Vaccination Drive in the state of Texas

TEAM DETAILS:

Ajinkya Zalkikar

Divya Parmar

Jagadishraj Sambasivam

Pratyush Kumar

Executive Summary

The objective of this project was to determine the performance index of the state of Texas for the vaccination drive during a period of month, such that all the counties in Texas perform at a similar rate. Thus, to solve this problem, a linear integer programming was developed based on the available data and the given set of constraints and this model was run through the AMPL software. The summary of the solution obtained has been summarized below.

Main objective of this project was to vaccinate as many people as possible from the vulnerable population equivalently for all the counties. Thus, the solution of our model concludes that only 3 priority groups for all the counties can be fully vaccinated (refer section 3). Also, it can be inferred that a total of 1,610,510 vaccines will be administered during the vaccination drive across all the counties.

Various what if scenarios were also considered and evaluated like what if maximizing the number of vaccines administered was the main objective of the project, then (refer section 4.2) the number of doses administered is 1,857,210, i.e., an increase of 246,700 doses compared with that of the primary solution. However, the performance index of Texas would be 0. Another scenario is maximizing the number of vaccines administered while also maintaining the same performance. The number of vaccines administered is 18,35,577 (refer section 4.3).

The other scenarios considered are minimizing the budget required to keep the performance index at 3 (refer section 4.5). The minimum budget required is 176,47,362.9 for achieving the worst performance of 3 for all the counties. Further another case is to maximize the number of warehouses to be setup keeping rest of the constraints same. The number of warehouses to be setup is 4 and the performance index is 0 (refer section 4.6).

The analysis has been carried out by factoring in various scenarios that can occur in the real world that might affect the vaccination of the vulnerable population. Based on the priority of the state the specific analysis can be considered and executed as per the requirements.

1. *Introduction*

The COVID-19 pandemic has changed our lives in ways that we could not have imagined. For the past 18 months, the pandemic has impacted everyone in some or another way. But the most affected are the vulnerable people including frontline workers, old age people, people having comorbidities, and so on. As the Delta and Omicron variants of COVID-19 puts more people at risk, there is a newfound desire to administer vaccines to as many people as possible on a priority basis.

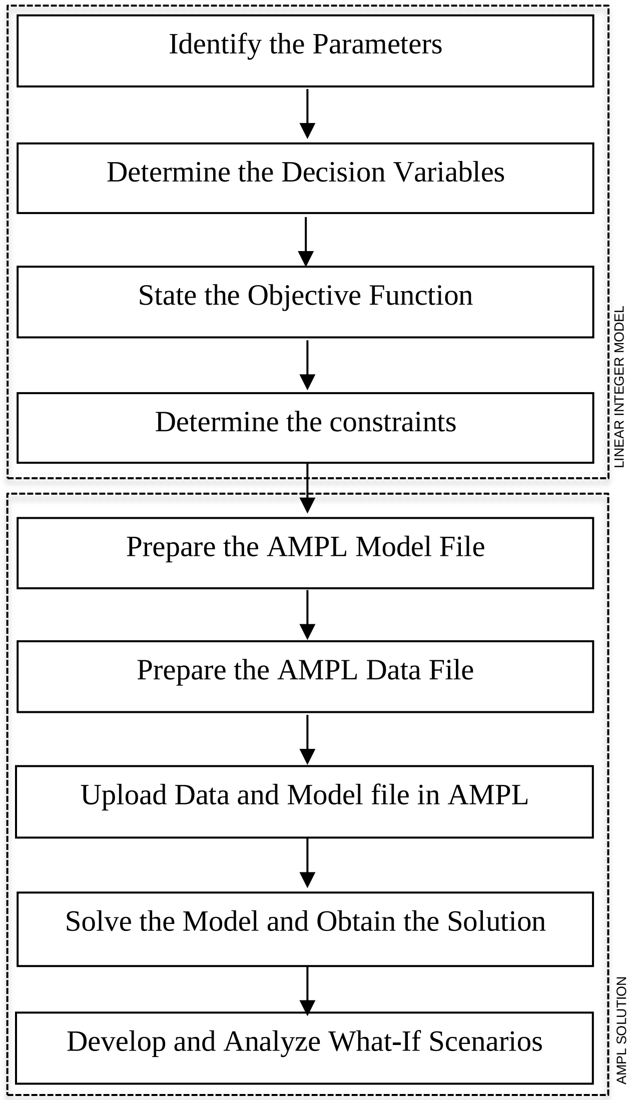
In order to address the problem, the governor of Texas has approached Texas A&M University's ISEN department's consulting firm with the aim of vaccinating as many people from the most vulnerable group as homogeneously as possible throughout Texas' counties. To achieve this goal, the main idea is to push the performance of the worst-performing county as high as possible. Eventually, this type of objective tends to promote that all counties will have approximately the same performance.

