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

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The 2026 World Cup is projected to be the largest coordinated sporting event in history, with 104 matches held across North America over a five-week period. An anticipated influx of approximately 6 million international visitors poses heightened concerns regarding the potential introduction and spread of novel infectious diseases. Among these, Ebola remains a significant threat due to its high transmissibility and a historical case-fatality rate near 50%. Following the declaration of an active Ebola outbreak in the Democratic Republic of the Congo on September 4th, 2025, the need for proactive preparedness in the United States became even more pressing.

A highly effective Ebola vaccine—approved by the CDC in 2019 with an efficacy of roughly 84%—serves as a critical tool for mitigating outbreak risk. However, current vaccine reserves are limited, and large-scale production would only be expanded in the event of a major emergency. To support strategic planning, this project develops a Mixed-Integer Linear Programming (MILP) model designed to maximize the number of individuals vaccinated in Ohio Emergency Response Region #4 during a single operational week.

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

Two sets I and K are used to represent county names and team types. They are:

> 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}

```python
# 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 individuals vaccinated across the region depends directly on how staff teams and vaccine doses are allocated among counties. Each team type delivers vaccines at a distinct rate and requires a specific combination of vaccinating and administrative personnel. The allocation of vaccines further constrains how many individuals can be vaccinated in each location. These key quantities constitute the model's decision variables.

```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

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

Because public health operations often evolve rapidly during outbreaks, response planning is typically performed one week at a time. This objective function reflects that operational reality by maximizing the total number of individuals vaccinated across the region during a single week. The formulation enables planners to re-run the model at the start of subsequent weeks using updated parameter values without modifying the underlying structure.

```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 requires several foundational parameters related to vaccine availability, population characteristics, and facility capacities. County-level populations were obtained from recent census data. Building sizes were simulated using a lognormal distribution to approximate the right-skew typical of real community structures such as schools and recreation centers. These simulated areas serve as reasonable estimates of the physical constraints that vaccination clinics would face.

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

```
# 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
}
```

```
# 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

Vaccination throughput depends heavily on staff configuration. Each team type reflects a different operational structure with a unique ratio of vaccinating to administrative personnel and a corresponding hourly vaccination rate. Table 1 summarizes the composition and throughput of the team types modeled, providing the foundation for staffing and capacity-related constraints.

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

A wide range of operational, logistical, and ethical considerations influence the implementation of a high-volume vaccination campaign. To ensure realistic outcomes, the model incorporates ten categories of constraints that collectively restrict vaccine distribution, staffing, clinic operations, and equitable access. These constraints mirror challenges faced in real emergency planning contexts and define the feasible space of solutions.

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.

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

```
# 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.

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

```
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.

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

```
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.

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

```
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 $2500\,\text{ft}^2$ of space at the clinic site.

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

```python
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.

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

```python
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.

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

```python
# 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

All decision variables are non-negative integers.

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

Results

A representative model run using expected parameter values is summarized in Table 2. Counties with low baseline coverage are prioritized, provided they do not violate fairness requirements. Larger counties receive proportionally more doses and staffing due to their greater populations. All vaccinating staff and vaccines are fully utilized, while some administrative staff remain unused, reflecting their higher relative availability.

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.

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
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

County	Population P_i	Est. Building Size S_i
Fayette	28,782	159,251
Wyandot	21,394	72,137

Performance Analysis by Parameter

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

The model was extended into a 20-week iterative simulation to examine long-term progression toward herd immunity. Weekly coverage values were updated, and optimal allocations were recalculated at each step. The simulation demonstrated steady advancement in coverage, with all counties reaching the 80% threshold by week 20. Licking county was the final county to reach herd immunity due to its relatively low building size. This behavior reflects the model's ability to consistently allocate resources efficiently while respecting participation, space, and fairness constraints.

Appendices

Appendix I - Video

Video link

Appendix II - GitHub

The GitHub repository includes complete code for the 1-week and 20-week models, as well as output used in this report:
https://github.com/curlydogz/group22_project

Appendix III - Contributions

Team Member	Modeling	Coding	Writing	Editing	Figures/Tables	Video
Daphne Kaur	X	X	X		X	
Joshua Brown	X	X		X		X
Ajit Ubhi	X			X		X