Dartmouth College COVID-19 Vaccination Staff Scheduling

ENGS103 Spring 2021
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Dr. Lisa Adams and Joshua Keniston Inbox - Dartmouth April 23, 2021 at 1:38 PM

COVID-19 Campus Update: On-Site Vaccination Clinics

To: All Students:;, All Faculty:;, All Staff:;

To the Dartmouth community,

We are pleased to share that we have partnered with the state of New Hampshire to offer on-site, first-dose vaccination clinics for Dartmouth students, staff, and faculty who are 18 or older. The clinics will take place from 8 a.m. to 6:30 p.m. on Wednesday, May 5, and Thursday, May 6, in Thompson arena. These appointments are open to those who have not yet received their first COVID-19 vaccine. They can be booked online at http://dartgo.org/vaxappt. An appointment is necessary to receive a vaccine.

The state has indicated that they will provide us with doses of either Moderna or Pfizer-BioNTech vaccines. The clinics are open to everyone regardless of whether they are residents of New Hampshire. More details, including appointment instructions, are being emailed to students and employees today.

We will announce the dates of clinics to provide a second dose of vaccine to individuals who receive their first dose at Dartmouth as soon as those details have been finalized.

We are excited to be able to offer our community this opportunity, which we hope will help bring us even closer to a more normal on-campus environment.

Sincerely,

Dr. Lisa V. Adams
Josh Keniston

Dartmouth COVID-19 Task Force Co-Chairs

Background

- Where: Thompson arena
- When: May 5th, May 6th
- Who: Dartmouth students, faculty & staff

- ~6500 population, 20% unvaccinated
    - Vaccinate 1300 people in 2 days

Problem Statement

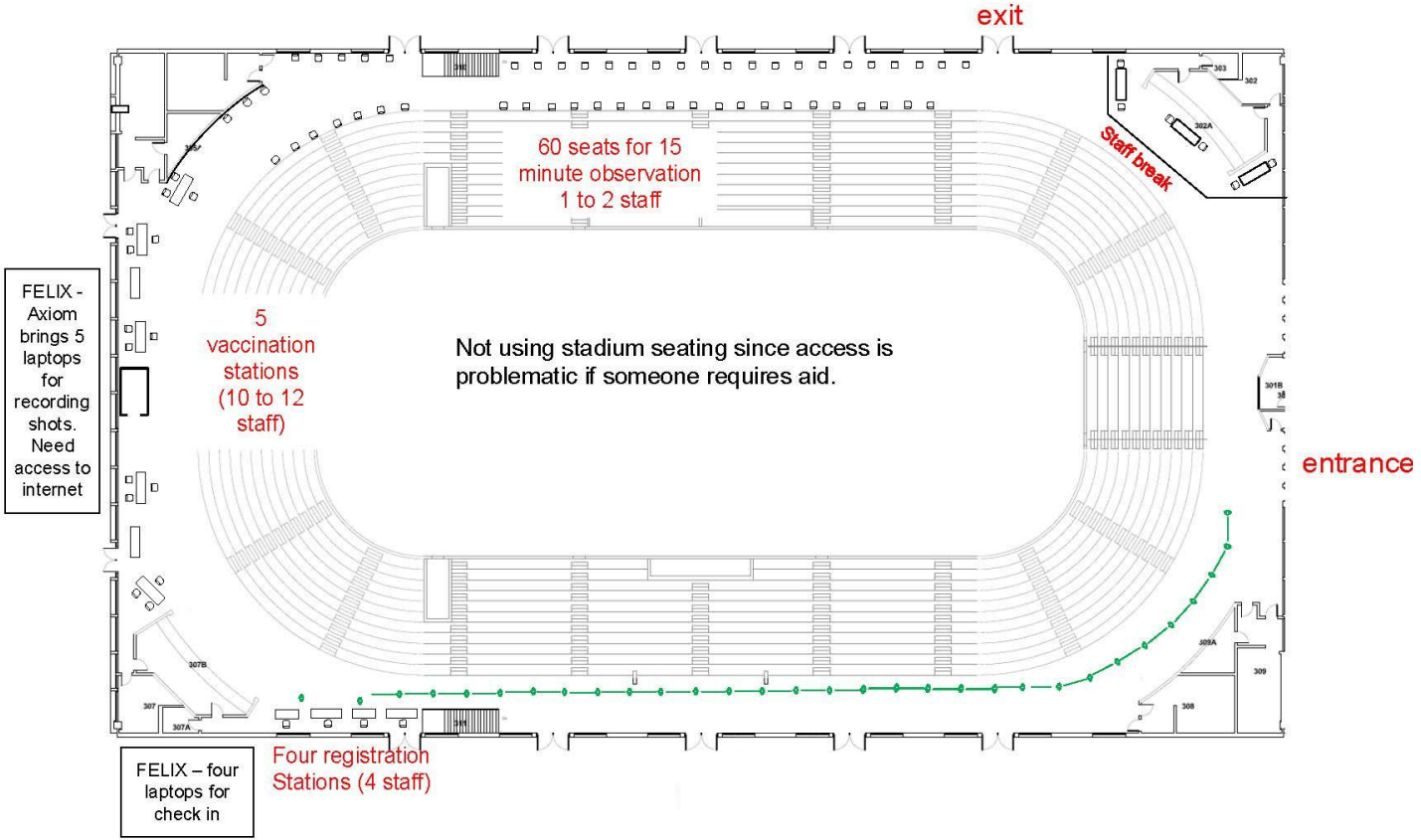
To accelerate the path of returning to campus on fall, **Dartmouth College** is **managing medical workforce** to efficiently provide **on campus** first dose COVID-19 vaccination appointments to Dartmouth students, staff and faculty on **May 5th and 6th**, so that the vaccination can be **completed within a reasonable time** and the **unnecessary waste of medical workforce is avoided**.

1. How much human resource is required to satisfy demand? ---> Queuing theory and simulation
2. What is the lowest cost to assign workers with different skills and salary? -----> Integer programming

Agenda

- Process Overview
- No pre-registration: Queueing Theory
- Pre-registration: Simulation
- Nurse scheduling: Integer Programming
- Potential Improvement & Future Steps

Overview of Vaccination Process



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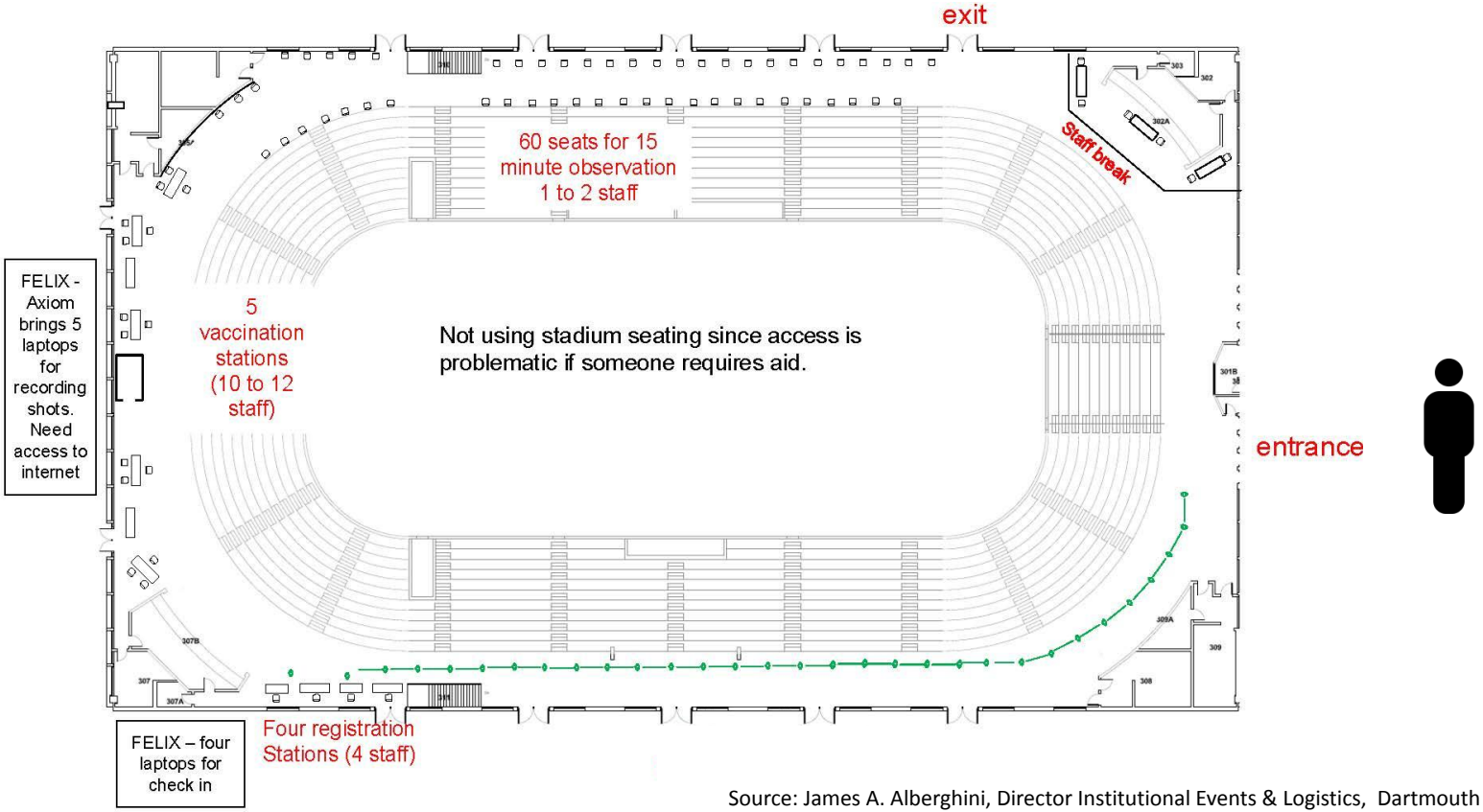