In order to design an efficient supply chain, there are three main components to consider: vaccine manufacturer, distribution centers/warehouses, and vaccine administration sites. The manufacturer has a certain number of vaccines that it can provide to the distribution centers at the end of each week and before the next week begins. From distribution centers, vaccines are transported to each vaccination center located in each county. Vaccines arrive at the vaccination center before each week starts and are available for administration at the beginning of each week.

An Integer linear optimization model is developed to design a vaccine distribution supply chain considering the various constraints associated with the identified parameters. In the following sections, the methodology of developing the model, the solution of the model and the what-if scenarios and its analyses are explained in detail.

2. Methodology

The purpose of this report is to formulate the integer linear optimization model and provide solutions for vaccine distribution. The objective of the problem is to vaccinate as many people from the most vulnerable groups as homogeneously as possible throughout all of Texas' counties.



Integer Linear Programming Model

The problem at hand is tackled using the linear integer programming approach to reach an optimal solution for warehouse setup, vaccine distribution and the efficient and cost-effective completion of the vaccination drive at the end of the given time period. Given below are the various aspects of the integer linear programming model (mentioned henceforth as IP model) that has been developed to achieve the stated purpose.

2.1 Parameters

Parameter	Description	Index	Notation
N	Number of Weeks over which the vaccination drive takes place.		N
J	Number of Vaccination Centers (Number of counties)		J
K	Number Of Candidate Locations for Warehouses (Distribution Centers)		K
M	Number of Priority Groups of population		M
B	Budget Limit		B
Cm	No. of Vaccines manufacturer can sell in each week(i)	for i in 0, … , N-1	Cm_i
Sv	Cost of vaccine per dose		Sv
St	Cost per vaccine to transport for each candidate from distribution center(k) to Vaccination center(j)	for k in 1, ... , K for j in 1, … , J	St_{jk}
Cw	Storage Capacity for each Distribution Center(k)	for k in 1, … , K	Cw_k
Sc	Set-up Cost for each Distribution Center(k)	for k in 1, … , K	Sc_k
Cv	Storage Capacity of Vaccination Center(j)	for j in 1, … , J	Cv_j
Lv	No. of Vaccines each Vaccination center(j) can administer	for j in 1, … , J	Lv_j
Sa	Storage fee per dose stored at the end of each week for each vaccination center(j)	for j in 1, … , J	Sa_j
Q	Population of each priority group(m) at each Vaccination center(j)	for m in 1, … , M for j in 1, … , J	Q_{mj}

Table 1. Parameters, description, and indices

2.2 Decision Variables

Decision Variable	Description	Index	Notation
X1	Number of vaccines(given by X1) bought from each of the manufacturer (given by k) at the end of each week(given by i).	for k in 1, … , K for i in 0, …, N-1	$X1_{ki}$
X2	Number of vaccines(given by X2) transported to each vaccination center (given by j) from each warehouse (given by k) at the start of each week (given by i).	for i in 1, … , N for k in 1, … , K for j in 1, … , J	$X2_{ikj}$
X3	Number of vaccines (given by X3) administered to population of each group (given by m) in each county (given by j) each week (given by i).	for j in 1, … , J for i in 1, … , N for m in 1, … , M	$X3_{jim}$
Y	Binary variable that determines if each of the warehouses (given by k) is setup or not.	for k in 1, … , K	Y_k
Z	Binary variable that determines if each population group (given by m) in each county (given by j) is vaccinated or not.	for j in 1, … , J for m in 1, … , M	Z_{mj}
I1	Inventory (given by I1) of each warehouse (given by k) at the end of each week (given by i)	for k in 1, … , K for i in 0, … , N	$I1_{ki}$
I2	Inventory (given by I2) of each county (given by j) at the end of week (given by i)	for j in 1, … , J for i in 1, … , N	$I2_{ji}$
P	The vaccination performance(given by P) of each county(given by j).	for j in 1, … , J	P_j
WP	The variable that gives the vaccination performance index of the state.		WP

Table 2. Decision variables, description, and indices

2.3 Objective Function

Maximize the vaccination performance index of Texas

$$Max\ WP$$

The objective function determines the maximum vaccination performance index of the state of Texas that can be achieved subject to the given cost, capacity, and administrative constraints. The WP can range from 0 to 7, where 0 indicates that there exists at least one county where none of the priority group is fully vaccinated, while 7 indicates that all the priority groups in all the counties have been fully vaccinated.

