A Mixed-Integer Linear Program for Ebola Vaccine Campaign in Ohio Emergency Response Region 4

Daphne Kaur (kaur.443), Joshua Brown (brown.8675), Ajit Ubhi (ubhi.4)

2025-12-03

The World Cup 2026 is expected to be the largest event of its kind in all of history. The equivalent of 104 Super Bowls will be held in North America in just five weeks. This event will bring as many as 6 million foreigners into the United States, increasing concerns for the introduction of novel infectious diseases. One disease of major concern is Ebola, a highly infectious viral fever that kills about half of those infected. On September 4th, 2025, an active outbreak of Ebola was declared in the Democratic Republic of the Congo, further heightening concerns from public health workers. A vaccine for Ebola was approved by the CDC in 2019 and is 84% effective. Though the current supply of vaccines is limited, production could be significantly increased in the event of a serious outbreak and vaccination clinic offered to the general public. Planning for such an event can be exceedingly complicated with many variables that must be considered. The creation of a linear program that appropriately models needs for the planning of vaccine campaigns could save lives and reduce burden on public health workers. The goal of this project was to develop a Mixed Integer Linear Programming Model which allows the user to quickly create a staffing plan that maximizes the number of people vaccinated in Ohio Emergency Response Region 4 over a week.

Assumptions

The assumptions of the model are as follows:

- The Ebola vaccine is able to be manufactured in sufficient quantities to permit it's use in vaccination campaigns.
- The number of available vaccines, vaccinating staff, administrative staff, population and proportion of vaccinated individuals in each county, and building square footage are known and fixed.
- The objective is to maximize the number of vaccinated persons and assumes that all people living in Region 4 are of equal priority.
- Staff members are interchangeable between team types and are unrestricted in assignment to county or team type within the region. All teams work 40 hours per week in the same location.
- The number of available adminstrative staff always outnumbers availible vaccinating staff.
- The unvaccinated populations in a county will participate in the vaccine clinic at a maximum rate of exactly 10% per week.
- All teams will vaccinate at the maximum rate if participation and vaccines are available. There is no accounting of inefficiencies (such as downtime or scheduling gaps).
- Building square footage restricts only the number of vaccinating teams, not the number of attendees, since the required space per team is larger than that required for building occupancy.
- All shipped vaccines will arrive before the week begins and have no accounting for storage or loss. Vaccines *must* be administered in the week they are allocated, in the county where they were allocated. None are permitted to be carried forward or relocated. Since the vaccines are very expensive to manufacture, it is assumed that there will never be a surplus.

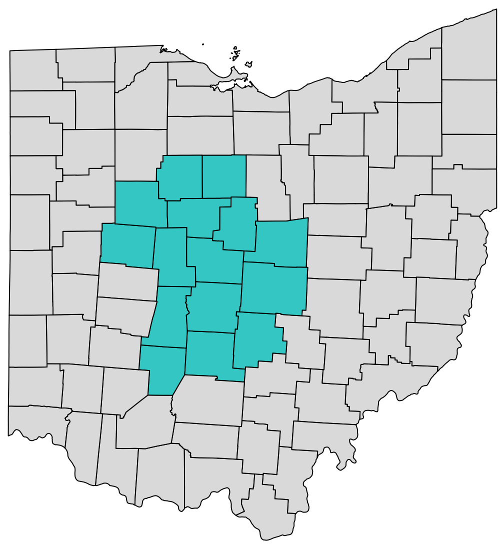
Sets

I = counties in Ohio Emergency Response Region 4 {Franklin, Hardin, Logan, Wyandot, Delaware, Marion, Fayette, Pickaway, Union, Crawford, Morrow, Knox, Licking, Fairfield, Madison}

K = team types {1to1, 3to1, 7to1}

These sets are used throughout this report to represent represent county names and team types. I includes the names of the 13 counties that have been designated as Ohio Emergency Response Region 4. Emergency response regions are created to allow counties to plan the sharing of staff and other resources in the event of an emergency.

