Voting Poll Queuing Analysis: Reconfiguring Voting Center Layouts and Making Recommendations to Reduce Waiting Times

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I. INTRODUCTION

As the 2020 presidential election approaches, the long lines at voting stations raises our attention. In this paper, voting stations are modeled as service systems where voters utilizes the voting facilities and with the staff's help, completes a 'voting' service. The objective of this paper is to explore various methods that can reduce the voter waiting time outside of voting centers and thus improve the voting experience. Starting with the current voting station layouts, we modeled other alternative layouts by adding or reducing certain components to identify the bottleneck process in a voting station and the corresponding optimal solution.

Why Research on Voting Practices is Important

Every year millions of Americans head to the polls on Election Day to cast their ballot. The process of voting may take less than ten minutes or longer than two hours depending on the community. Extreme waiting times predominantly occur due to a lack of resources in low income and minority areas. On average minority voters are six times as likely to wait more than an hour to vote.[1] The long wait times for these groups take away from the time they could be working to pay their bills or spending time with their children. In some cases, the lines have become so long that voters have been turned away or decide their vote is not worth standing in line for that long. It has been questioned if long waiting times decided the 2000 and 2004 elections. In 2000 one state, Florida was the deciding factor. The winner was favored by only 537 votes.[2] News outlets reported the long wait times and speculated how many of the voters in line balked or reneged. The long wait times in minority communities contribute to a decrease in votes for the candidates that have a special interest in these underserved communities. It is less likely for minority favored candidates to be elected with this ongoing problem and the cycle of long waiting times continues. In addition to addressing the waiting time problem, these candidates aim to help minority communities which improves the country as a whole.

Psychology of Waiting to Vote

Voting is an important part of being a good citizen. Voting is key to the running of the nation and improving the local community. People will willingly wait 90 minutes to ride the Avatar Flight of Passage ride at Disney, but do not want to wait that long to cast their ballot. As analyzed by David Maister[4], there is a psychology of waiting in lines. The experience of waiting in line for Disney's 5-minute Avatar ride is the complete opposite of waiting to cast a ballot. In Disney's Animal Kingdom families enter the line surrounded by plants and animals that are interactive. As the line moves, kids feel as if they are entering Avatar's alien world of Pandora. Gravity-defying rocks appear overhead while fake bioluminescent plants perk up from all around. Due to the interactive nature of the line, the time feels shorter. The ride feels as if it is already beginning while it will still be a 60-minute wait until the actual ride begins. The line also has waiting times down the path. Guests feel better knowing the time is finite until they get to the front of the line. Each of these aspects of waiting in line is not true for voting. In the worst circumstances, people have to stand in line for two hours outside the polling place, usually a school or public building. There is no entertainment or interaction on this 120-minute long wait. The time feels longer than 2 hours with nothing to do or even look at. Upon entering the line voters do not know how long it will take. There are no signs that update the voter on how much time is left until voting. People feel uncertain whether waiting times will be longer than finite known ones. These attributes provide reasoning for why people are less likely to wait to vote than wait to ride the new Avatar adventure at Disney.

II. DATA ANALYSIS -- ITHACA VS NYC

To begin the data analysis, we first found data on how long voters wait in each state. However, there's no public data on how long it takes at each station. Our model aims at identifying the bottleneck station that impacts waiting time the most by testing adding or removing service capacities at each station (for example, adding a check-in desk, voting stations, etc.). In order to obtain an accurate estimation of the arrival times and polling time, in reality, we visited a polling station in Ithaca and recorded the layout of the polling station, time spent at each station and queue lengths from 8 AM-10 AM and again from 4 PM-6 PM. From the data recorded, if we can generalize such observations to a larger geographic area, such as New York City, then we are confident that the conclusion drawn from the models can be well applied to other metropolitan cities.

Approximation of Inter-Arrival Times

Based on our empirical data collected on November 5, 2019 at a polling station in Ithaca. NY, we estimate the interarrival times in a more densely populated city. In our case study, we will use New York City as an example. *Let* $\lambda_{i,j}$ *= the rate of arrivals during time period i in city j*. Time period $i = m$ denotes the morning hours of 6:00am to 11:00am, time period $i = b$ denotes 11:00am to 4:00pm, time period $i = e$ denotes the evening times between 4:00pm to 9:00pm. From our empirical data, the average interarrival time in Ithaca, during the morning hours of 8:06am to 8:49am was 2.5 minutes. The average interarrival time in the evening hours was 1.83 minutes. We approximate the interarrival times using our empirical data and with reference to the *Data for Democracy* study done by the Pew Charitable Trusts organization. In particular, having a medium rate of arrivals in the morning, a calm rate of arrivals mid-day and a high rate of arrivals in the evening from 4:00pm to 9:00pm is consistent with arrival data from the *Data for Democracy* study performed on polling stations in three counties in California[3]. As a result, in the following simulations, we apply a non-homogeneous Poisson process as defined below to simulate arrivals into the Ithaca voting center.

$$\text{Let } \frac{1}{\lambda_{m,I}} = 2.50 \textit{ minutes}, \ \frac{1}{\lambda_{e,I}} = 1.42 \textit{ minutes}, \ \frac{1}{\lambda_{b,I}} = 3.17 \textit{ minutes}$$

$$\lambda(t)_{\text{ITHACA}} = \begin{cases} 24 \text{ people / hr} & 6{:}00 \text{ am} \le t < 11{:}00 \text{ am} \\ 42.254 \text{ people / hr} & 11{:}00 \text{ am} \le t < 4{:}00 \text{ pm} \\ 18.827 \text{ people / hr} & 4{:}00 \text{ pm} \le t \le 9{:}00 \text{ pm} \end{cases}$$

Now we extend our empirical results to approximate interarrivals for New York City. The population of Ithaca, NY is approximately 30,999 people. There are 10 polling stations in Ithaca.2 Therefore, there are approximately 3099 people assigned to each station. In New York City, with a population of 8.623 million people and 1231 polling stations, we expect approximately 8,623,000/1231= 7005 people to be assigned to each polling station. There are 2.26 more people assigned to polling stations in New York City than in Ithaca. Therefore, we approximate interarrival times in New York City to be 2.26 times more frequent than our empirical data.

$$\frac{1}{\lambda_{m,N}} = \frac{\frac{1}{\lambda_{m,I}}}{2.26} = \frac{2.5}{2.26} = 1.106 \text{ minutes}, \quad \frac{1}{\lambda_{b,N}} = \frac{3.58}{2.26} = 1.584 \, minutes, \quad \frac{1}{\lambda_{e,N}} = \frac{\frac{1}{\lambda_{m,I}}}{2.26} = \frac{1.42}{2.26} = 0.628 \text{ minutes}$$

$$\lambda(t)_{NYC} = \begin{cases} 54.250 \text{ people / hr} & 6{:}00 \text{ am} \le t < 11{:}00 \text{ am} \\ 37.877 \text{ people / hr} & 11{:}00 \text{ am} \le t < 4{:}00 \text{ pm} \\ 95.493 \text{ people / hr} & 4{:}00 \text{ pm} \le t \le 9{:}00 \text{ pm} \end{cases}$$

Simulation Model

Our initial voting center layout includes two check-in stations, three voting stations where individuals can fill out their ballot, and a check-out station containing a machine where ballots are submitted. An arriving individual goes to check-in table 1 or check-in table 2 according to the first initial of their surname. Therefore, in our simulations, the paths connecting the arrival to a check-in station are each weighted with a 50% probability. Based on our observations at the Ithaca polling stations, the check-in procedure took as few as 27 seconds, at most 138 seconds and 72 seconds on average. In our simulation, we approximate the check-in service time using a triangular distribution with parameters: minimum = 27 seconds, maximum = 138 seconds and mode = 72 seconds.