2.4 Constraints

2.4.1 Performance of the worst-performing VC

$$WP \leq P_j$$

for j = 1, …, J

The vaccination performance index of Texas (given by WP) is not allowed to exceed the performance of the worst performing county (given by P_j). Thus, if $P_{16} = 3$, for county 16 , while for all other counties, the value of P_j is greater than 3, the variable WP will not exceed 3.

2.4.2 Performance of the county

$$P_j = \sum_{m=1}^{M} Z_{mj}$$

For j = 1, … , J

The vaccination performance of county (given by P_j) will be the number of priority groups the county has been able to fully vaccinate. Thus, if county 3 has fully vaccinated 4 priority groups, P_4 will be set to 4.

2.4.3 Priority Group Requirement I

$$\sum_{i=1}^{N} X3_{jim} \geq Q_{mj} * Z_{mj}$$

For m = 1, … , M & for j = 1, … , J

If a priority group(m) is fully vaccinated in a given county(j) (which means Z_{mj}=1) , then the total number of vaccines administered in the county(j) over N weeks to the given group (m) must be greater than the population of that priority group (given by Q_{mj}). Thus, if group 3 in county 6 is fully vaccinated, then Z_{36} =1, which means that $\sum_{i=1}^{N} X3_{6i3} \geq Q_{36}$.

2.4.4 Priority Group Requirement II

$$\sum_{i=1}^{N} X3_{jim} \leq Q_{mj} * Z_{(m-1)j}$$

for m = 2, … , M & for j = 1, … , J

If priority group of higher priority (m-1) is not fully vaccinated, then total vaccines administered to next priority group(m) should be zero. Thus, if group 2 is not fully vaccinated in county 4, then the total vaccines administered to group 3 in county 4 should be zero.

2.4.5 Priority Group Requirement III

$$\sum_{i=1}^{N} X3_{ji1} \leq Q_{1j}$$

for m=1 & for j = 1, … ,J

This imposes an upper bound on the vaccines administered to the population of priority group 1 for each of the counties over the period of vaccination drive. Thus, total vaccines administered to group 1 of a given county j will not exceed the population of group 1 in that county.

2.4.5 Budget Requirement

$$B \geq \sum_{i=1}^{N}\sum_{k=1}^{K} Sv * X1_{ik} + \sum_{k=1}^{K} Y_k * Sc_k + \sum_{i=1}^{N}\sum_{j=1}^{J}\sum_{k=1}^{K} X2_{ijk} * St_{jk} + \sum_{i=1}^{N}\sum_{j=1}^{J} I2_{ij} * Sa_j$$

The administration has a fixed budget to administer vaccines during the period of the entire vaccination drive. Thus, the above constraint considers the storage costs of vaccines in vaccination centers, distribution centers, as well the transportation costs from distribution centers to the counties. Also, how many distribution centers/warehouses should be set up because each warehouse incurred a fixed setup cost is also determined.

2.4.6 County Inventory Constraint I

$$I2_{j1} = \sum_{k=1}^{K} X2_{1kj} - \sum_{m=1}^{M} X3_{j1m}$$

for j = 1, … , J & for i = 1

The inventory in county j at end of week 1 is given by the difference between vaccines transported to the county j at the beginning of week 1 and the total vaccines administered to the M population groups in week 1.

2.4.7 County Inventory Constraint II

$$I2_{ji} = I2_{j(i-1)} + \sum_{k=1}^{K} X2_{ikj} - \sum_{m=1}^{M} X3_{jim}$$

for j = 1, … , J & for i = 2, … , N

The inventory in county j at end of week i is given by the difference between vaccines transported to the county j at the beginning of week i and the total vaccines administered to the M population groups in week i. This difference and the inventory in county j at the end of previous week (i-1) together form the inventory at the end of this week.