Figure 1. Map of Ohio Emergency Response Region 4



```
# Set of counties in Region 4
I = [
    "Franklin", "Delaware", "Licking", "Fairfield", "Union",
    "Marion", "Knox", "Pickaway", "Logan", "Madison",
    "Crawford", "Morrow", "Hardin", "Fayette", "Wyandot"
]

# Set of vaccination team types (administrator-to-vaccinator staffing ratios)
K = ["1to1","3to1","7to1"]
```

Decision Variables

$t_{i\in I,\, k\in K}$ = the total number of teams of type k assigned to county i

$d_{i\in I}$ = the number of vaccines shipped to county i

$z_{i\in I}$ = total number of people vaccinated in county i

The number of people who are vaccinated in the region is determined by the assignment of staff and associated allotment of vaccines. Vaccinating and administrative staff members are placed in team types of different ratios, which administer vaccines at different rates. These items make up the decision variables and are modeled below.

```python
# Decision variables
t = m.addVars(I, K, vtype=GRB.INTEGER, lb=0, name="t")
d = m.addVars(I, vtype=GRB.INTEGER, lb=0, name="d")
z = m.addVars(I, vtype=GRB.INTEGER, lb=0, name="z")
```

Objective

$$\text{Maximize } z = \sum_{i \in I} z_i$$

Since public health emergency plans are often made only one week at a time due to the potential for rapid change, the objective of this model is to optimize the number of people vaccinated over a week. The model optimizes the placement of staff and vaccine supplies in each county to ensure that the maximum number of people can be vaccinated, preventing accidental over-staffing. The model parameters may be updated at the beginning of the weekly planning period and used to optimize placements again.

```python
# Objective
m.setObjective(quicksum(z[i] for i in I), GRB.MAXIMIZE)
```

Parameters

Primary Parameters

$V =$ the number of available vaccines

$P_{i\in I} =$ the population of county i

$S_{i\in I} =$ the square footage of the clinic building in county i

$C_{i\in I} =$ the vaccine coverage in county i, expressed as the proportion vaccinated

The model assumes that the number of available vaccines, vaccinating staff, administrative staff, population, the proportion of vaccinated individuals in each county, and building square footage are known, so this data must be provided.Population numbers have been obtained from census data for testing. Building areas were generated from a lognormal distribution to simulate the positive, right-skewed distribution of real building The simulated values for S_i are reasonable values to represent schools and community centers which are commonly chosen as the site for public health interventions.

```python
# Number of available vaccines for the week
V = 150000
```

```python
# County population P[i]
P = {
    "Franklin": 1356303, "Delaware": 237966, "Licking": 184898,
    "Fairfield": 167762, "Union": 71721, "Marion": 64976, "Knox": 63848,
    "Pickaway": 62158, "Logan": 46085, "Madison": 45531, "Crawford": 41626,
    "Morrow": 35927, "Hardin": 30402, "Fayette": 28782,"Wyandot": 21394
}
```

```python
# Initial vaccine coverage C[i] in each county (as proportion vaccinated)
C = {
    "Franklin": 0.18,
    "Delaware": 0.09,
    "Licking": 0.0,
    "Fairfield": 0.0,
    "Union": 0.0,
    "Marion": 0.0,
    "Knox": 0.0,
    "Pickaway": 0.0,
    "Logan": 0.0,
    "Madison": 0.09,
    "Crawford": 0.18,
    "Morrow": 0.18,
    "Hardin": 0.18,
    "Fayette": 0.18,
    "Wyandot": 0.18
}

# Maximum available clinic square footage S[i] for each county
S = {
    "Franklin": 452082,
    "Delaware": 123766,
    "Licking": 27336,
    "Fairfield": 64526,
    "Union": 314164,
    "Marion": 55737,
    "Knox": 376007,
    "Pickaway": 55507,
    "Logan": 73185,
    "Madison": 49019,
    "Crawford": 50491,
    "Morrow": 144270,
    "Hardin": 30751,
    "Fayette": 159251,
    "Wyandot": 72137
}
```

Team Parameters

E_V = the number of available vaccinating staff

E_A = the number of available administrative staff

$n_{V,\, k \in K}$ = the number of vaccinating staff in team k

$n_{A,\, k \in K}$ = the number of administrative staff in team k

$r_{k \in K}$ = the number of people that a team of type k can vaccinate in one hour

The team parameters are summarized below in Table 1.