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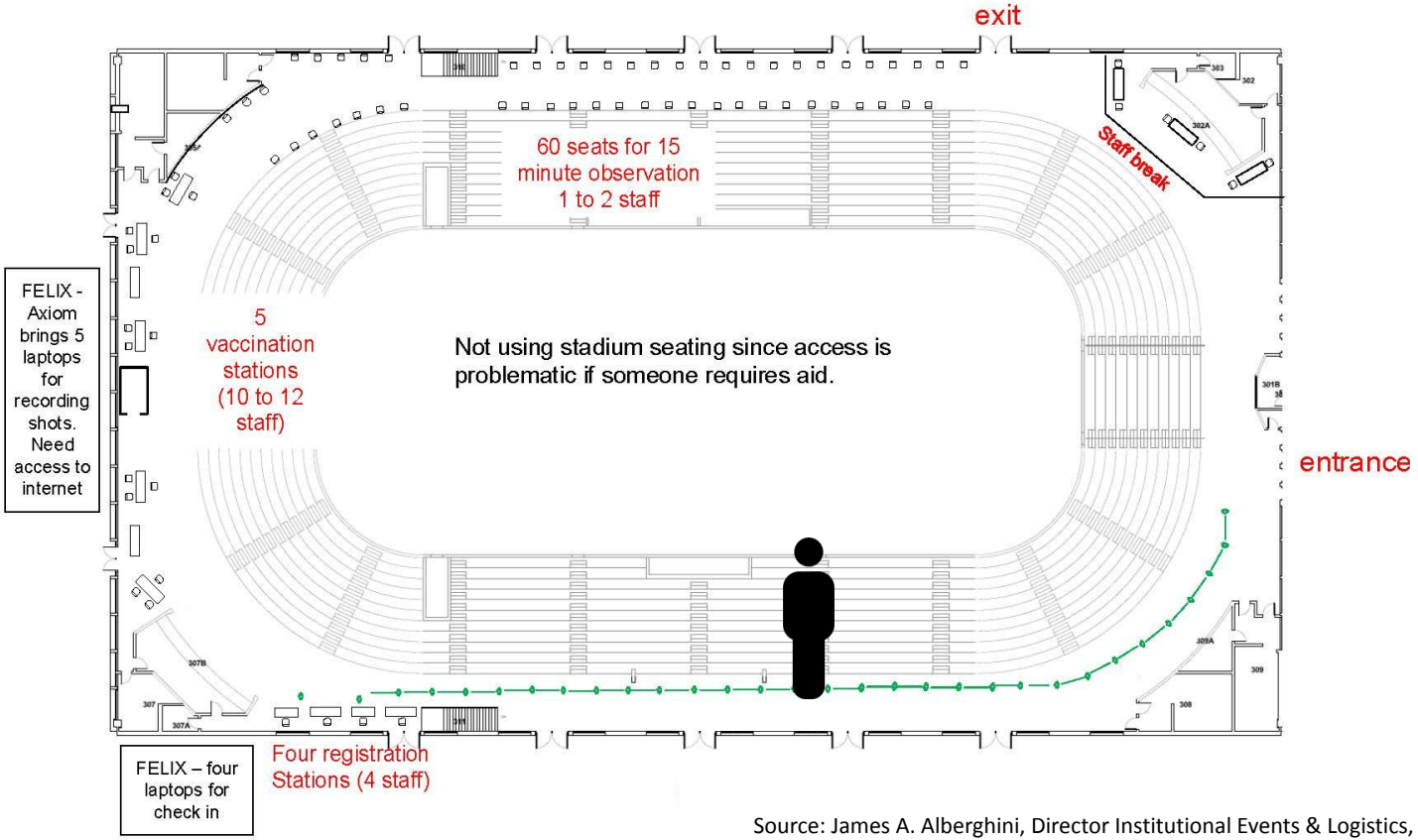

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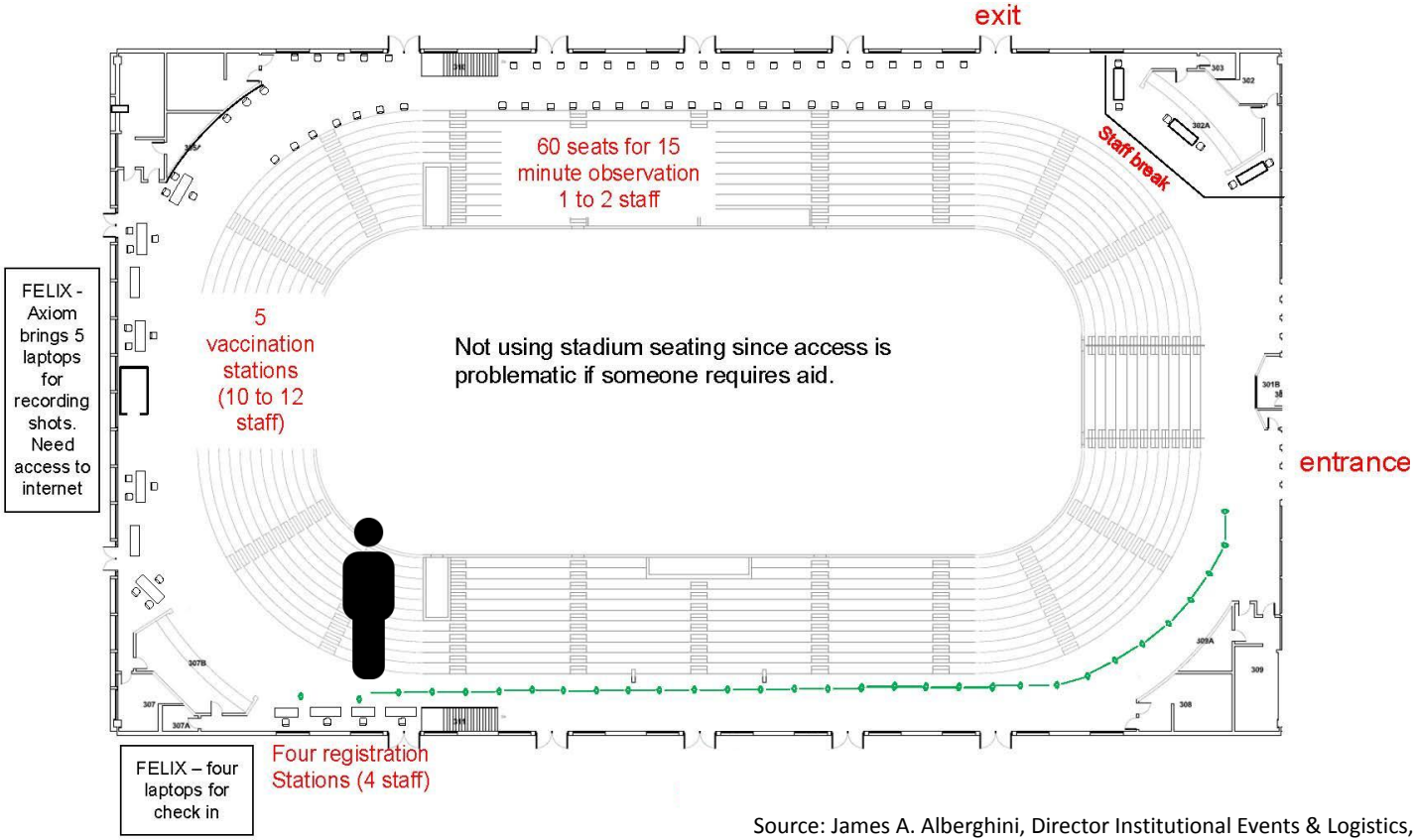