2.4.8 Capacity of Vaccination Center

$$\sum_{k=1}^{K} X2_{1kj} \leq Cv_j$$

for j = 1, … , J & for i=1

$$\sum_{k=1}^{K} X2_{ikj} + I2_{j(i-1)} \leq Cv_j$$

for j = 1, … ,J & i = 2, … , N

The total number of vaccines transported to county j from all the distribution centers (k) in a given week (i) cannot exceed the storage capacity of the vaccination center. Also, previous inventory (for week (i-1)) will also be available in the county storage, effectively the available storage for new vaccines in week i.

2.4.9 Distribution Setup Scenario

$$X1_{ki} \leq Cw_k * Y_k$$

for k = 1, … ,K & for i = 0, … , N-1

A distribution center k can only purchase vaccines from the manufacturer at the end of every week i only if the distribution center is setup. As Y_k is a binary variable, thus if distribution center k is setup, Y_k holds a value of 1, implying through the above mathematical equation that the maximum vaccines purchased from the manufacturer cannot exceed the holding capacity of the distribution center, given by Cw_k.

2.4.10 Warehouse Inventory I

$$I1_{k0} = X1_{k0}$$

for k = 1, … ,K & for i = 0

The inventory in warehouse k at the end of week 0 will be the total vaccines purchased from the manufacturer at the start of week 0.

2.4.10 Warehouse Inventory II

$$I1_{ki} = I1_{k(i-1)} + X1_{ki} - \sum_{j=1}^{J} X2_{ikj}$$

for k = 1, … , K & for i = 1, … , N-1

The inventory in warehouse k at the end of week i the total of warehouse inventory at the end of previous week (i-1) and the difference between the total of vaccines purchased from the manufacturer at the start of week i and total vaccines distributed to the J counties in week i from the warehouse k.

2.4.11 Warehouse Inventory III

$I1_{ki} \leq Cw_k$
for k = 1, … ,K & for i = 0, … ,N

The maximum inventory of the warehouse k at the end of week i cannot exceed the storage capacity of the warehouse given by Cw_k.

2.4.12 Maximum Vaccines transported from Warehouse

$$\sum_{j=1}^{J} X2_{ikj} \leq I1_{k(i-1)}$$
for k=1, … ,K & for i = 1, … ,N

The maximum vaccines sent from warehouse k to J counties at the start of week I cannot exceed the vaccines in the inventory of the warehouse k at the end of previous week (i-1).

2.4.13 Manufacturer's selling capacity

$$\sum_{k=1}^{K} X1_{ki} \leq Cm_i$$
for i = 0, … , N-1

The total number of vaccines purchased by all the warehouses K cannot exceed the manufacturer's selling capacity in the given week i.

2.4.14 Vaccine Administration Limit of Counties

$$\sum_{m=1}^{M} X3_{jim} \leq Lv_j$$
for j =1, … ,J & i =1, … ,N

The maximum vaccines that a county j can administer to all the priority groups M in a given week I is bound by the vaccine administration limit of the vaccination center j.

2.4.13 Non-negativity constraints

None of the decision variables can be negative. Also, apart from the binary decision variables Z_{mj} & Y_k, all other decision variables are integer variables, as the number of vaccines or the number of vaccination groups fully vaccinated cannot be fractional values, but only whole numbers.

$X1_{ki} \geq 0, integer$	for i=0,...,N-1 & k=1,...,K
$X2_{ikj} \geq 0, integer$	for i=1,...,N, j=1,...,J & k=1,...,K
$X3_{jim} \geq 0, integer$	for i=1,...,N & j=1,...,J
$I1_{ki} \geq 0, integer$	for i=0,...,N & k=1,...,K
$I2_{ji} \geq 0, integer$	for i=1,...,N & j=1,...,J
$P_j \geq 0, integer$	for j = 1, … ,J
$WP \geq 0, integer$	
Y_k *is binary*	for k=1,...,K
Z_{mj} *is binary*	for m=1,...,M & j=1,...,J

3. Solution

The problem is solved using the AMPL CPLEX optimizer. The AMPL output obtained for the problem is as following:

AMPL Window Output

```
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 3
1200 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J, i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1610510

Y:
ampl: display Y;
Y [*] :=
1  1
2  0
3  1
4  0;

P:
ampl: display P;
P [*] :=
 1  3
 2  3
 3  3
 4  3
 5  3
 6  3
 7  3
 8  3
 9  3
10  3
11  3
12  3
13  3
14  3
15  3
16  3
17  3
18  3
19  3
20  3;
```

AMPL Output Explanation

The obtained output can be interpreted as following:

```
CPLEX 20.1.0.0: optimal integer solution; objective 3
```