Table 1. Summary Table of Team Parameters

Team Type (k)	Number of Vaccinating Staff (n_{V,k})	Number of Administrative Staff (n_{A,k})	Maximum Number of Vaccines Administered per Hour (r_k)
1to1	1	1	6
3to1	1	3	19
7to1	1	7	30

Reasonable representative numbers for available staff have been chosen to demonstrate the model's capabilities.

```
# Number of available staff for the week (V-vaccinating, A-administrative)
E_V = 205
E_A = 789

# Number of staff in each team
n_V = {"1to1": 1, "3to1": 1, "7to1": 1}
n_A = {"1to1": 1, "3to1": 3, "7to1": 7}

# Hourly vaccination rates for each team
R = {"1to1": 6, "3to1": 19, "7to1": 30}
```

Constraints

Though vaccine availability may present a major challenge in the case of an Ebola outbreak, many other difficult constraints are faced by vaccination campaigns. The model has ten types of constraints: vaccine supply, vaccinator availability, administrative staff availability, dose feasibility, herd immunity, participation, building size, throughput, fairness, and other constraints. Each is described and modeled as follows:

1. Vaccine supply

The Ebola vaccine is currently extremely expensive to produce.It is expected that the number of vaccines available may be even more limited than staff, though a sizeable up shift in manufacturing in the event of a widespread outbreak is possible. The total number of vaccines shipped to all counties may not exceed the total number available.

$$\sum_{i \in I} d_i \leq V$$

```
# 1. Vaccine supply
m.addConstr(quicksum(d[i] for i in I) <= V, name="VaccineSupply")
```

2. Vaccinator availability

The administration of vaccines requires licensed medical professionals who are very limited. Physicians, pharmacists, nurses, and volunteer medical students make up the bulk of vaccinating staff. This means that other types of staff may not serve as vaccinators as they lack appropriate licensure. The total number of vaccinating staff allocated to all counties must not exceed the number available.

$$\sum_{i \in I} \sum_{k \in K} n_{V,k} t_{i,k} \leq E_V$$

```
# 2. Vaccinator availability
m.addConstr(quicksum(n_V[k] * t[i, k] for i in I for k in K) <= E_V,
            name="TotalVaccinators")
```

3. Administrative staff availability

Administrative staff positions are typically filled through the use of volunteers, which are also frequently limited, though not as much as vaccinating staff since licenses are not required.The total number of administrative staff allocated must not exceed the number available.

$$\sum_{i \in I} \sum_{k \in K} n_{A,k} t_{i,k} \leq E_A$$

$$2500 \sum_{k \in K} t_{i,k} \leq S_i, \quad \forall i \in I$$

```python
# 3. Admin staff availability
m.addConstr(quicksum(n_A[k] * t[i, k] for i in I for k in K) <= E_A,
            name="TotalAdmin")
```

4. Dose feasibility

In order to be able to vaccinate someone, an available vaccine dose my exist within the county. Therefore, the total number of vaccines administered in a county must not exceed the number of vaccines shipped to that county.

$$z_i \leq d_i, \quad \forall i \in I$$

```python
for i in I:

    # 4. Dose feasibility
    m.addConstr(z[i] <= d[i], name=f"FeasibleDoses[{i}]")
```

5. Herd immunity

Since the number of vaccines is likely to be extremely limited, vaccines should not be offered to populations who have already reached herd immunity. The herd immunity for Ebola is approximately 80%. Vaccines will not be administered beyond the herd immunity in each county.

$$z_i \leq (0.8 - C_i)\, P_i, \quad \forall i \in I$$

```python
for i in I:

    # 5. Herd immunity
    m.addConstr(z[i] <= (0.8 - C[i]) * P[i], name=f"HerdImmunity[{i}]")
```