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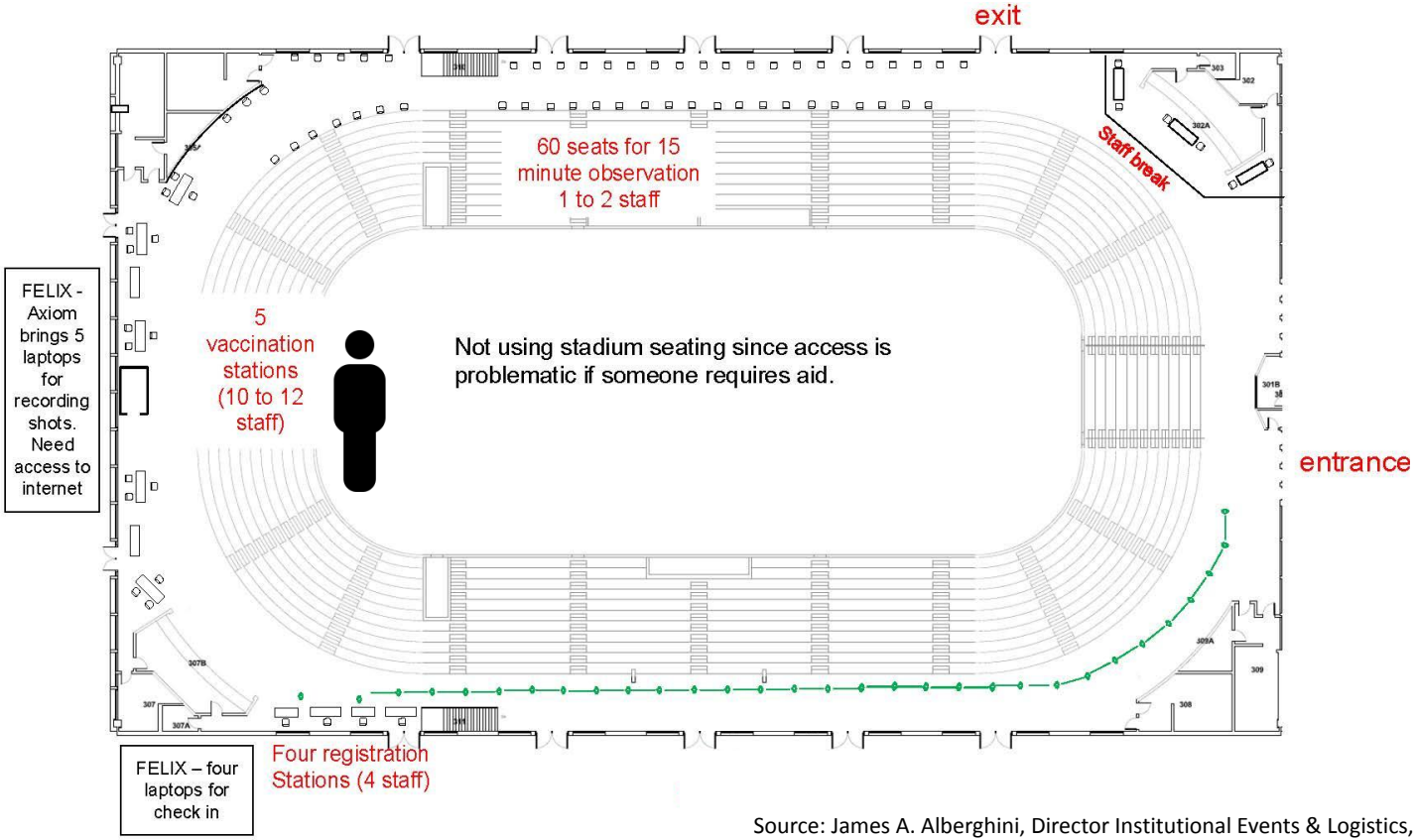

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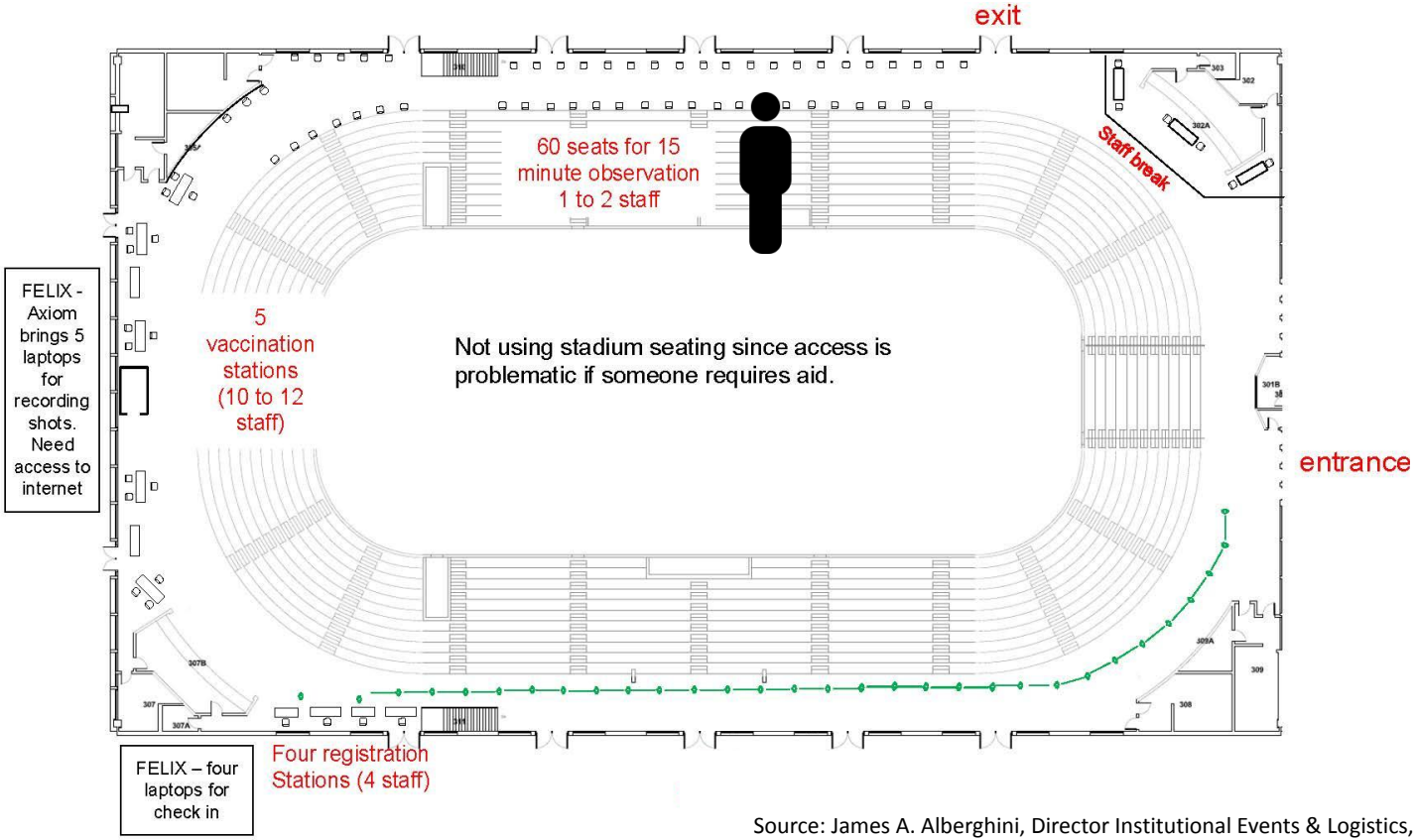

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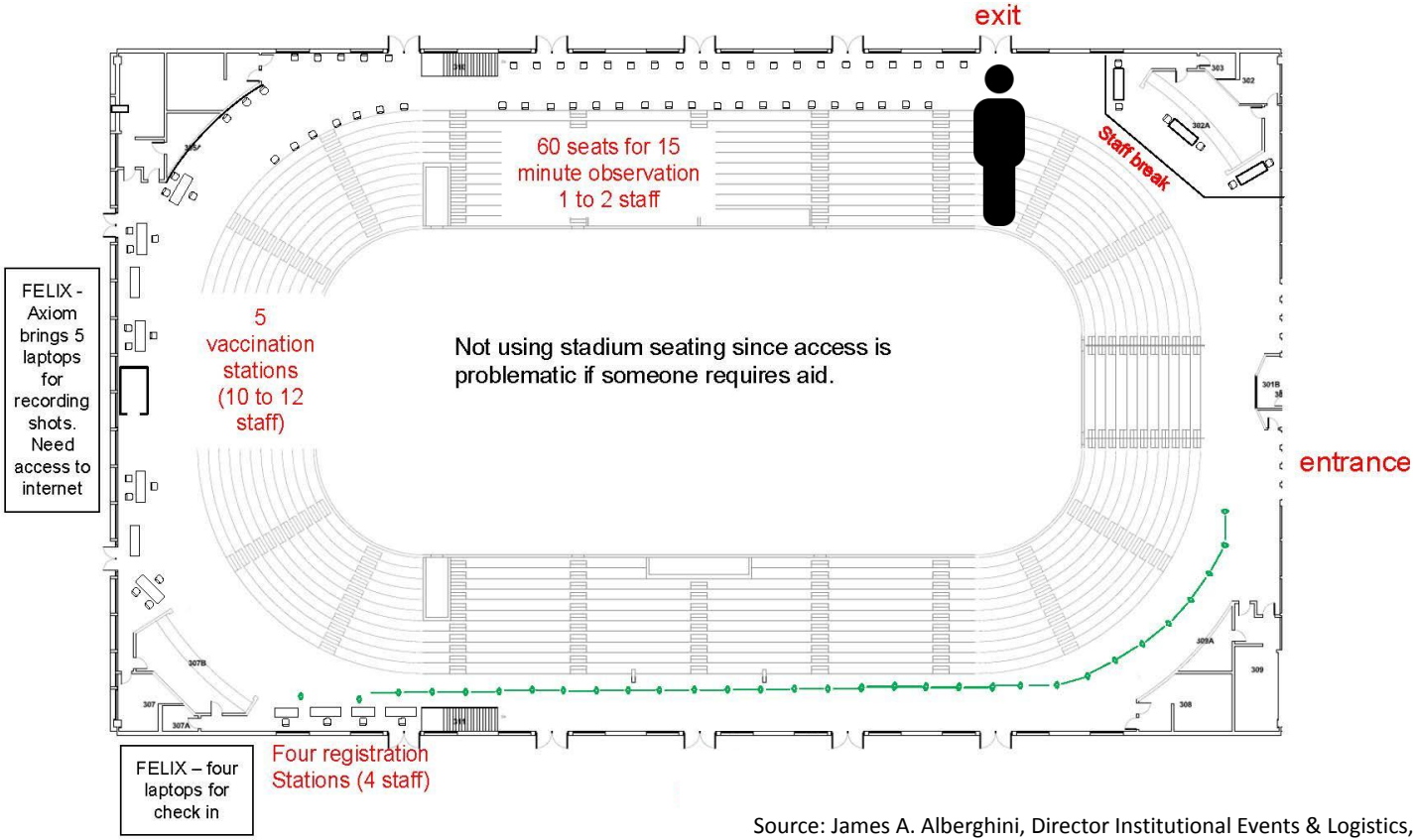