The text “optimal integer solution” denotes that the problem has a unique optimal solution. The AMPL output shows the optimal value of the objective function as 3. That is the value of the performance index of the state of Texas.

```
ampl: display sum{j in 1..J, i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1610510
```

The first line is the syntax written in AMPL to obtain the sum of the total vaccines administered during the vaccination drive. The second line is the AMPL output obtained to deduce the total number of vaccines administered throughout the state during the vaccination drive. The total vaccines administered during the drive is 1610510.

```
Y:
ampl: display Y;
Y [*] :=
1  1
2  0
3  1
4  0;
```

The value of Y shows that if the distribution center is set-up or not. Y is a binary variable.
The value of 1 confirms that a particular distribution center is set up. Y takes the value of 0 when a particular distribution center is not set up for the vaccine distribution. Here, the output shows that the distribution centers 1 & 3 are setup, while the centers 2 & 4 are not setup.

```
P:
ampl: display P;
P [*] :=
 1  3
 2  3
```

The P is our performance index which shows the number of groups fully vaccinated at each county at the end of the time period. In the given example above, for county 1 the P value is 3 that means the county 1 was able to vaccinate total of 3 priority groups during the vaccination drive. For county 2 the P value is 3 which means county 2 was able to vaccinate total of 3 groups.

Solution Summary

County-wise Performance										
Counties	1	2	3	4	5	6	7	8	9	10
Performance	3	3	3	3	3	3	3	3	3	3
Counties	11	12	13	14	15	16	17	18	19	20
Performance	3	3	3	3	3	3	3	3	3	3

No of Counties	***20***	***No of warehouses Set-up***	***2***
Total Vaccines Administered	***1610510***	***Performance of the State***	***3***

4. Solution Summary

4.1 What is the number of vaccines administered when solving the original model?

```
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 3
1200 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J, i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1610510
```

From the above output the optimal performance is 3 and the number of vaccines administered is 1610510.

4.2 What if the objective function was to maximize the number of vaccines administered ?

```
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: integer optimal with unscaled infeasibilities; objective 1857210
36432 MIP simplex iterations
4962 branch-and-bound nodes

ampl: display WP;
WP = 0

ampl: display P;
P [*] :=
 1  1
 2  2
 3  5
 4  5
 5  6
 6  5
 7  6
 8  4
 9  0
10  0
11  0
12  0
13  3
14  4
15  6
16  5
17  4
18  6
19  4
20  0;

ampl: display Y;
Y [*] :=
1  0
2  0
3  1
4  0;
```

The objective of the model is changed to maximize the number of vaccines administered (sum of X_3) in order to obtain the maximum number of vaccines that can be administered. The solution is 1857210 and further the display command of the P provides the performance of the counties. The counties 9, 10, 11, 12 and 20 were not able to vaccinate even a single priority group leaving the population of these counties vulnerable to Covid-19 infection. Thus, the performance index of state is found to be 0.

County-wise Performance										
Counties	1	2	3	4	5	6	7	8	9	10
Performance	1	2	5	5	6	5	6	4	0	0
Counties	11	12	13	14	15	16	17	18	19	20
Performance	0	0	3	4	6	5	4	6	4	0

No of Counties	***20***	***No of warehouses Set-up***	***1***
Maximum Vaccines Administered by the Counties	***1857210***	***Performance of the State***	***0***

4.3 What if the model is changed to maximize the vaccines administered given the best performance index?

```
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 1835577
2077 MIP simplex iterations
0 branch-and-bound nodes
ampl: display WP;
WP = 3
ampl: display P;
P [*] :=
 1  3
 2  3
 3  3
 4  3
 5  3
 6  3
 7  6
 8  4
 9  3
10  3
11  3
12  3
13  3
14  4
15  6
16  3
17  3
18  3
19  4
20  3;

ampl: display Y;
Y [*] :=
1  0
2  0
3  1
4  0;
```

First the model is run to obtain the best worst performance which is 3 and this is then added as a constraint for the next model to obtain the maximum number of vaccines administered, which come out to be 1835577 and the display P gives the performance of each county as shown above and from the display Y it is visible that number of warehouses is reduced to 1.