6. Participation

All unvaccinated people cannot be expected to show up at a clinic within the same week. For many reasons, people may delay or decide not to vaccinate. Therefore, we will assume that at most 10% of the unvaccinated population will participate in the vaccine clinic in a week.

$$z_i \leq 0.1\, P_i\, (1 - C_i), \quad \forall i \in I$$

```python
for i in I:

    # 6. Weekly participation
    m.addConstr(z[i] <= 0.1 * P[i] * (1 - C[i]), name=f"Participation[{i}]")
```

7. Building size

Medical procedures such as the administration of vaccines require a certain amount of physical space by law to protect patient safety and maintain privacy. This space requirement is more restrictive than building occupancies and so will not affect the number of patients permitted in the building, only the number of teams. Each vaccinating team requires $2500\,\mathrm{ft}^2$ of space at the clinic site.

$$2500 \sum_{k \in K} t_{i,k} \leq S_i, \quad \forall i \in I$$

```
for i in I:

    # 7. Building Size
    m.addConstr(sqft * quicksum(t[i, k] for k in K) <= S[i], name=f"Building[{i}]")
```

8. Throughput

Each team type has its own hourly rate at which it can vaccinate and each team works a total of 40 hours per week. The number of people vaccinated in each county cannot exceed the capabilities of the teams assigned to that county.

$$z_i \le 40 \sum_{k \in K} r_k \, t_{i,k}, \quad \forall i \in I$$

```
for i in I:

    # 8. Throughput
    m.addConstr(z[i] <= quicksum(M[k] * t[i, k] for k in K), name=f"Throughput[{i}]")
```

9. Fairness

Fairness constraints take humanitarian issues into account. All people must be provided reasonable access to vaccines. To keep vaccine availability fair across counties, the vaccinated proportion for any two counties i and j must not differ by more than 0.2.

$$|(C_i P_i + z_i)P_j - (C_j P_j + z_j)P_i| \le 0.2 \, P_i P_j, \quad \forall i, j \in I$$

```
# 9. Fairness constraint
for i in I:
    for j in I:

        # Only compare different counties
        if i != j:

            m.addConstr((C[i] * P[i] + z[i]) * P[j] - (C[j] * P[j] + z[j]) * P[i] <= 0.2 * P[i] * P[j], name=f"FairnessLow[{i},{j}]")
            m.addConstr((C[j] * P[j] + z[j]) * P[i] - (C[i] * P[i] + z[i]) * P[j] <= 0.2 * P[i] * P[j], name=f"FairnessHigh[{j},{i}]")
```

10. Integrality and Nonnegativity Constraints

The integrality and nonnegativity constraints ensure that all decision variables and parameters in the model take on feasible, real-world values.

$$t_{i,k}, \; d_i, \; z_i \in \mathbb{Z}_{\ge 0}, \quad \forall i \in I, \; \forall k \in K$$

$$V, \; E_V, \; E_A, \; P_i, \; n_{V,k}, \; n_{A,k}, \; r_k \in \mathbb{Z}_{\ge 0}, \quad \forall i \in I, \; \forall k \in K$$

$$S_i \ge 0, \quad 0 \le C_i \le 1, \quad \forall i \in I$$

Results

Output

A sample output from a run using expected values i shown in Table 2.This output demonstrates the expected functionality of the model. Counties with lower beginning coverage rates are prioritized to keep coverages within the fairness constraint, with more resources being allocated to counties with larger populations. Initially we ran this simulation without the fairness constraint thinking that the model would allocate to every county anyways. However after doing our initial tests we found that it only maximized the total number of people vaccinated, so some counties would be left under-vaccinated and wouldn't meet herd immunity requirements. All vaccinating staff and vaccines have been allocated, with some administrative staff overflowing and left unassigned. The values for P_i used for model are the counties population at the last census. S_i values are the simulated building sizes discussed in the parameter section above. For ease of interpretation, counties are listed descending order by population. Note that Licking county has access to an usually small clinic space, which has a negative effect on that county reaching herd immunity as shown later. The values used for P_i and S_i are shown in Table 3.