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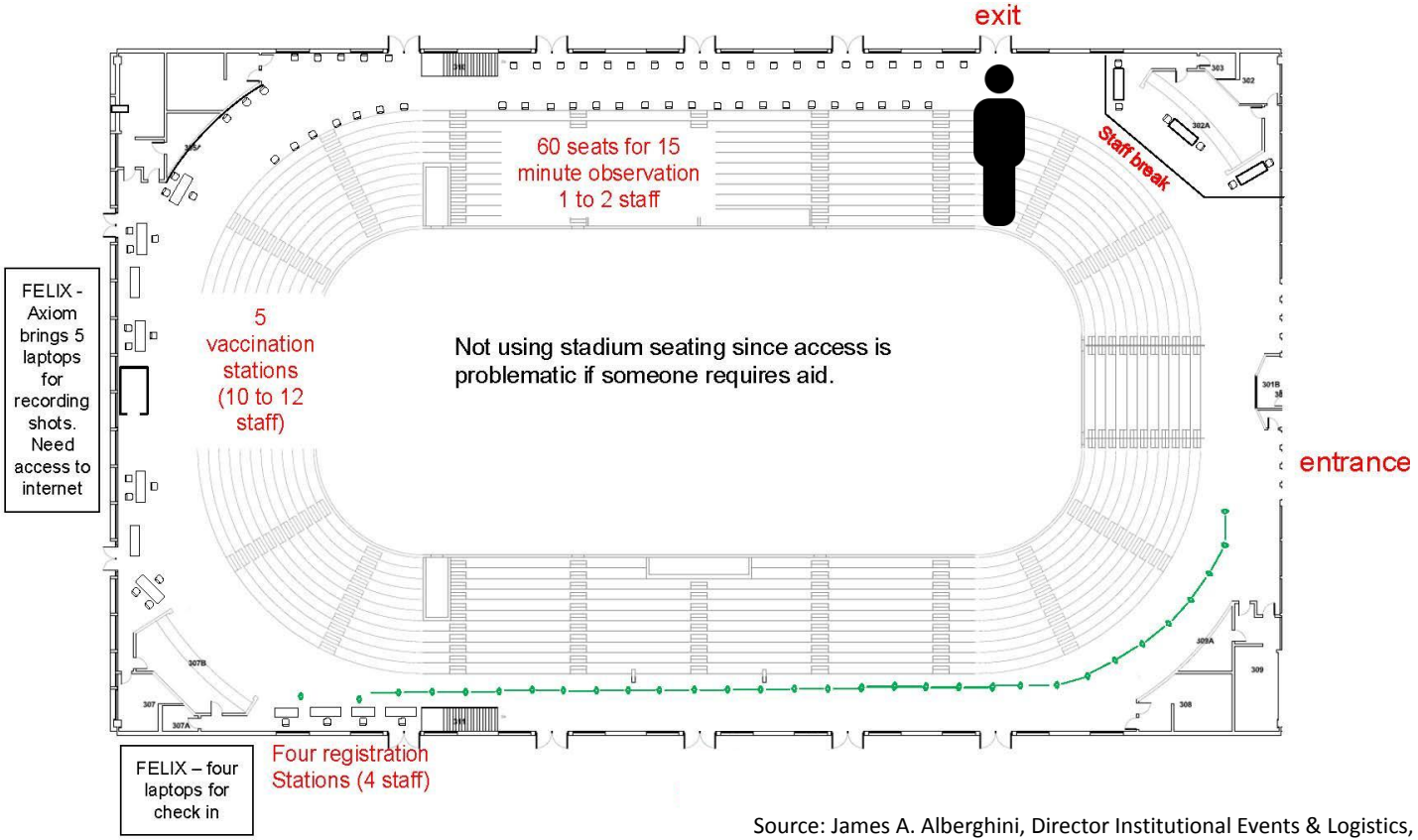