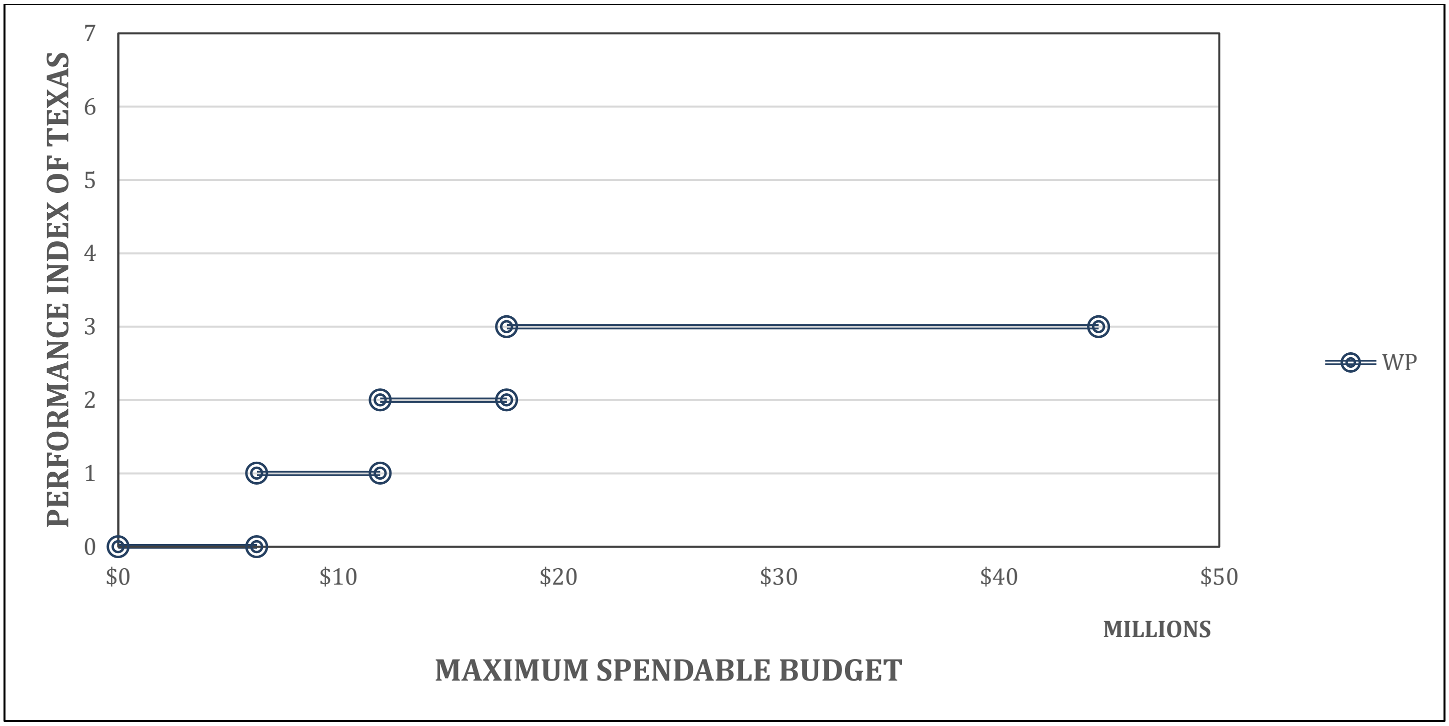
County-wise Performance										
Counties	1	2	3	4	5	6	7	8	9	10
Performance	3	3	3	3	3	3	6	4	3	3
Counties	11	12	13	14	15	16	17	18	19	20
Performance	3	3	3	4	6	3	3	6	4	3

No of Counties	***20***	***No of warehouses Set-up***	***1***
Maximum Vaccines Administered by the Counties	***1835577***	***Performance of the State***	***3***

4.4 Create a graph/plot of the "Performance Index (y axis)" Vs the "Budget (x axis)" as the budget varies from $0 to $infinity.

```
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 0
0 MIP simplex iterations
0 branch-and-bound nodes

ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 6296461.1
1281 MIP simplex iterations
0 branch-and-bound nodes

ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 11897260.5
1829 MIP simplex iterations
0 branch-and-bound nodes

ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 17647362.9
1475 MIP simplex iterations
0 branch-and-bound nodes

ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: integer infeasible.
275 MIP simplex iterations
```

To plot the graph, the work performance is added to the constraint in the order of 0,1,2,3 and 4. The Budget is infeasible if the WP is greater than 4, while the values of $6296461.1, $11897260.5 & $17647362.9 indicate the steps in the graph below.