Table 2. Representative Output (V = 150,000,E_V = 205,E_A = 789)

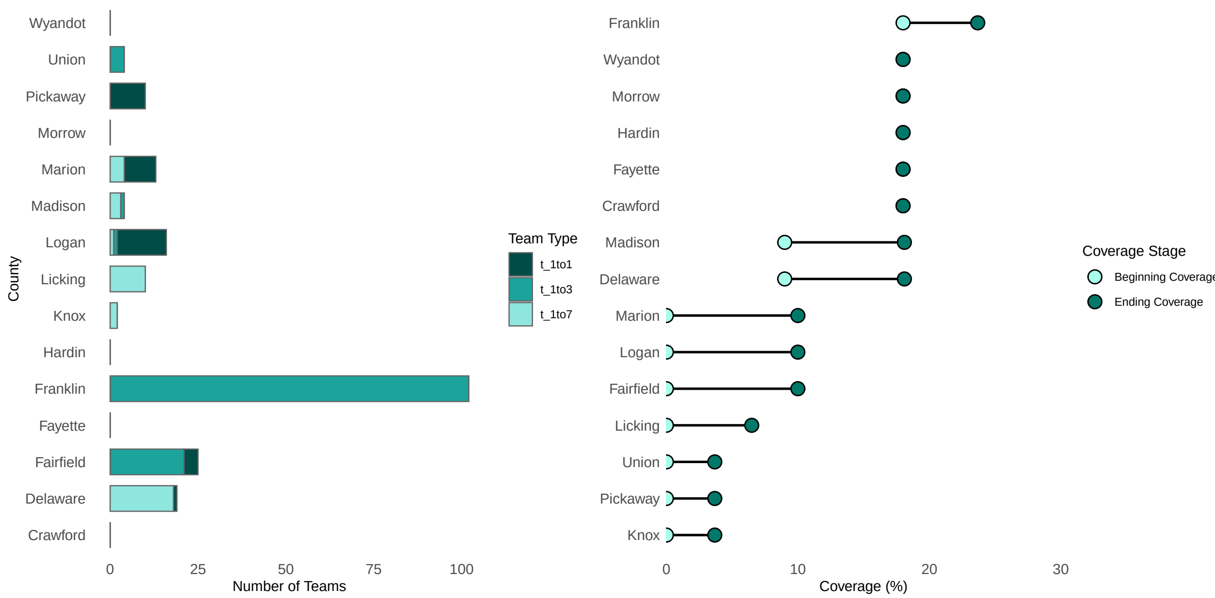
County i	Coverage C_i	New Coverage	Doses Sent d_i	Vaccinated z_i	$t_{i,1to1}$	$t_{i,1to3}$	$t_{i,1to7}$	Vaccinators	Admin Staff
Franklin	0.1800	0.2368	77,044.00	77,044.00	0	102	0	102	306
Delaware	0.0900	0.1810	21,654.00	21,654.00	1	0	18	19	127
Licking	0.0000	0.0649	12,000.00	12,000.00	0	0	10	10	70
Fairfield	0.0000	0.1000	16,776.00	16,776.00	4	21	0	25	67
Union	0.0000	0.0368	2,640.00	2,640.00	0	4	0	4	12
Marion	0.0000	0.1000	6,497.00	6,497.00	9	0	4	13	37
Knox	0.0000	0.0368	2,350.00	2,350.00	0	0	2	2	14
Pickaway	0.0000	0.0368	2,288.00	2,288.00	10	0	0	10	10
Logan	0.0000	0.1000	4,608.00	4,608.00	14	1	1	16	24
Madison	0.0900	0.1810	4,143.00	4,143.00	0	1	3	4	24
Crawford	0.1800	0.1800	0.00	0.00	0	0	0	0	0
Morrow	0.1800	0.1800	0.00	0.00	0	0	0	0	0
Hardin	0.1800	0.1800	0.00	0.00	0	0	0	0	0
Fayette	0.1800	0.1800	0.00	0.00	0	0	0	0	0
Wyandot	0.1800	0.1800	0.00	0.00	0	0	0	0	0
Totals			**150,000**	**150,000**				**205**	**691**