Following the check-in procedure, individuals proceed to a voting booth to fill out their ballot. The individual will select an open voting booth if one is available. Otherwise, they will wait until a booth becomes free. By our observations at the Ithaca polling center, people took 173 seconds to denote their candidate selections on the ballot. The fastest voter took just 40 seconds and the tardiest voter took 361 seconds. In our simulation, we approximate the ballot-filling time using a triangular distribution with parameters: minimum = 40 seconds, maximum = 361seconds and mode = 173 seconds.
After filling out the ballot, the individual proceeds to hand in their ballot to a polling employee who then submits the ballot into a machine. We observed this process to take 10 seconds and included this service time in the "Check Out" server in our network. See Table 1 for a summary of the input parameters and distributions:

Table 1: Input Parameters and Distributions Used In Simulations for Ithaca Polling Station

Stations	Distribution	Parameters
Arrival	Poisson	λ =54.25 persons/hr when $6\,AM \le t < 11\,AM$ =37.88 persons/hr when $11\,AM \le t < 4\,PM$ =95.49 persons/hr when $4\,PM \le t < 9\,PM$
CheckIn 1 & 2	Triangular	(min, max, mode)=(27,138,72) secs
Voting Booth 1, 2 & 3	Triangular	(min, max, mode)=(40,361,173) secs
Check Out (Casting Vote)	Constant	10

Simulation result for Ithaca Polling Station Case:

Figure 1. Voting Center Layout for the Ithaca Polling Station System

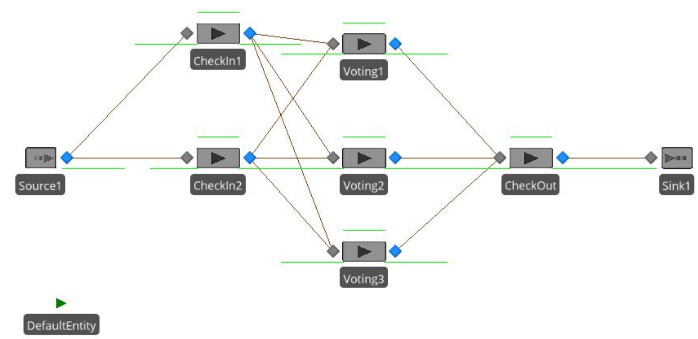
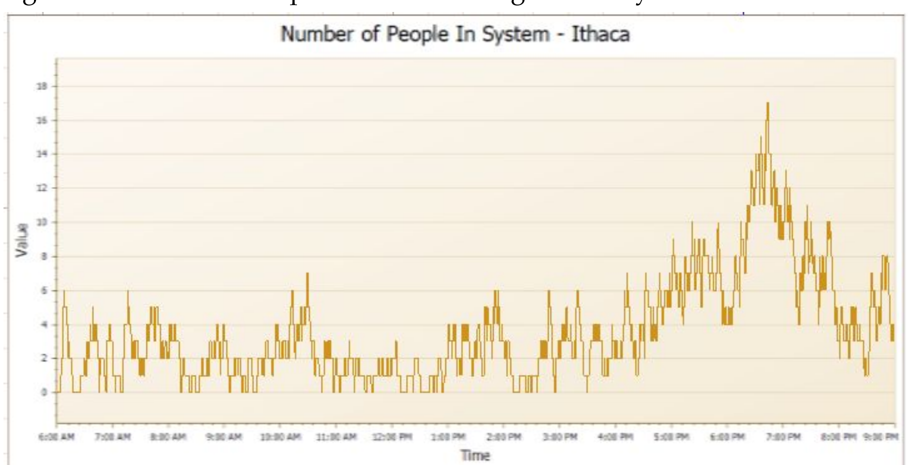


Figure 2. Number of People in Ithaca Polling Station System

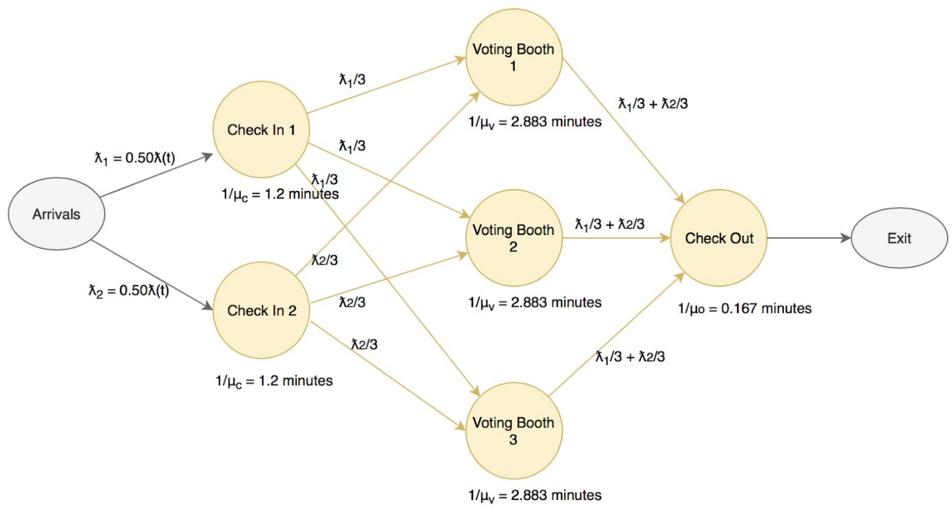


Average time spent in the system: 7.9843 minutes
Input buffer time for CheckIn1: 0.3923 minutes
Input buffer time for CheckIn2: 0.3990 minutes
The average number of people in the system : 3.6670 people (max 15.7880 people)
Max time in the system: 18.8152 minutes

The simulation results show that an average voter spends about 8 minutes to vote, from walking in to the voting center to exiting the system. And the time they use to check-in is about 0.39 minutes = 23.4 seconds. And the average number of people in the polling station at any moment is about 3.7 $\approx$ 4 persons. Such simulation results align with our observations at the Ithaca polling station. And it helps us verify the model in terms of validating the parameters we used for “Check-in” table service time, “voting station” service time, etc. Now we will perform a mathematical verification of our model by applying queueing theory.

III. MODEL VERIFICATION

Figure 3: Flow Diagram of Baseline Voting Center Layout



Initial Model for NYC Built Based on Ithaca Polling Station

For the purposes of verifying our model, we start by assigning an exponential distribution to the check-in service time, as well as to the voting booth service time, which means 1.2 minutes and 2.883 minutes respectively. We also assume Poisson arrivals with an average arrival rate of 28.36 people/hour, which is the time-weighted average of the non-homogenous arrival process. Assuming the independence of the check-in and voting services and arrivals, we can predict performance measures of the queuing system. Then, after running 250 replications of our simulation using exponentially distributed services, we compare the results to our predicted metrics. Additionally, for the purposes of verifying the model we suppose people choose a voting booth to wait for at random. However, in the remainder of our simulations we apply the policy that after checking in, a person will go to the nearest *open* voting station, otherwise wait in line for a voting booth.

