Pure Single	316	631	310
Best Case	437	631	194

Table 7: Minimum Slack with LDC, Excluding 1st Wave

	Heuristics	Optimization	Difference
Pure single	360	691	331
Pure double	509	550	41
Hybrid double	387	606	219
Modified double	509	624	115

Best case	509	691	182

Table 8: Minimum Slack with no LDC, Excluding First Wave