Table 3. Values of P_i and S_i

County	Population P_i	Est. Building Size S_i
Franklin	1,356,303	452,082
Delaware	237,966	123,766
Licking	184,898	27,336
Fairfield	167,762	64,526
Union	71,721	314,164
Marion	64,976	55,737
Knox	63,848	376,007
Pickaway	62,158	55,507

County	Population P_i	Est. Building Size S_i
Logan	46,085	73,185
Madison	45,531	49,019
Crawford	41,626	50,491
Morrow	35,927	144,270
Hardin	30,402	30,751
Fayette	28,782	159,251
Wyandot	21,394	72,137

Figure 2



The left plot displays the number and types of vaccinator teams allocated across each county. The counties are listed on the vertical axis, and the horizontal bars show how many teams of each type were assigned. The stacked bars allow quick comparison across counties. Some counties—like Fairfield, Marion, Pickaway, and Logan—received a higher total number of teams, while several rural counties received few or none. The chart highlights how staffing resources are distributed geographically and which counties required the more vaccination support due to population.

The right plot shows the change in vaccination coverage for each county from the beginning to the end of the simulation period. This makes it easy to see both the absolute coverage levels and the direction of change. Several counties, including Franklin, Delaware, Fairfield, Logan, and Marion, show clear increases after vaccinator deployment. Some counties remain unchanged, reflecting low or zero expected improvement due to limited staffing or already-maxed-out capacity.

Performance Analysis

In order to asses the performance of the model, extreme and expected values of all parameters $V, E_v, E_a, C_i, S_i and P_i$ were tested and output evaluated.

- V : The model distributes all vaccines appropriately. It does not ship vaccines to counties where they will not be used and instead leaves them in reserve. Only the exact number, which corresponds to the maximum throughput for that county is allocated.

- E_V : The model assigns the number of vaccinating staff appropriately, neither assigning more than is needed, nor leaving any unassigned or unused. If not enough administrative staff exist to accompany them, the model will not assign vaccinating staff. This is appropriate and expected as the model assumes the number of administrative staff always outnumbers vaccinating staff.

- E_A : The model assigns the number of administrative staff appropriately. It does not assign them without the required number of vaccinating staff to accompany them.

- C_i : The model assigns staff and vaccine doses appropriately to counties that lag behind in vaccine coverage *so long as it is not lagging by more than 20%.* Initial coverage differences of more than 20% cannot be optimized by this model. This is something that would need to be improved before being used in a real-world application.

- S_i : The model assigns staff appropriately according to building size. It does not exceed the required space, nor fail to assign when space is available.

- P_i :The model assigns staff and vaccines appropriately based on a county's population size. More resources are allocated to counties with greater populations to meet the fairness constraint, even if building size allows for much more staff.

20 Week Simulation

A 20 week simulation version of the model was run to asses model behavior over a longer term. This 20 week iterative run demonstrates how a vaccine campaign might progress from no coverage to full herd immunity. Vaccine coverage (C_i) was set at 0.0 for all counties and re-calculated at the end of each week to demonstrate cumulative effect.Values for P_i and S_i are as in Table 3. All other parameters were as above, assuming they remained the same over each week, though this simulation accommodates changes in vaccine availability and staff. The model proceeded as anticipated, staying within provided constraints and iteritively assigning staff to optimize the number of vaccines given. By week 20, all counties had reached herd immunity. The full code and output are available on GitHub.

Appendices

Appendix I - Video

https://youtu.be/fyqWLY4QMVo

Appendix II - GitHub

The GitHub repository includes a copy of this report, code for 1 week and 20 week simulations and their respective output.

https://github.com/curlydogz/group22_project

Appendix III - Contributions

Team Member	Modeling	Coding	Writing	Editing	Figures/Tables	Video
Daphne Kaur (kaur.443)	X	X	X		X	

Team Member	Modeling	Coding	Writing	Editing	Figures/Tables	Video
Joshua Brown (brown.8675)	X	X		X		X
Ajit Ubhi (ubhi.4)	X	X		X	X	X