PERFORMANCE INDEX OF TEXAS
7
6
5
4
3
2
1
0
$0
$10
$20
$30
$40
$50
MILLIONS
MAXIMUM SPENDABLE BUDGET
WP

4.5 What if given the best performance index, the objective is to minimize the budget?

```
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 17647362.9
1475 MIP simplex iterations
0 branch-and-bound nodes
ampl: display WP;
WP = 3

ampl: display P;
P [*] :=
 1  3
 2  3
 3  3
 4  3
 5  3
 6  3
 7  3
 8  3
 9  3
10  3
11  3
12  3
13  3
14  3
15  3
16  3
17  3
18  3
19  3
20  3;
```

The constraint is added to the model by setting the work performance is 3 to obtain the minimum budget required to achieve this performance for all the counties and the budget required is $17647362.9.

Minimum Budget which keeps Worst Performance = 3	***$17647362.9***

No of Counties	***20***	***No of warehouses Set-up***	***1***
Maximum Vaccines Administered by the Counties	***1605420***	***Performance of the State***	***3***

4.6 What if our objective is to maximize the number of warehouses?

```
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 4
0 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J, i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 0

ampl: display WP;
WP = 0

ampl: display P;
P [*] :=
 1  0
 2  0
 3  0
 4  0
 5  0
 6  0
 7  0
 8  0
 9  0
10  0
11  0
12  0
13  0
14  0
15  0
16  0
17  0
18  0
19  0
20  0;

ampl: display Y;
Y [*] :=
1  1
2  1
3  1
4  1;
```

The Main objective is changed to maximize the number of warehouses and from the above output the objective value obtained is 4 which the maximum number of warehouses that can be set-up. The limitation of this model is that for the objective function of maximization of the number of warehouses the total vaccines administered during the entire drive come out to be 0.

Number of Warehouse Set-up	***4***
Performance of the State	***0***
Number of Vaccines Administered	***0***

4.7 What if the number of warehouses are fixed ?

```
ampl: reset; reset;
ampl: let A:=1;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 3
2419 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J, i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1681450

ampl: let A:=2;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 3
1177 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J, i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1642050

ampl: let A:=3;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 3
942 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J, i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1615010

ampl: let A:=4;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: integer optimal with unscaled infeasibilities; objective 3
752 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J, i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1612710
```

In this analysis the constraint number of warehouses is increased in the order of 0,1,2,3, and 4 to obtain the main objective and from above the values are 0, 3, 3, 3 & 3 respectively.

No of warehouses	***1***	***2***	***3***	***4***
Performance Index of Texas	***3***	***3***	***3***	***3***
Total Vaccines Administered	***1681450***	***1642050***	***1615010***	***1612710***

4.8 Create a graph/plot of the " Per dose vaccine cost (x axis)" Vs the " Performance (y axis)" as the cost of vaccine varies from $0 to $infinity