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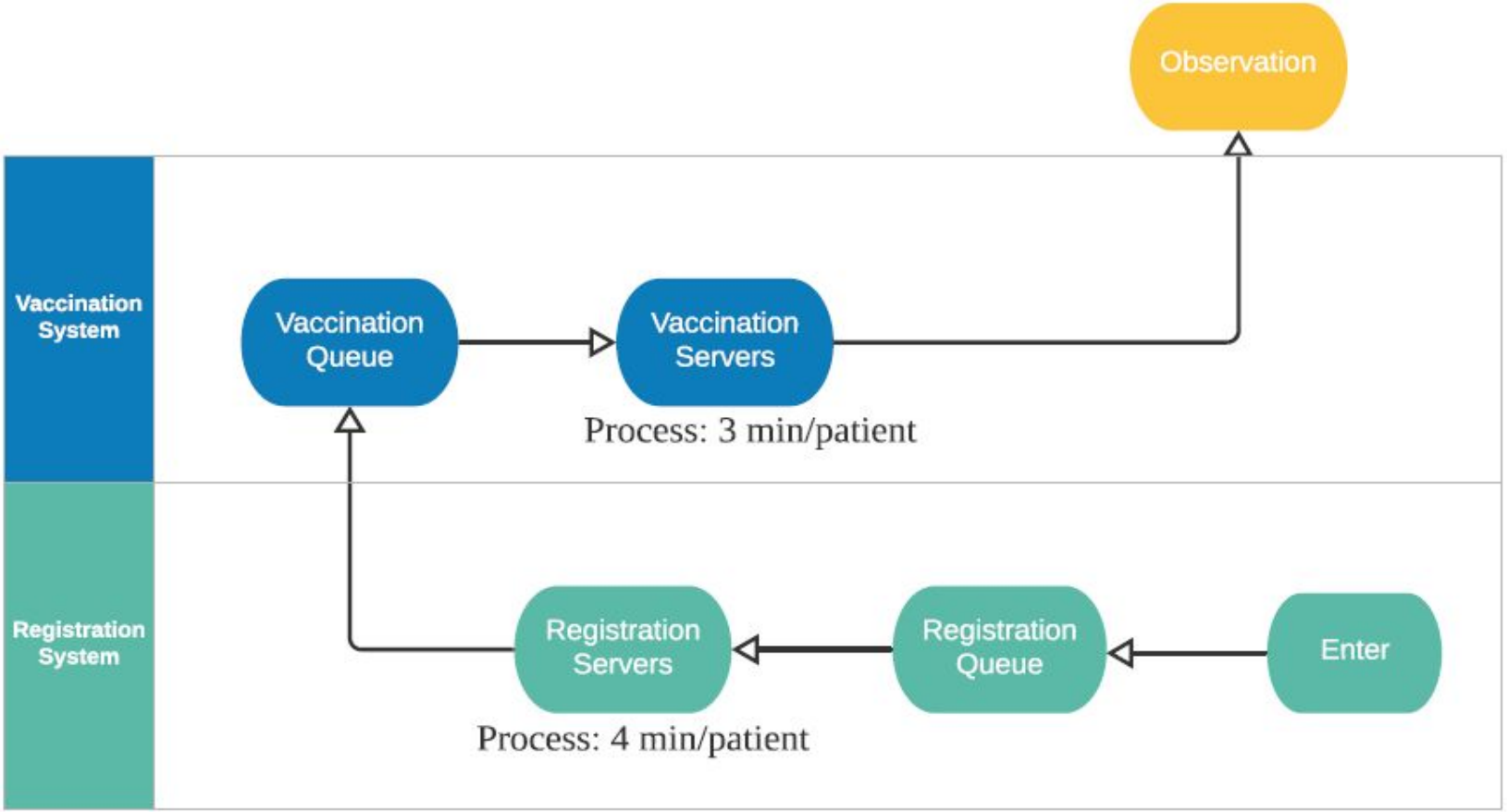
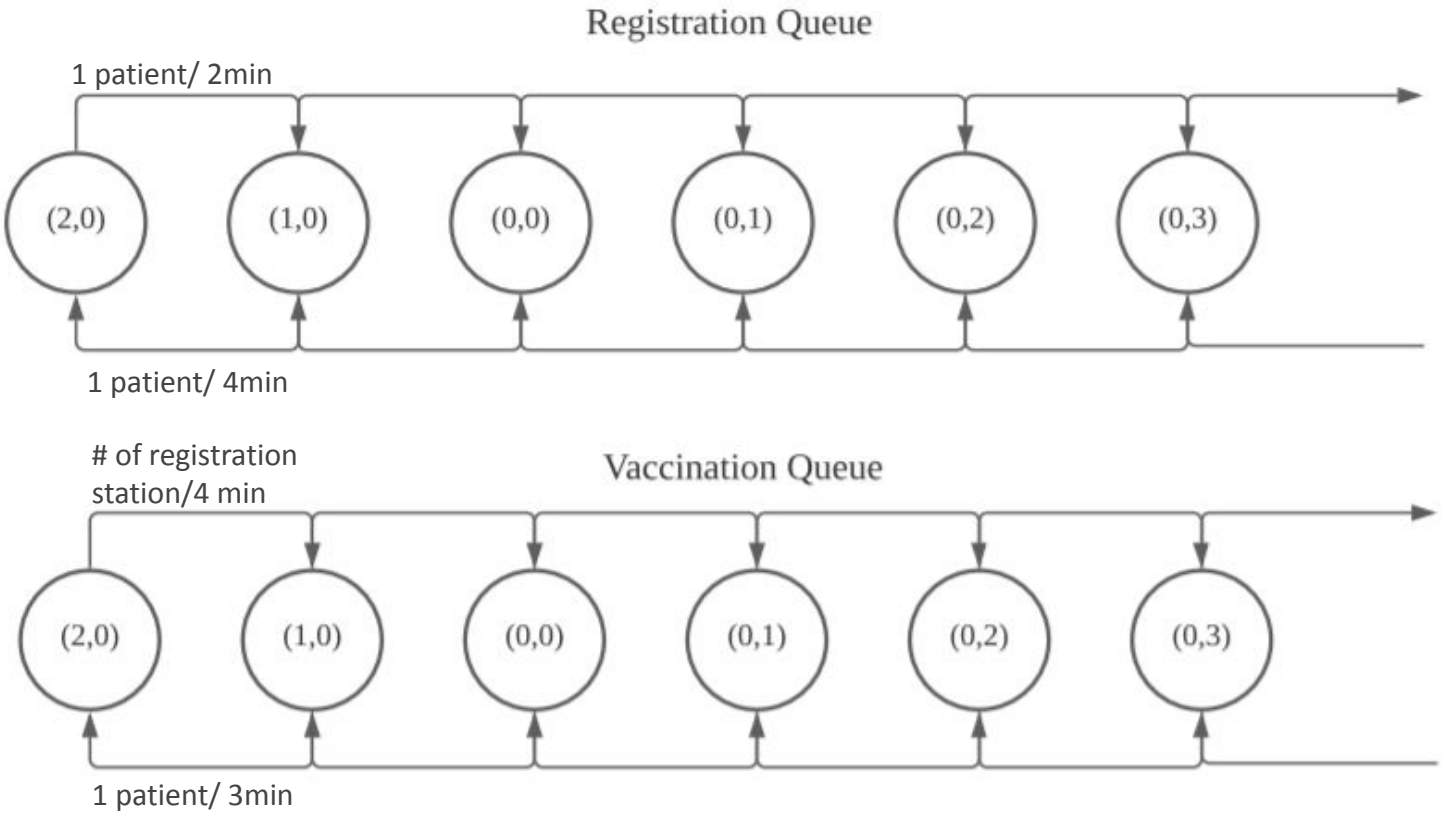
Queuing Theory

No Pre-Registration: Queuing theory

Assumptions:

- Registration times are negative exponential with mean rate of 1 every 4 minutes
- Vaccination times are negative exponential with mean rate of 1 every 3 minutes
- Recording times are negative exponential with mean rate of 1 every 3 minutes
- Observation 15 min for all
- Arrival process is Poisson:
    - 8:00-11:30: inter arrival time mean = 2 min
    - 11:30-3:00: inter arrival time mean = 1.43 min
    - 3:00-6:30: inter arrival time mean = 1.11 min


Observation
Vaccination System
Vaccination Queue
Vaccination Servers
Process: 3 min/patient
Registration System
Registration Servers
Registration Queue
Enter
Process: 4 min/patient


Registration Queue
1 patient/ 2min
(2,0)
(1,0)
(0,0)
(0,1)
(0,2)
(0,3)
1 patient/ 4min
# of registration station/4 min
Vaccination Queue
(2,0)
(1,0)
(0,0)
(0,1)
(0,2)
(0,3)
1 patient/ 3min

Results

Shift 1

		Vaccination & Recording						
		3	4	5	6	7	8	9
Registration	3							
	4							
	5							
	6							

Shift 2

		Vaccination & Recording						
		3	4	5	6	7	8	9
Registration	4							
	5							
	6							
	7							
	8							

Shift 3

		Vaccination & Recording						
		3	4	5	6	7	8	9
Registration	5	-	33.6	24.3	23.5	23.3	23.2	23.2
	6	-	-	26.9	23.1	22.6	22.4	22.3
	7	-	-	-	24.8	22.8	22.3	22.2
	8	-	-	-	-	23.8	22.5	22.2

Simulation

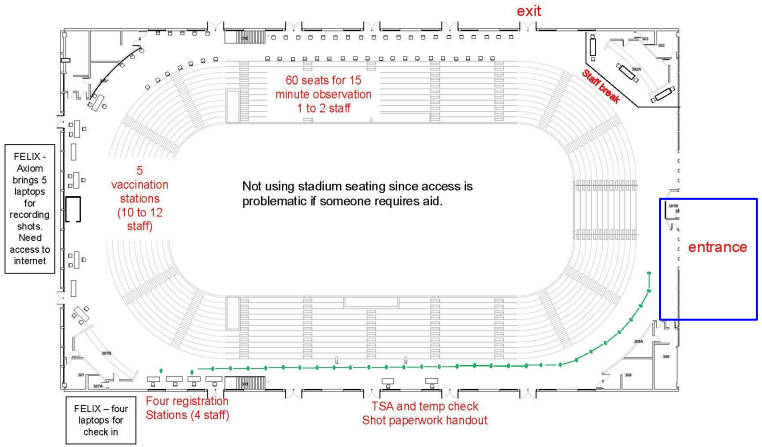
Simulation Set up

- # registration stations and # vaccination stations varied to find the reasonable set of staff numbers that yields reasonable total time in the system (<30min)

- 8:00am-6:30pm, 10 min appointments slots available, 10 slots per 10 min
- Level of busyness varied by % of people who signed up
- 3.5hr simulation periods, equivalent to shift length, simulated multiple times

Simulation Set up

Outside of Arena Capacity = Infinite	← Arrive
	← TSA start
Registration Queue Capacity = 30	← TSA complete
	← Registration Start
Registration Stations Capacity = a	← Registration Complete
Vaccine Queue Capacity = 5	← Vaccination/Recording Start
Vaccination Stations Capacity = b	← Both Complete
Observation Capacity = 60	← Process Complete



Arrival time = [-10 10] min away from appointment time

Simulation Set up

Outside of Arena Capacity = Infinite	← Arrive
Registration Queue Capacity = 30	← TSA start ← TSA complete
Registration Stations Capacity = a	← Registration Start ← Registration Complete
Vaccine Queue Capacity = 5	← Vaccination/Recording Start
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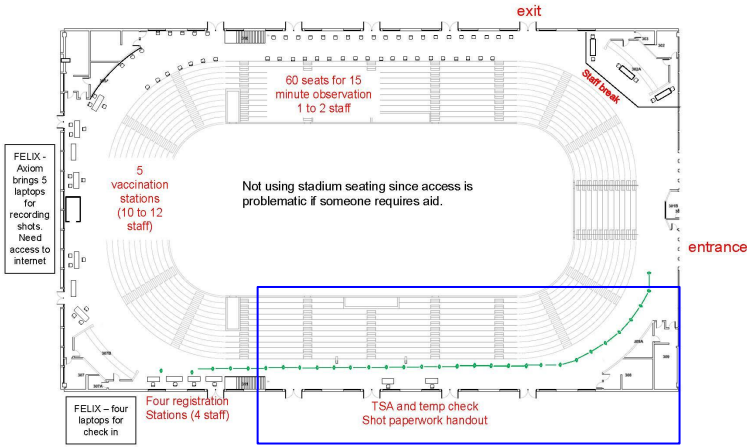

TSA complete time = uniform [1,2]