$\lambda = (54.250 + 37.877 + 95.4943) \div 3 = 28.36\ people/hr$

$1/\mu_c = 1.2\ minutes$

$1/\mu_v = 2.883\ minutes$

Check In i :

$\lambda_{eff,c} = 0.50(28.36\ people/hr) = 14.18\ people/hr$ arrive to a check in table on average throughout the day

Voting Booth j :

$\lambda_{eff,\,v} = 2\lambda_{eff,\,c}/3 \; = \; (14.18\,people/hr)\,/\,3 \; + (14.18\,people/hr)\,/\,3 \; = 9.453 \;\; people/hr$ arrive to a particular voting booth on average throughout the day.

Check Out:

$\lambda_{eff} = \lambda \; = 28.36\,people/hr$

Each Check-In Station: M/M/1 with $\rho = \frac{\lambda_1}{\mu_c}$

Each Voting Booth: M/M/1 with $\rho = \frac{\frac{\lambda_1}{3}+\frac{\lambda_2}{3}}{\mu_v}$

Check Out: M/M/1 with $\rho = \frac{\lambda_1+\lambda_2}{\mu_o}$:

Table 2: Input Parameters and Distributions Used In Simulations for New York City

M/M/1	**Utilization**	**Mean time to go through server**	**Mean waiting Time**	**Mean number in queue**	**Mean Number In Server's System**
Performance Measures Used for Verification	ρ	$\frac{\rho}{\lambda(1-\rho)}$	$\frac{\rho}{\lambda(1-\rho)} - \frac{1}{\mu}$	$\frac{\rho^2}{1-\rho}$	$\frac{\rho}{1-\rho}$

Table 3: Check In Stations Performance, where $\lambda_{eff,C} = 14.18\frac{people}{hr}, \mu_C = \frac{1}{0.02} = 50/hr$

	Theoretical	**Simulation**
Utilization of Server	$\rho_C = \frac{\lambda_{eff,C}}{\mu_C} = \frac{14.18\,people/hr}{1/0.02\,hr} = 0.2836$	Check In 1 : [0.2883±0.0035] Check In 2: [0.2885±0.0037]
Mean time to go through server	$\frac{\rho_c}{\lambda_{eff,C}(1-\rho_c)} = \frac{0.396}{14.18} = 0.02792\,h = 1.675\,min$	Check In 1 : [1.6854±0.0220] Check In 2: [1.6800±0.0241]
Mean time spent waiting	$\frac{\rho_C}{\lambda(1-\rho_c)} - \frac{1}{\mu} = 1.675\,min - 1.2\,min = 0.475\,min$	Check In 1: [0.4934±0.0213] Check In 2: [0.5041±0.0242]
Mean number in queue	$\frac{\rho_C^2}{1-\rho_C} = 0.112$	Check In 1: [0.1179±0.0055] Check In 2: [0.1213±0.0063]
Mean Number In Server's System = Queue + Server	$\frac{\rho_C}{1-\rho_C} = \frac{0.2836}{1-0.2836} = 0.396$	Check In 1: $0.2883 + 0.1179 \approx 0.4062$ Check In 2: $0.2885 + 0.1213 \approx 0.4098$

Table 4: Voting Stations Performance, where $\lambda_{eff,V} = \frac{14.18\frac{people}{hr}}{3}(2) = 9.453\frac{people}{hr}$, $\mu_V = 20.812/hr$

	Theoretical	Simulation
Utilization of Server	$\rho_V = \frac{\lambda_{eff,V}}{\mu_V} = \frac{9.453\frac{people}{hr}}{20.812/hr} = 0.4542$	Vote 1 : [0.4542±0.0065] Vote 2 : [0.4525±0.0069] Vote 3: [0.4508±0.0069]
Mean time to go through server	$\frac{\rho_V}{\lambda_{eff,V}(1-\rho_V)} = \frac{0.832}{9.453} = 0.0880\ h = 5.28\ min$	Vote 1 : [5.2697±0.1190] Vote 2 : [5.2697±0.1189] Vote 3: [5.2894 ±0.1192]
Mean time spent waiting	$\frac{\rho_C}{\lambda(1-\rho_c)} - \frac{1}{\mu} = 5.28 - 2.883 = 2.397\ min$	Vote 1 : [2.2515 ±0.1047] Vote 2 : [2.2419±0.1189] Vote 3: [2.2904 ±0.1275]
Mean number in queue	$\frac{\rho_C^2}{1-\rho_C} = (0.832)(0.4542) = 0.378$	Vote 1 : [0.3627 ±0.0188 Vote 2 : [0.3615±0.0213] Vote 3: [0.3681 ±0.0228]
Mean Number In Server's System = Queue + Server	$\frac{\rho_V}{1-\rho_V} = \frac{0.4542}{1-0.4542} = 0.832$	Vote 1 : $0.4500 + 0.3627 \approx 0.8127$ Vote 2 : $0.4532 + 0.3615 \approx 0.8147$ Vote 3: $0.4487 + 0.3681 \approx 0.8168$

Table 5: Check Out Station Performance, where $\lambda_{eff} = 28.36\frac{people}{hr}$, $\mu_o = \frac{1}{0.167\ min} = 359.28/hr$

	Theoretical	Simulation
Utilization of Server	$\rho_o = \frac{\lambda_{eff}}{\mu_o} = \frac{28.36}{359.28} = 0.0789$	Check Out : [0.0784±0.0007]
Mean time to go through server	$\frac{\rho_o}{\lambda_{eff}(1-\rho_o)} = \frac{0.0857}{28.36\ /hr} = 0.1812\ min$	Check Out : [0.1804±0.0013]
Mean time spent waiting	$\frac{\rho_o}{\lambda_{eff}(1-\rho_o)} - \frac{1}{\mu} = 0.1812\ min - 0.167\ min = 0.0142\ min$	Check Out : [0.0145±0.0005]

Mean number in queue	$\frac{\rho_o^2}{1-\rho_o} = 0.00676$	Check Out : [0.0068±0.0003]
Mean Number In Server's System = Queue + Server	$\frac{\rho_o}{1-\rho_o} = \frac{0.0789}{1-0.0789} = 0.0857$	Check Out : [0.2883±0.0035]

Notice that for the tested performance measures for each individual component of the system, our theoretical expectations correspond to the experimental results. Now that we have confidence in the simplified baseline model, we can adjust the input distributions and proceed with our simulations. First we examined our model for Ithaca using two check-in stations and three voting booths using the input distributions in Table 1. Next we will modify the arrival process to be suitable for New York City and examine the impact adjusting servers in the voting center has on waiting times.

IV. FOUR APPROACHES TO SYSTEM IMPROVEMENT

Baseline Model
The Baseline model has the same set up as the Ithaca polling station with a change in parameters. As mentioned in the Data Analysis of Ithaca vs NYC, the interarrival time for NYC was scaled from the Ithaca data we collected on Election Day. Ithaca's system did not have long wait times, but when this system is used in an area like NYC the time in system can be as high as 135.71 minutes. Our baseline system is what we aim to improve by adjusting different variables in the following models.