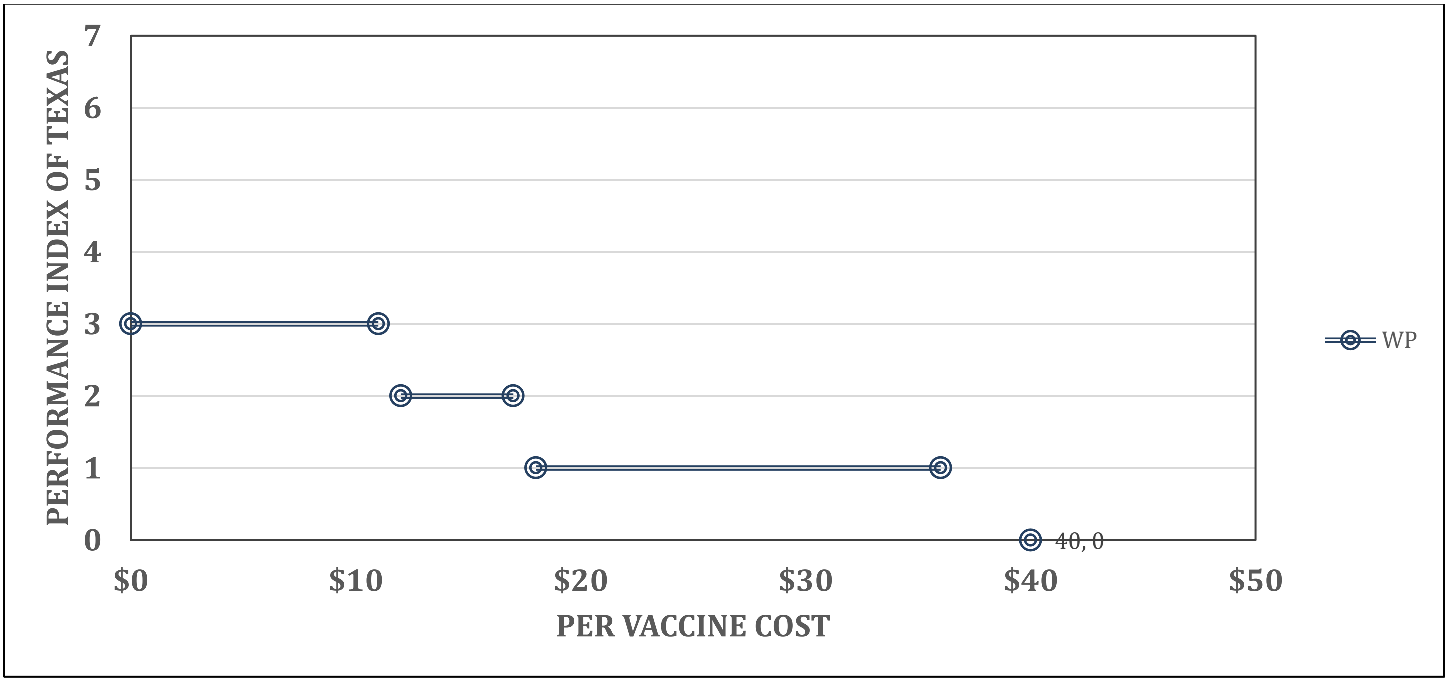
```
ampl: let Sv:=13;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 2
1032 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J,i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1140700


ampl: let Sv:=14;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 2
1122 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J,i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1058580

ampl: let Sv:=15;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 2
1138 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J,i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1058580


ampl: let Sv:=16;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 2
1043 MIP simplex iterations
0 branch-and-bound nodes
ampl: display sum{j in 1..J,i in 1..N, m in 1..M}X3[j,i,m];
sum{j in 1 .. J, i in 1 .. N, m in 1 .. M} X3[j,i,m] = 1088480

ampl: let Sv:=1;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
```

```
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 3
835 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=11;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 3
1144 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=12;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 2
1257 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=20;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 1
1197 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=18;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 1
926 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=17;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 2
989 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=25;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
```

```
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 1
912 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=30;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 1
2463 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=35;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 1
1684 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=40;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 0
846 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=37;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 0
2259 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=36;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 1
1705 MIP simplex iterations
0 branch-and-bound nodes

ampl: let Sv:=0;
ampl: solve;
CPLEX 20.1.0.0: mipgap=0
```

```
integrality=0
CPLEX 20.1.0.0: optimal integer solution; objective 3
835 MIP simplex iterations
0 branch-and-bound nodes
```

The per vaccine dose cost is varied from 0 to infinity (as integers, to maintain consistency with the model)with the same objective to check how the objective value varies if the cost of the vaccines is increased. The analysis can be seen in the below graph.



5. Conclusion

The model formulated and the results obtained in the presented report show that to vaccinate people as homogeneously as possible it is essential to have an efficient supply chain in place for the vaccination distribution throughout the state. The report outlines a detailed description of the methodology which concludes that the maximum possible performance index that Texas can achieve during its one-month long vaccination drive is 3.

In section 4, different scenarios are considered by manipulating the model. It can be shown that changing these values impacts the performance of the State in most of these cases. The graphs are plotted to show the relationship between the variables and parameters to help conclude how changing the value of one affects the value of the other, keeping other conditions unchanged.

Finally, for the future use of the model, the report has identified some of the limitations associated with the model. The What-If analyses have to be considered before proceeding and manipulating with the objective and data.

6. *References*

a. Rastegar, M., Tavana, M., Meraj, A., & Mina, H. (2021). An inventory-location optimization model for equitable influenza vaccine distribution in developing countries during the COVID-19 pandemic. Vaccine, 39(3), 495–504. https://doi.org/10.1016/j.vaccine.2020.12.022

b. Winston, W. L., & Goldberg, J. B. (2004). Operations research: applications and algorithms (Vol. 3). Belmont: Thomson Brooks/Cole.

c. ISEN 620 –Material posted for Fall 2021 coursework on CANVAS (Lectures, videos, handouts)