Simulation Set up

Outside of Arena Capacity = Infinite	← Arrive
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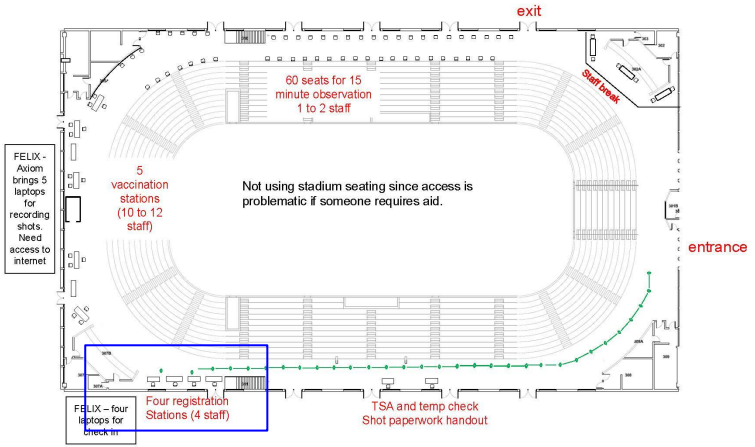

Registration complete time = exponential with rate 1/4min

Simulation Set up

Outside of Arena Capacity = Infinite	← Arrive
	← TSA start
Registration Queue Capacity = 30	← TSA complete
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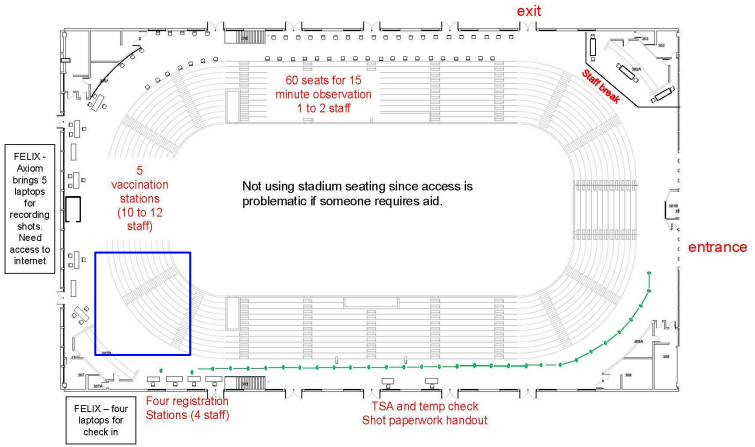

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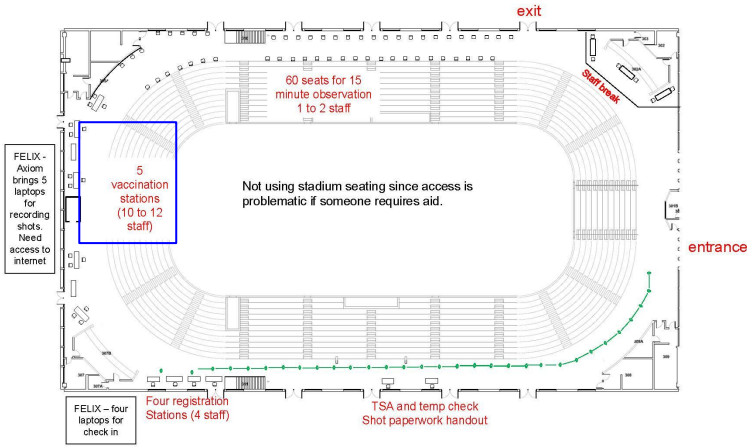

Vaccination complete time = exponential with rate 1/3min

Recording time = uniform [2,4]

Simulation Set up

Outside of Arena Capacity = Infinite	← Arrive
	← TSA start
Registration Queue Capacity = 30	← TSA complete
	← Registration Start
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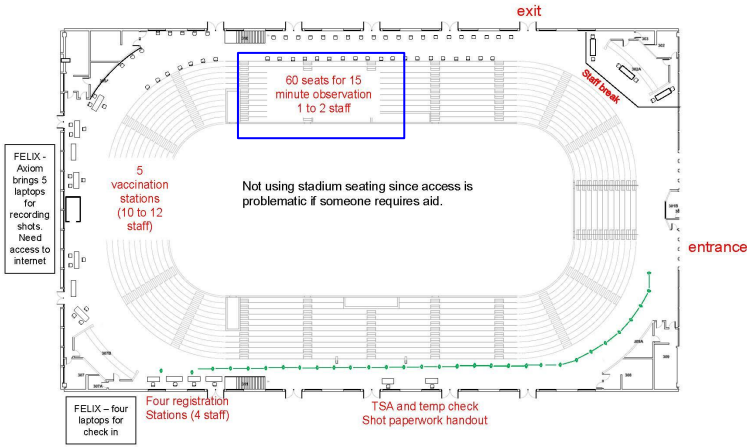
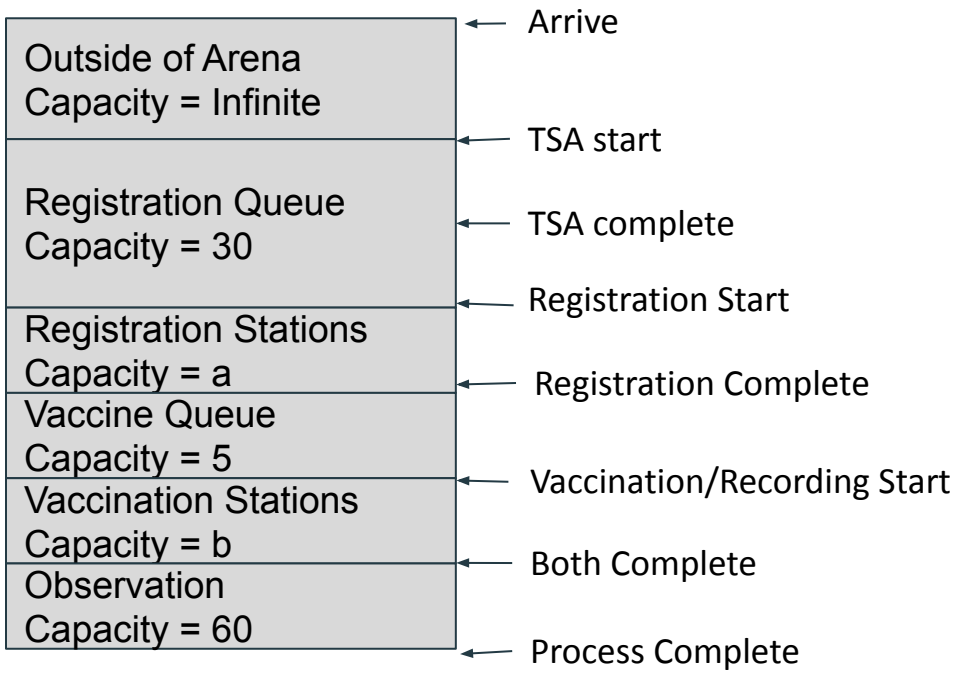