Figure 4. Voting Center Layout for the NYC Baseline Polling Station System

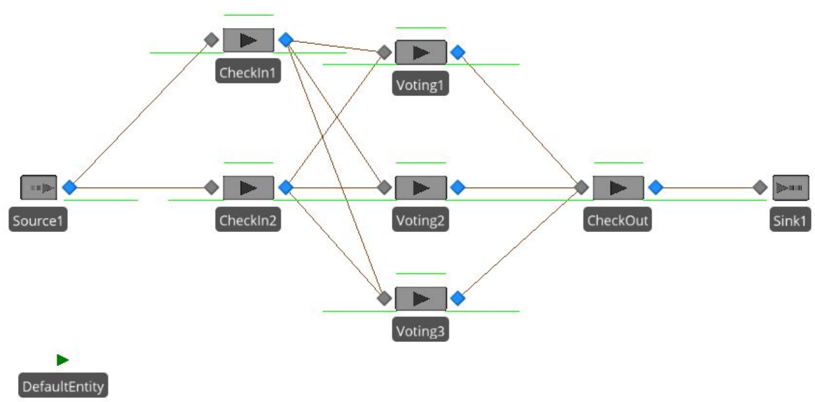
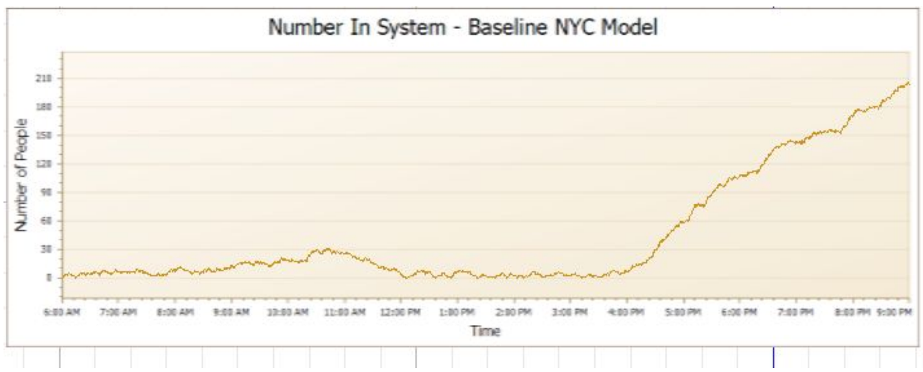


Table 6: Input Distributions Used In NYC Model

	6AM-11AM	11AM-4PM	4PM-9PM
Interarrival time	54.25/hr	37.879/hr	95.541/hr
Checkin service time	Triangular distribution Min: 0.45 min Max: 2.3 min Mode: 1.2 min	Triangular distribution Min: 0.45 min Max: 2.3 min Mode: 1.2 min	Triangular distribution Min: 0.45 min Max: 2.3 min Mode: 1.2 min

Voting time (service)	Triangular distribution Min: 0.67 min Max: 6.02 min Mode: 2.88 min	Triangular distribution Min: 0.67 min Max: 6.02 min Mode: 2.88 min	Triangular distribution Min: 0.67 min Max: 6.02 min Mode: 2.88 min
Checkout (Fetching the ballot and walking out of the voting room)	0.17 min	0.17 min	0.17 min

Figure 5. Time Plot of Number In People In System for the NYC Baseline Polling Station System



Average time spent in system: 31.2869 minutes
Input buffer time for CheckIn1: 24.3175 minutes
Input buffer time for CheckIn2: 23.6951 minutes
Average number of people in system : 40.1982 people
Max time in system: 135.71 minutes

For the total 31.3 minutes that voters spend in the system, they spend about 24 minutes (about 77% of total time) waiting in line to enter the polling station. From the simulation graph, we can see that there is a local maxima around 10:30 AM of about 30 people in line. This is due to the mismatch between service rate and arrival rate. The queues continue to lengthen as new voters arrive and the previously entered voters are unable to depart from the system. Such phenomenon aggravates as the arrival rate increases significantly from 4PM and the queue grows until closing time.

IMPROVEMENT I: Adding One Voting Station to the Baseline Model

Figure 6. Voting Center Layout for the NYC Polling Station System with an additional voting station

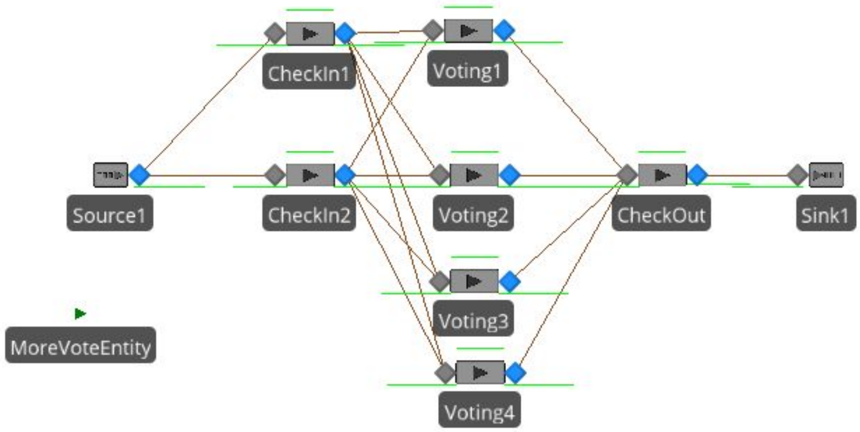
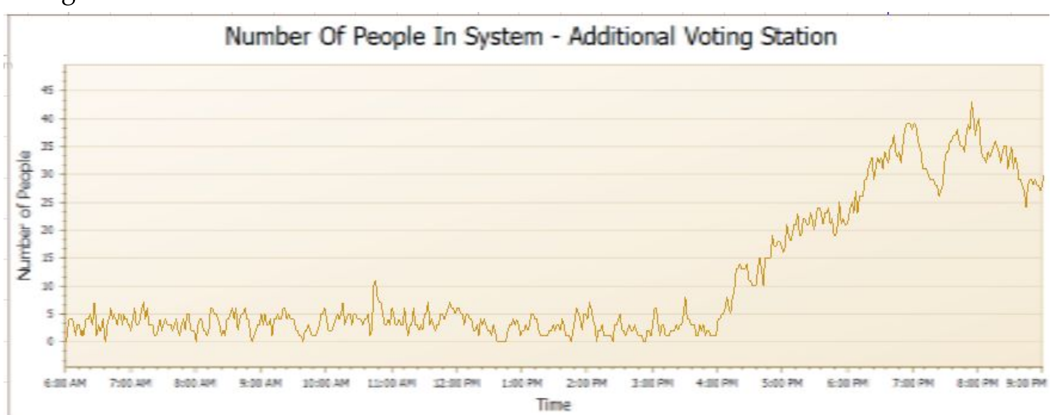


Figure 7. Time Plot of Number In People In System for the NYC Polling Station System with an additional voting station



Average time spent in system: 10.4188 minutes
Input buffer time for CheckIn1: 7.1728 minutes
Input buffer time for CheckIn2: 6.6022 minutes
The average number of people in system : 11.1322 people
Max time in system: 40.4795 minutes

By adding a voting station, we can see the results improved significantly. The average time spent in the system dropped from 31.3 minutes to 10.4 minutes (66.8% decrease). And the time people spend waiting in line dropped from around 24 minutes to around 7 minutes (70.8% decrease). And compared to the baseline model, the peak around 10:30 AM is smoother and almost invisible looking at the voter flow throughout the day. The maximum number of people in the system decreased from 135 people to 40 people, which is more ideal.

IMPROVEMENT II: Adding A Check In Station

Figure 8. Voting Center Layout for the NYC Polling Station System with an additional check-in station

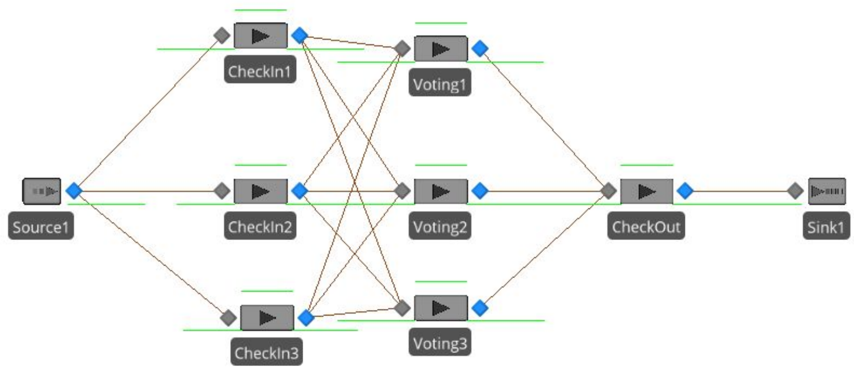
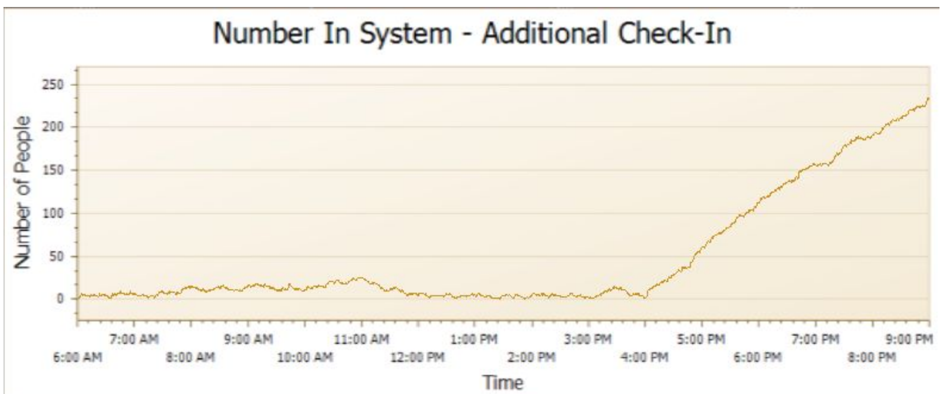


Figure 9. Time Plot of Number In People In System for the NYC Polling Station System with an additional check-in station



Average time spent in system: 30.6565 minutes
Input buffer time for CheckIn1: 22.2577 minutes
Input buffer time for CheckIn2: 21.5608 minutes
Average number of people in system : 39.3988 people
Max time in system: 140.53 minutes

Then we wanted to explore the effect of adding a check-in desk instead. We want to know whether this can improve the baseline model as much or more than the model of adding a voting station. Compared to the baseline model, the average time spent in the system decreased by around 2%, the waiting time in line for entering the voting station (before check-in) decreased by 8.24% and the average number of people in the system is about the same as the baseline model. Adding a check-in table does not improve the voting system more than adding a voting station because the voting stations are creating a bottleneck at the moment.

IMPROVEMENT III: Adding A Help Desk, While Maintaining Ample Voting Stations

From the previous simulation, we found that the lack of voting stations was creating a bottleneck in the system. Although adding a voting station had a substantial impact on waiting times, the queue

So now, we continue to eliminate this bottleneck by supplying ampl voting stations, and now look at the impact of adding a help desk. We instantiate a policy that if the time to check in exceeds 1.5 minutes, the voter is rerouted to a help desk to continue service. Now, the maximum time for service at each check in station is 1.5 minutes, and the maximum time for service at the help desk is set to 0.8 minutes. Therefore, the maximum total service time for customers re-routed to the help desk remains to be 2.3 minutes, as in the rest of the simulations.

Figure 10: Voting Center Layout for the NYC Polling Station System with an additional check-in station

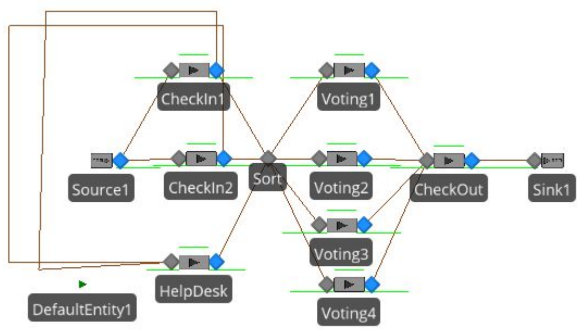


Figure 11: Time Plot of Number In People In System for the NYC Polling Station System with a Help Desk

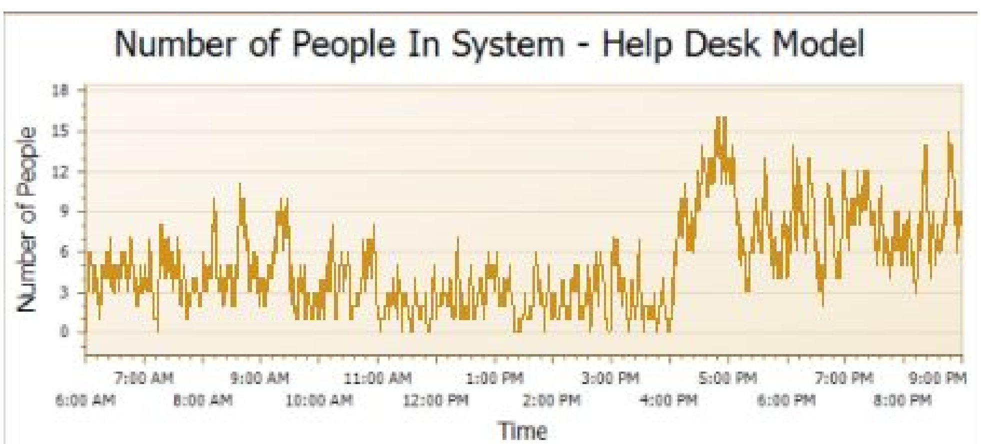
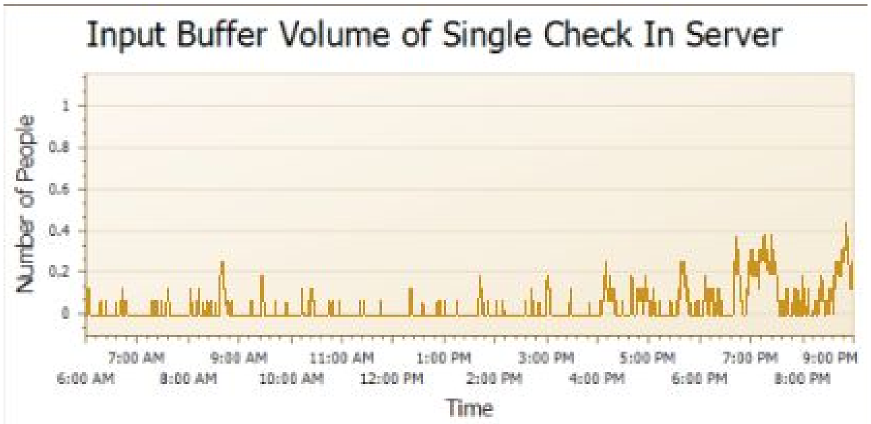