Observation time = 15 min

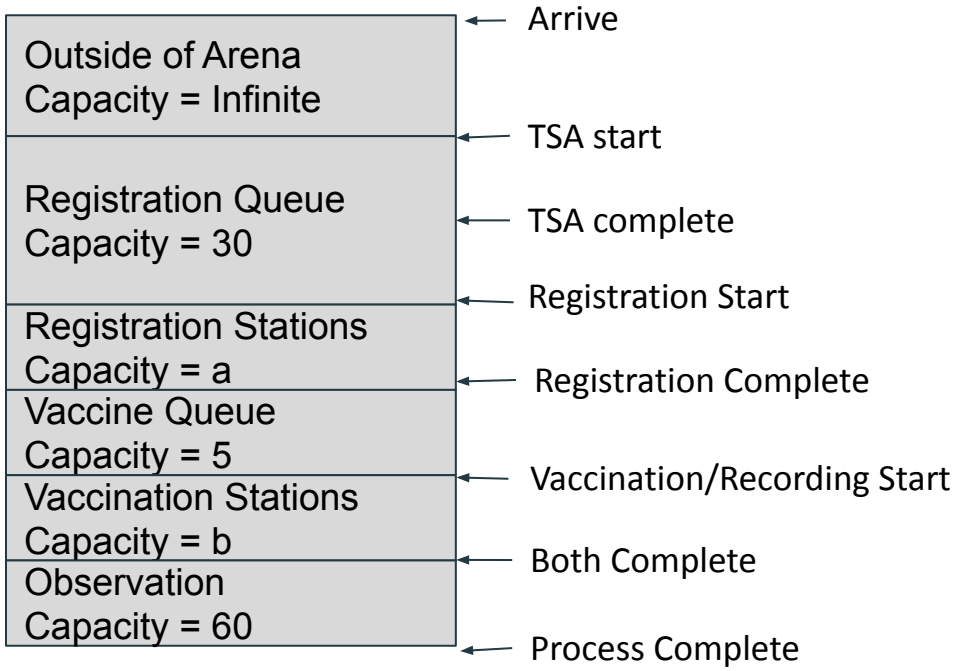
Simulation Set up



Simulation Set up

Number of people in each State = N

There is an N for each state for every Δt



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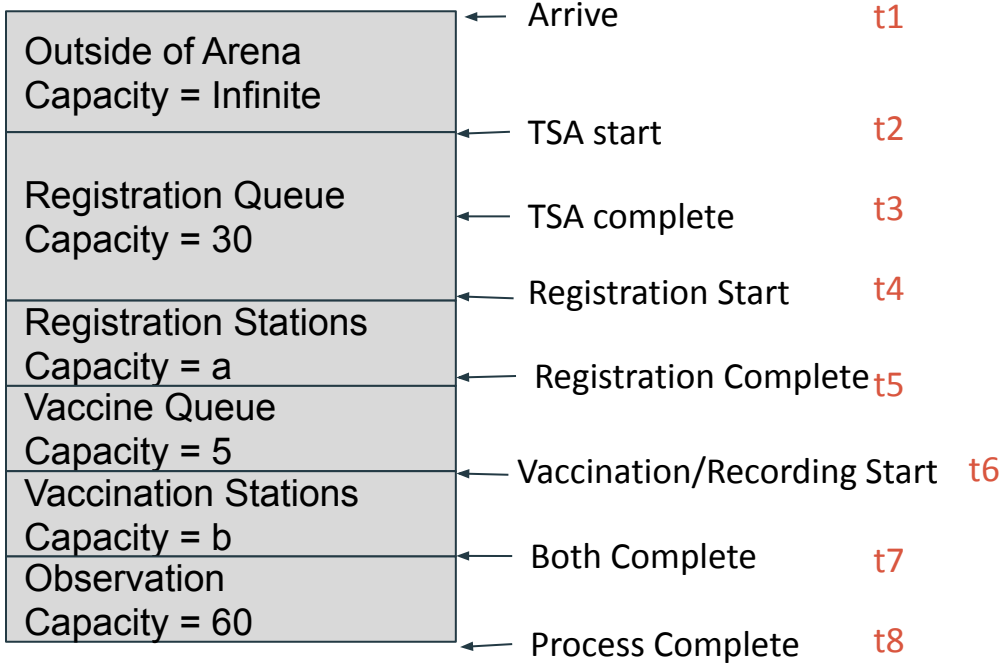


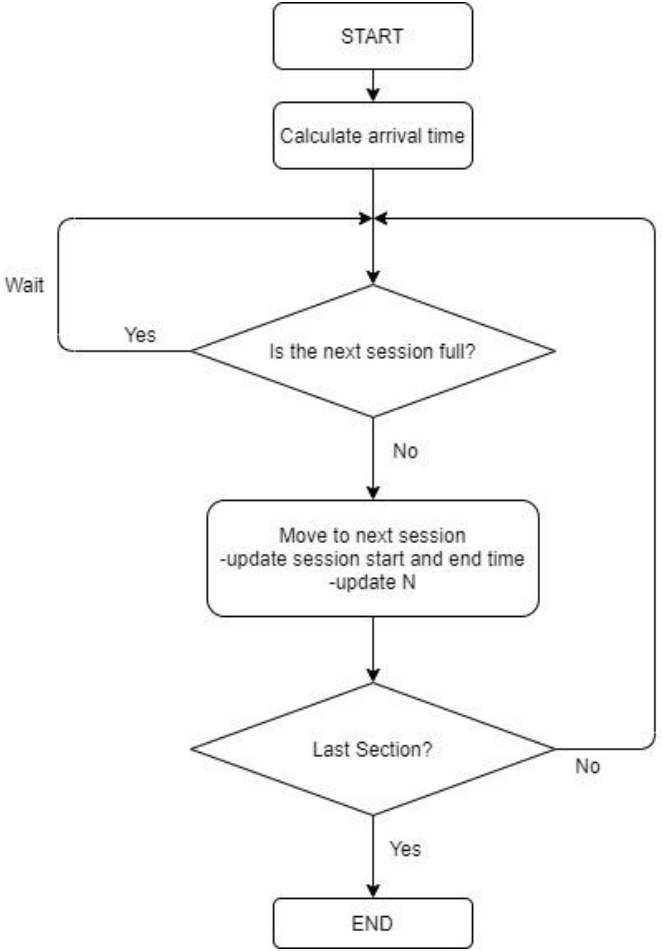
Timestamp for each event = t

There is a t for every event for every patient

Simulation Set up

For each person that comes to the vaccination
Simulation Algorithm ->

Then time in the system W is calculated



Simulation Results

Time in systems calculated with different # of stations

# Registration Stations \ # vaccination stations	1	2	3	4	5	6
1	248.2986	205.1096	205.0978	206.4149	204.1084	205.4796
2	214.3726	85.02821	68.76478	66.92255	66.89638	67.09747
3	212.1873	69.42814	35.36896	31.22662	30.52265	30.19805
4	211.2348	68.18714	29.83244	26.14779	25.66994	25.52728
5	212.3847	68.30247	29.32588	25.39201	24.95664	24.86789
6	211.6365	67.94748	28.56874	25.19043	24.80507	24.69743

Shift 2 Normal

# Registration Stations \ # vaccination stations	1	2	3	4	5	6
1	160.0589	128.4338	127.5529	127.4257	125.8966	126.9808
2	131.6591	44.6347	37.16632	36.18122	35.90469	35.98012
3	129.3792	35.09832	26.6427	26.06307	25.89047	25.86569
4	130.9925	34.20051	25.64519	24.99642	24.87306	24.85764
5	129.7175	34.243	25.39045	24.83361	24.69813	24.65446
6	129.663	34.04469	25.35193	24.78221	24.67269	24.63315

Shift 1 (relatively) Idle

# Registration Stations \ # vaccination stations	1	2	3	4	5	6
1	338.3333	286.6138	285.5161	283.9802	285.2086	284.4529
2	295.4905	128.3856	108.4287	106.2201	105.5732	105.5659
3	293.3481	109.7111	60.48912	49.60022	47.2973	47.22472
4	293.3535	107.9419	49.45368	31.10255	28.49382	28.11046
5	292.727	107.487	47.99694	27.71783	25.75922	25.38716
6	292.4625	107.9519	47.57065	26.96659	25.22146	24.93989

Shift 3 Busy

Simulation Results

Conditions with time less than 30 min

# Registration Stations \ # vaccination stations	1	2	3	4	5	6
1	248.2986	205.1096	205.0978	206.4149	204.1084	205.4796
2	214.3726	85.02821	68.76478	66.92255	66.89638	67.09747
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Shift 3 Busy

Simulation Results

- More staff, less average time
- Improvement of wait time per additional station decreases as # stations increase

	# vaccination stations 1	2	3	4	5	6
1	338.3333	286.6138	285.5161	283.9802	285.2086	284.4529
2	295.4905	128.3856	108.4287	106.2201	105.5732	105.5659
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Less time

Less time

SImulation Results

- More staff, less average time
- Improvement of wait time per additional station decreases as # stations increase

	# vaccination stations 1	2	3	4	5	6	
1	338.3333	286.6138	285.5161	283.9802	285.2086	284.4529	178.8871
2	295.4905	128.3856	108.4287	106.2201	105.5732	105.5659	58.34115
3	293.3481	109.7111	60.48912	49.60022	47.2973	47.22472	19.11426
4	293.3535	107.9419	49.45368	31.10255	28.49382	28.11046	2.723297
5	292.727	107.487	47.99694	27.71783	25.75922	25.38716	0.447269
6	292.4625	107.9519	47.57065	26.96659	25.22146	24.93989	
	184.5106	60.38122	20.60406	1.745135	0.281564		

SImulation Results

- More staff, less average time
- Improvement of wait time per additional station decreases as number of the same type of station increase

	1	2	3	4	5	6	
1	338.3333	286.6138	285.5161	283.9802	285.2086	284.4529	178.8871
2	295.4905	128.3856	108.4287	106.2201	105.5732	105.5659	58.34115
3	293.3481	109.7111	60.48912	49.60022	47.2973	47.22472	19.11426
4	293.3535	107.9419	49.45368	31.10255	28.49382	28.11046	2.723297
5	292.727	107.487	47.99694	27.71783	25.75922	25.38716	0.447269
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4	293.3535	107.9419	49.45368	31.10255	28.49382	28.11046	2.723297
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6	292.4625	107.9519	47.57065	26.96659	25.22146	24.93989	
	184.5106	60.38122	20.60406	1.745135	0.281564		

Comparison with Queuing Model

- Same trend
- Difference in time due to different assumptions

	3		4		5		6	
	Sim	Que	Sim	Que	Sim	Que	Sim	Que
3	26.6427	26.1						
4	25.64519	24.2	24.99642	23.8	24.87306	32.5		
5	25.39045	23.9	24.83361	22.7	24.69813	23.2	24.65446	26.6
6	25.35193	23.8	24.78221	22.4	24.67269	22.4	24.63315	22.8

Comparison of shift 1 results

Integer Programming

Parameters

Parameters	Value
Number of candidate staff	11
Number of candidate staff manager	3
Number of candidate vaccination specialist	12
Number of candidate medical student	5
Number of shifts per day	3
Minimum number of shift each day	0
Maximum number of shift each day	2