Figure 12: Input Buffer Volume for the NYC Polling Station System with a Help Desk



Average time spent in system: 6.8720 minutes
Input buffer time for CheckIn1: 3.3241 minutes
Input buffer time for CheckIn2: 3.3998 minutes
Input buffer time for HelpDesk: 0.024 minutes
Average number of people in system : 7.3163 people
Max time in system: 11.6441 minutes

The help desk acts as an assistant to alleviate queuing at the check-in stations. Therefore the average processing times at CheckIn1 and CheckIn2 capture the arriving voters who *do not* have an issue with either showing their identification, or not being on the list of registered voters. The help desk can handle the instances where the check-in process takes slightly longer because there is an issue. This reduces the queues at the check-in station and prevents bottlenecking at the check-in due to an arriving voter who has a check-in issue. Notice that now, the average time a voter spends in the system is approximately 6.9 minutes, which is about a 3.5 minute reduction when compared to having just 2 check-in stations (and 4 voting stations). In addition, there is less variation in the time someone spends in the system compared to the previous simulations since the maximum time a voter spent in the system is 11.6 minutes.

IMPROVEMENT IV: Adding Both a CheckIn Station and a Voting Station

Figure 13 :Voting Center Layout for the NYC Polling Station System with an additional check-in station and voting station

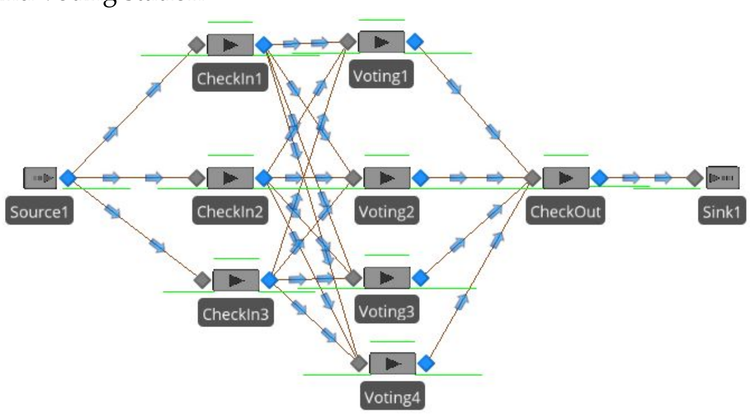
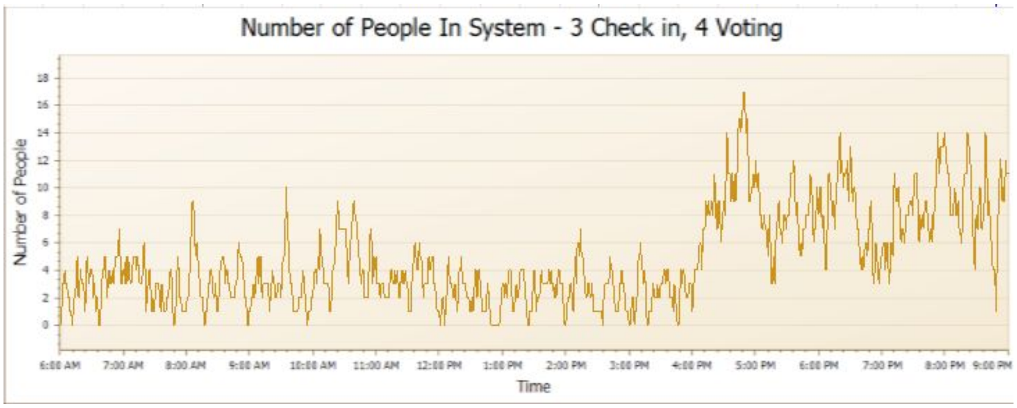


Figure 14: Time Plot of Number In People In System for the NYC Polling Station System with an additional check-in station and voting station



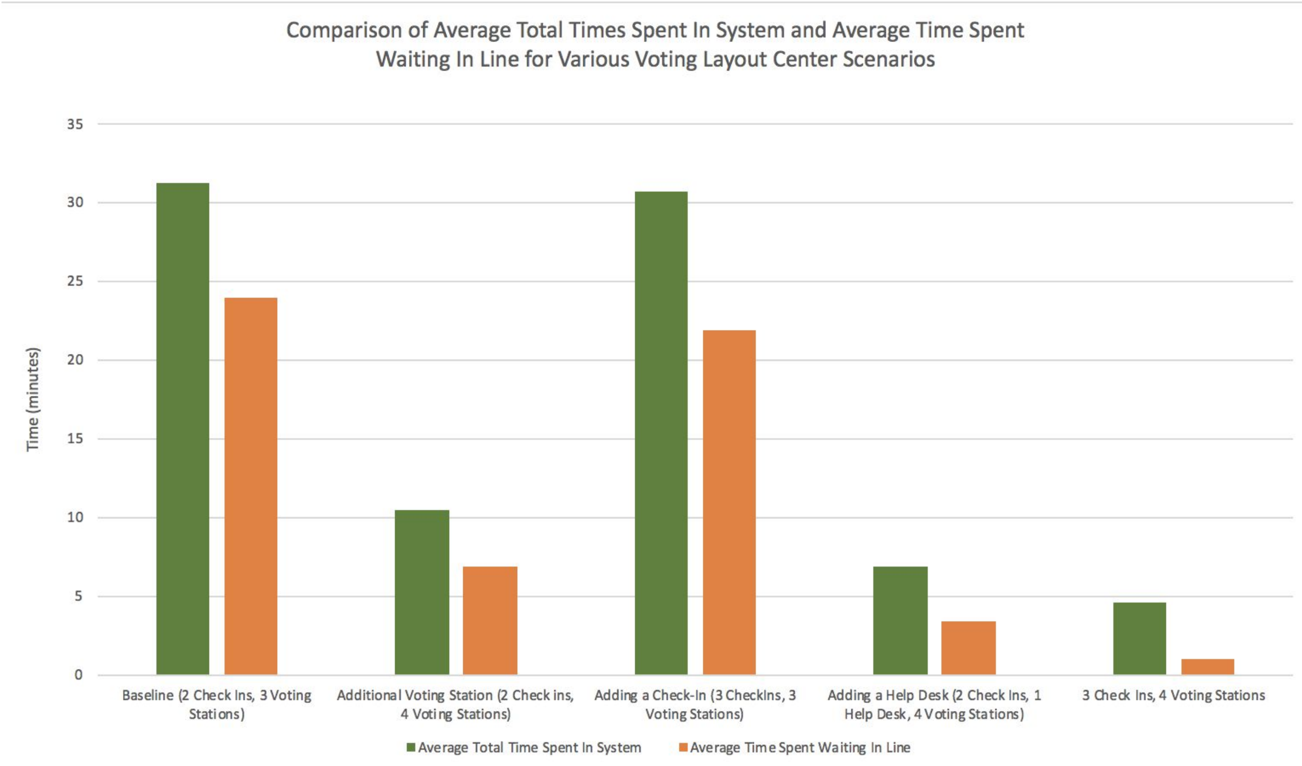
Average time spent in system: 4.5925 minutes
Input buffer time for CheckIn1: 0.9628 minutes
Input buffer time for CheckIn2: 1.0067 minutes
Input buffer time for CheckIn3: 0.9824 minutes
Average number of people in system : 4.7702 people
Max time in system: 15.8172 minutes

Previously, we saw reduction in waiting time by adding either an additional voting station (Improvement model I) or adding a check-in table (Improvement model II). And the addition of a voting station improved the system more than the addition of a check-in table. What if we add both? Here the result shows a significant reduction in average time spent in the system. Compared to Improvement Model I, it reduced the time spent in the system by 56% and improved the time spent in queue by 86%. Compared to Improvement Model I, it reduced the time spent in the system by 85% and improved the time spent in queue by 95%. We can see that adding a voting station each time reduces the time spent in the system and time spent in the queue significantly.

V. ANALYSIS AND RESULTS

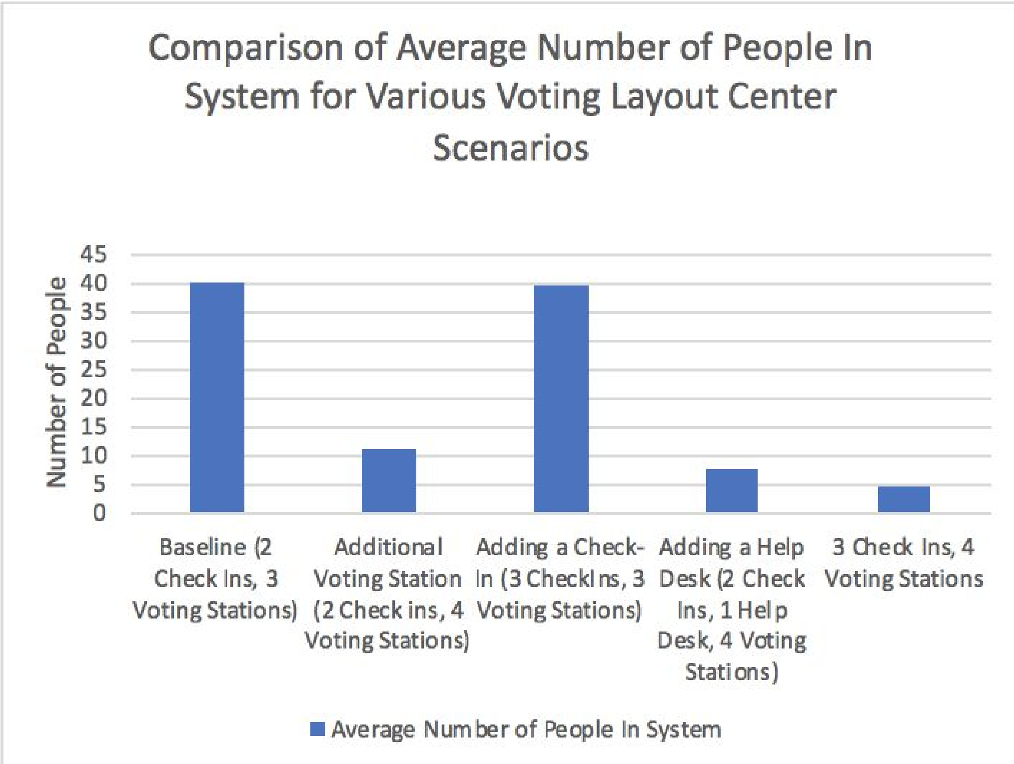
After modeling and running each of the polling station layouts we are able to compare all of the systems and make further recommendations. As shown in Plot 1, the Ithaca model would not work in a large city like New York. The waiting time in line is 24.00 minutes across check in stations in New York compared to .39565 minutes in Ithaca. The waiting time for New York voters is 6065.97% the wait for an Ithacan voter. The total time spent in the system is 31.29 minutes compared to 7.98 minutes in Ithaca. The total time voting for a New Yorker is over 392.12% the wait for an Ithacan voter.

Plot 1: Comparing the Performance of Voting Center Layouts Simulated



The amount of time New Yorkers have to wait in the queue is not fair. As mentioned in the psychology of waiting times section, the amount of time spent waiting in line is important and can influence elections. We were able to evaluate how changes to the system would make the polling process better for city voters. The smallest, most cost effective change to make is to add just one more voting station. By adding one more voting booth in NYC the average time waiting in line was 6.89 minutes. This a 71.29% decrease compared to the baseline. The average total time in the system was 10.42 minutes. This is a 66.70% decrease compared to the baseline. The times are still both longer than Ithaca, but a typical New Yorker used to congestion would consider these wait times as pretty good. This conclusion is also supported by Plot 2. There are many less people in the system when a voting booth is added. The baseline has 40.2 people in the system while adding one extra voting station brings that number down to 11.13 people; this is a 72.31% decrease in people in the system.

Plot 2: Comparing the Average Number of People In Each System



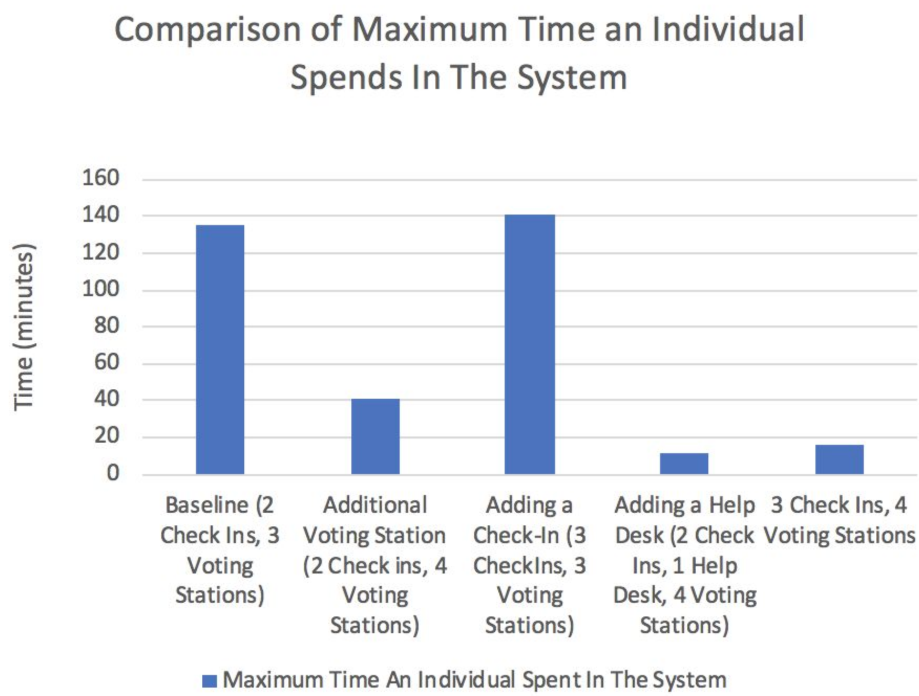
Adding another check in table also decreased the waiting time in line and overall experience. The average wait time in line was 21.91 minutes and the total time in the system was 30.66 minutes. This is a 8.71% decrease in time waited in line and a 2.01% decrease in total time spent in the system. More check in tables decrease the time waiting, but are not as effective as adding another voting machine. The check in experience is on average 1.2 minutes while the time it takes voters to fill out their ballot is on average 2.88 minutes. Therefore since the voting experience takes longer adding another voting machine would help to alleviate the line. This also holds true for the number of people in the system, but not as drastically. With another check in station the number of people in the system is brought down to 39.4. This is a 2% decrease in people.