Parameters	Value
Cost for each registration staff	$10
Cost for each registration manager	$15
Cost for each vaccination staff	$30
Cost for each medical student	$0
Number of staff in each vaccination station	2
Number of staff in each registration station	1
Number of staff in each observation station	1
Number of vaccination stations per shift	**based on scenario**
Number of registration stations per shift	**based on scenario**
Number of observation stations per shift	**based on scenario**

Integer Programming Formulation

Data:

V: set of all vaccination specialists and medical students
V_s: set of medical students
R: set of staff responsible for registration and observation
R_m: set of staff manager
S: set of shifts
D: set of days

v_i: cost of assigning a vaccination specialist or a medical student i
r_j: cost of assigning a staff j
q_s: number of total staff required a shift s
q_v: number of vaccination specialist and medical students required for a shift s
s_d: subset of shifts in day d

Decision Variables:

x_i: whether or not to assign the vaccination specialist or the medical student i
y_j: whether or not to assign the staff to registration or observation station j

Integer Programming Formulation

$$Minimize \sum_{i \in V} v_i * x_i + \sum_{j \in R} r_j * y_j \quad (1)$$

Subject to:

$$\sum_{i \in V} x_i + \sum_{j \in R} y_j = q_s, \forall s \in S \quad (2)$$

$$\sum_{i \in V} x_i \geq q_v, \forall s \in S \quad (3)$$

$$0 \leq \sum_{i \in V} x_i \leq 2, \forall d \in D \quad (4)$$

$$0 \leq \sum_{j \in R} y_j \leq 2, \forall d \in D \quad (5)$$

$$\sum_{i \in V_s} x_i \leq 2, \forall s \in S \quad (6)$$

$$\sum_{j \in R_m} y_j \geq 1, \forall s \in S \quad (7)$$

$$x_i \in \{0, 1\}, \forall i \in V \quad (8)$$

$$y_j \in \{0, 1\}, \forall j \in R \quad (9)$$

Simulation Results

Benchmark Scenario

1. Shortest time
2. Fewest People
3. Similar Time

vaccination stations

# Registration Stations	1	2	3	4	5	6
1	160.0589	128.4338	127.5529	127.4257	125.8966	126.9808
2	131.6591	44.6347	37.16632	36.18122	35.90469	35.98012
3	129.3792	35.09832	26.6427	26.06307	25.89047	25.86569
4	130.9925	34.20051	25.64519	24.99642	24.87306	24.85764
5	129.7175	34.243	25.39045	24.83361	24.69813	24.65446
6	129.663	34.04469	25.35193	24.78221	24.67269	24.63315

Shift 1 (relatively) Idle

vaccination stations

# Registration Stations	1	2	3	4	5	6
1	248.2986	205.1096	205.0978	206.4149	204.1084	205.4796
2	214.3726	85.02821	68.76478	66.92255	66.89638	67.09747
3	212.1873	69.42814	35.36896	31.22662	30.52265	30.19805
4	211.2348	68.18714	29.83244	26.14779	25.66994	25.52728
5	212.3847	68.30247	29.32588	25.39201	24.95664	24.86789
6	211.6365	67.94748	28.56874	25.19043	24.80507	24.69743

Shift 2 Normal

vaccination stations

# Registration Stations	1	2	3	4	5	6
1	338.3333	286.6138	285.5161	283.9802	285.2086	284.4529
2	295.4905	128.3856	108.4287	106.2201	105.5732	105.5659
3	293.3481	109.7111	60.48912	49.60022	47.2973	47.22472
4	293.3535	107.9419	49.45368	31.10255	28.49382	28.11046
5	292.727	107.487	47.99694	27.71783	25.75922	25.38716
6	292.4625	107.9519	47.57065	26.96659	25.22146	24.93989

Shift 3 Busy

Scenarios & Results

Scenario				Simulation W (min)				Cost ($)
No.	Vaccination Station	Registration Station	Observation Station	Shift 1 (min)	Shift 2 (min)	Shift 3 (min)	Average (min)	
benchmark	4,4,4,4,4,4	5,5,5,5,5,5	1,1,2,1,1,2	24.8336	25.3920	27.7178	25.9811	1160
1	6,6,6,6,6,6	6,6,6,6,6,6	1,1,2,1,1,2	24.63315	24.6974	24.9399	24.7568	2060
2	3,3,4,3,3,4	3,4,5,3,4,5	1,1,2,1,1,2	26.6427	29.8324	27.7178	28.0643	800
3	4,5,5,4,5,5	4,5,5,4,5,5	1,1,2,1,1,2	24.7964	24.9566	25.2215	25.1705	1340

Shift Assignment (benchmark scenario)

Shift No.	Specialist	Student	Reg Manager	Reg Staff
May 5th - shift 1	3,4,5,6,7	13,15	1,2,3	11
May 5th - shift 2	1,2	16,17	2,3	4,5,6,7,8
May 5th - shift 3	1,2	16,17	1	4,5,6,7,8,9,10,11,12,14
May 6th - shift 1	9,10,11	14,16	1,2,3	4,5,7
May 6th - shift 2	7,9,10,11	13,17	3	4,6,10,11
May 6th - shift 3	7,8	15,17	1,2	5,6,7,8,9,10,11,12,14

Shift Assignment (scenario 1)

Shift No.	Specialist	Student	Reg Manager	Reg Staff
May 5th - shift 1	4,5,7,12	14,17	1,2,3	4
May 5th - shift 2	1,2,3,5,6,7,8,9,10	14,16	2,3	5,6,8,10,11,13
May 5th - shift 3	1,2,3,4,6,8,9,10,11	12,16	1	4,5,6,7,8,9,10
May 6th - shift 1	1,2,3,4,8,9,10,11	13,16	2,3	4,6,7,8,9,10
May 6th - shift 2	1,5,6,7,9,10,11,12	13,17	1	4,6,9,10,11,12,13,14
May 6th - shift 3	2,3,4,5,6,7,8,12	15,17	1,2,3	5,7,8,11,12,13,14

Shift Assignment (scenario 2)

Shift No.	Specialist	Student	Reg Manager	Reg Staff
May 5th - shift 1	2	13,15	1	4,5,9,10,13,14
May 5th - shift 2	1	16,17	3	6,7,8,10,11,12,14
May 5th - shift 3	1,2	16,17	1	3,4,5,6,7,8,9,11,12,13
May 6th - shift 1	11	14,16	3	4,5,9,10,12,13
May 6th - shift 2	12	13,17	2	4,6,7,8,11,13,14
May 6th - shift 3	8,9	15,17	2	3,5,6,7,8,9,10,11,12,14

Shift Assignment (scenario 3)

Shift No.	Specialist	Student	Reg Manager	Reg Staff
May 5th - shift 1	3,4,5,6,7	13,15	2,3	4,6,12
May 5th - shift 2	1,2,3	16,17	1,2,3	5,7,8,9,10,11,13,14
May 5th - shift 3	1,2,4	16,17	1	4,5,6,7,8,9,10,11,12,13,14
May 6th - shift 1	9,10,11	14,16	1,3	4,5,7,9,13
May 6th - shift 2	9,10,11,12	13,17	2	4,6,8,9,10,11,12,13,14
May 6th - shift 3	4,5,6,7,8	15,17	1,2,3	5,7,8,10,11,12,14

Conclusion

- More staffing results in less vaccination time, but the marginal benefit decreases
- To keep the average time under 30 min, at least 3 registration and 3 vaccination stations is needed.
- The staffing cost can be potentially decreased by 31% from benchmark situation if the health services is willing to increase the average wait time by 1 minute.

Potential Improvements & Future Steps

- Use more realistic data, especially for arrival rate
- Use weighted score to evaluate the scenario performance

Enjoy Summer!

Reference

Dartmouth Common Data Set. https://www.dartmouth.edu/oir/data-reporting/cds/index.html

New Hampshire COVID-19 Response. https://www.covid19.nh.gov/dashboard/vaccination

OFFICIAL SITE OF DARTMOUTH COLLEGE VARSITY ATHLETICS.
https://dartmouthsports.com/sports/2018/5/29/thompson-arena.aspx

Asgary, Ali, et al. "A drive-through simulation tool for mass vaccination during COVID-19 pandemic." Healthcare. Vol. 8. No. 4. Multidisciplinary Digital Publishing Institute, 2020.

Wiggers, Jochem, et al. "Design and Analysis of a Simulation Model for Drive-Through Mass Vaccination." IIE Annual Conference. Proceedings. Institute of Industrial and Systems Engineers (IISE), 2011.

Q&A

Data available: https://github.com/yezhang2020/ENGS103

Useless slides

Simulation Set up

a.

10min registration period

b. 10 slots per period

c.
   i. 8:00-11:30: inter arrival time mean = 2min, pct = 50%
   ii. 11:30-3:00: inter arrival time mean = 1.43min, pct = 70%
   iii. 3:00-6:30: inter arrival time mean = 1.11min, pct = 90%

d. Uniform distribution between [-10 10] min of scheduled time.

e. Assume infinite queue capacity after arrival (can always wait outside the arena)