When the help desk was implemented, voters spent an average of 6.87 minutes in the system. In this system we have two check in stations, four voting stations and a help desk. The percentage decrease from the additional voting station model is 34.04%. The percentage decrease from the baseline model is 78.06%. The average time in the queue is 3.39 minutes for this system. This is a 50.80% decrease compared to the extra voting station model and a 85.88% decrease in comparison with the baseline model.

If there are more resources we suggest that the polling station implement three check in stations and four voting machines. With more resources the time can be brought down drastically. With our model the average time in line is 2.95 minutes and the average total time in system is 4.59 minutes. This is an 87.71% decrease from the baseline in wait time and an 85.33% decrease in total time in the system. The average number of people in the system for this case is 4.77 and is an 88.13% decrease from the baseline. This is an even better improvement than just adding one help desk. If New Yorkers took on average 4.59 minutes to get through the whole voting process they would be blown away.

The pitfalls of each system are displayed in Plot 3. When looking at Plot 1, we observed that the time in line and the total time in system was less when adding an extra check in station. When we analyze the maximum time spent in the system, it takes longer to get through the system when a check in is added compared to the baseline. The baseline has a maximum time in the system of 135.71 minutes while adding a check in station has the time 140.53 minutes. The same truth holds as before, that the most effective change is to add just one more voting station. The maximum time in the system for adding a voting machine is 40.4795. When we add a help desk, 7.32 people go through the system. Since we channel all voters with check in time greater than 1.5 minutes to the help desk, the maximum time in system drops to 11.64 minutes. This is the lowest maximum time for any model. There is a 91.42% decrease between the baseline maximum time and the help desk maximum time. Again if resources are unlimited using three check in stations and four voting stations vastly reduces the maximum time in system to 15.8172 minutes. There is a 26.38% decrease between the help desk and three check in and four voting stations model.

Plot 3: Comparing the Maximum Service Time for Each System



Discussion of Model Simplifications

In the model we made multiple simplifications with the constraints given. The data we collected was over the course of Election Day in Ithaca, NY is not the best data to apply to a big city like New York. There were less than one hundred data points taken over the course of 8 am - 9 am and 4:30 pm - 6 pm. It is not surprising that this was the case given the population of Ithaca is 31,000 and the population has 40 polling stations. The election was also not during a Presidential election year. People typically believe that electing the President is more important than the local mayor. This could have impacted the number of people that showed up to vote.

The small data set translates to other simplifications in the model. The distributions for the service time at the check in and voting stations was triangular due to our single day of data collection. We used the triangular distribution for the Ithaca model and the New York model as well. The parameters of the Ithaca model might be more in line with the true service time because we observed them. Extrapolating the data to New York is more of a stretch because of the difference in population. We accounted for this as best as possible as mentioned in the data analysis section, but we could still be off from the true service times. We maintained the distributions throughout the simulations however to ensure a fair comparison between voting center layouts.

VI. Conclusion

Through data collection, analyses, modeling, and simulation. Our models show significant improvement by adding a help desk. And the second most significant improvement was from adding voting stations. In order to keep up with voter inflows in a city like New York, given our modeled arrival rate, our recommendations are to use 3 check in, 4 voting stations with a help desk in an idealist situation. However, when resources are limited, a voting station should first look at adding a help desk that deals with voters who have difficulty checking-in. Then a polling place should look at the possibility of adding a voting station to decrease the amount of time voters spend in the system, which helps reduce the line length outside of a voting center.

APPENDIX

Screenshots of Simulation Output for Model Verification:

Table I: Model Verification Results for Check In Servers

Object Type	Object Name	Data Source	Category	Data Item	Statistic	Average	Half Width
Server	CheckIn2	Processing	Content	NumberInStation	Average	0.2883	0.0035
			HoldingTime	TimeInStation	Average (Min...	1.2168	0.0102
		InputBuffer	Content	NumberInStation	Average	0.1179	0.0055
			HoldingTime	TimeInStation	Average (Min...	0.4934	0.0213
		[Resource]	ResourceState	TimeProcessing	Average (Min...	1.6854	0.0220
	CheckIn1	Processing	Content	NumberInStation	Average	0.2885	0.0037
			HoldingTime	TimeInStation	Average (Min...	1.2136	0.0101
		InputBuffer	Content	NumberInStation	Average	0.1213	0.0063
			HoldingTime	TimeInStation	Average (Min...	0.5041	0.0242
		[Resource]	ResourceState	TimeProcessing	Average (Min...	1.6800	0.0241

Table II: Model Verification Results for Voting Service Stations

Object Type	Object Name	Data Source	Category	Data Item	Statistic	Average	Half Width
Server	Voting1	Processing	Content	NumberInStation	Average	0.4542	0.0065
			HoldingTime	TimeInStation	Average (Min...	2.8679	0.0298
		InputBuffer	Content	NumberInStation	Average	0.3627	0.0188
			HoldingTime	TimeInStation	Average (Min...	2.2515	0.1047
		[Resource]	ResourceState	TimeProcessing	Average (Min...	5.2697	0.1190
	Voting2	Processing	Content	NumberInStation	Average	0.4525	0.0069
			HoldingTime	TimeInStation	Average (Min...	2.8722	0.0319
		InputBuffer	Content	NumberInStation	Average	0.3615	0.0213
			HoldingTime	TimeInStation	Average (Min...	2.2419	0.1189
		[Resource]	ResourceState	TimeProcessing	Average (Min...	5.2894	0.1338
	Voting3	Processing	Content	NumberInStation	Average	0.4508	0.0069
			HoldingTime	TimeInStation	Average (Min...	2.8642	0.0319
		InputBuffer	Content	NumberInStation	Average	0.3681	0.0228
			HoldingTime	TimeInStation	Average (Min...	2.2904	0.1275
		[Resource]	ResourceState	TimeProcessing	Average (Min...	5.2257	0.1192

Table III: Model Verification Results for Check Out Station

Object Type	Object Name	Data Source	Category	Data Item	Statistic	Average	Half Width
Server	CheckOut	Processing	Content	NumberInStation	Average	0.0784	0.0007
			HoldingTime	TimeInStation	Average (Min...	0.1660	0.0010
		InputBuffer	Content	NumberInStation	Average	0.0068	0.0003
			HoldingTime	TimeInStation	Average (Min...	0.0145	0.0005
		[Resource]	ResourceState	TimeProcessing	Average (Min...	0.1804	0.0013

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