Proceedings of the 2024 Winter Simulation Conference
H. Lam, E. Azar, D. Batur, S. Gao, W. Xie, S. R. Hunter, and M. D. Rossetti, eds.

USING SIMULATION TO ADDRESS INEQUALITY AND VARIABILITY IN ELECTIONS

Brock Spence[1], Alexander Cañedo[1], and Dima Nazzal[1]

[1]H. Milton Stewart School of Industrial and Systems Eng., Georgia Institute of Technology, Atlanta, GA, USA

ABSTRACT

In 2022, the State of Georgia experienced significant voter wait-time issues throughout the election season. Since then, Georgia has been front and center in the national conversation about election integrity, as legislators try to adapt voting systems to ever-changing technologies and cultural norms. Georgia law generally allocates election resources based on the number of registered voters a precinct serves, but size is only one differentiating factor among precincts. Voters across the state behave differently, so different precincts of similar sizes might require different resources depending on when voters arrive. Using simulation optimization based on voter arrival data obtained from the Georgia Secretary of State, we have found more efficient and equitable allocation methods, compared to simply considering registered voters. By considering the variation between precincts, election administrators can better safeguard the integrity and equality of elections without sacrificing efficiency.

1 INTRODUCTION

Maximizing election integrity and voter enfranchisement, while decreasing voter wait times, is an important goal of election administrators throughout the United States. However, with a limited budget and a scarce number of voting resources, election officials must carefully manage how election materials are allocated and purchased to maintain fair and efficient elections without excessive spending.

In the State of Georgia, the topic of election efficiency has become increasingly important considering record voter turnouts and long waiting times to vote in recent years (Alexander and Fields 2022). Additionally, the topic of equity among Georgia voters has become a critical issue amid discussion of whether long voting lines are disproportionately impacting specific geographic areas or demographic groups in the state. Fowler (2020) argues that voters from marginalized groups in Georgia experienced abnormally long waiting times in the early voting season of 2020, in part due to a scarcity of voting locations which could not accommodate the high number of early voters. To make matters worse, between 2012 and 2020, the average number of voters assigned to a given voting location increased approximately 47%, from 2,046 voters per location to 3,003 voters per location statewide (Fowler 2020). Some counties experienced dramatically greater increases in assigned voters per location than others. Since 2012, Georgia has faced significantly higher voting wait times than the national average (MIT Election Data and Science Lab 2020). In the same time frame, Georgia has also experienced an exceptionally large voter turnout. In 2022, Georgia ranked first in the southeast region and 17th nationally in overall voter turnout for the midterm election (Fabina 2023). With this combination of high voter turnout and long waiting lines in the state, it is important to examine what resources election officials can use to improve the efficiency of the Georgia elections system.

The Georgia Secretary of State's Office is responsible for purchasing voting machines and providing this equipment to county leaders. Georgia law then requires these county-level election officials to adequately provide voting machines to precincts where voters are assigned (GA Code § 21-2-367 2022). This law provides general guidelines for provisions of voting materials based on the number of registered voters assigned to a precinct, stating that county election officials must provide to each precinct "at least one voting booth or enclosure for each 250 electors therein, or fraction thereof." However, this law does provide allowances for greater or fewer machines being allocated if election officials determine there to be "relevant factors that inform the appropriate amount of equipment needed."

The goal of these election officials is to work within existing policy guidelines to properly allocate resources efficiently and equitably. However, to create a system that is both efficient and equitable is incredibly difficult because of the complex and oftentimes competing processes needed to achieve both. Creating an efficient system focuses on maximizing throughput, while equitable systems aim to achieve similar times for all voters within a system (Bertsimas et al. 2012). Thus, our goal in creating a simulation is to balance these factors to create an optimal allocation which is both efficient (with adequate voter throughput) and equitable. This paper will discuss how a simple voter-population based policy, like the policy dedicating one voting booth per 250 electors, may not necessarily lead to equitable nor efficient allocations because of the variability that exists within voter populations and voter behaviors between voting locations. In our analysis, we will be examining data from the November 2022 midterm election regarding voter arrival times within Fulton County at all 248 voting locations serving a combined total of 749,780 registered voters. From this data, we will create a simulation model to optimize the Georgia elections system. We will use this model to determine the extent to which simulation tools could be used to reduce wait times and increase equity throughout the system. This model will be created in Simio, an object-based simulation software used to predict the performance of systems by modeling queues and servers using random variables.

In section 2 we will examine the variability in and between voting locations in terms of voter arrival behavior and demographic data from each location. This section will further explain the necessity of building a model that is robust in accounting for these individual voting location characteristics. Section 3 will consist of an explanation of our simulation, its implantation into the Simio simulation software, and a brief overview of the voting process in Georgia. Section 4 will consist of an overview of our simulation results. In Section 5, we will wrap up our discussion and look towards future research in the topic.

2 CHARACTERIZING VARIABILITY AMONG VOTING LOCATIONS

2.1 Data Gathering and Fulton County

To build our simulation and analyze variability among voting locations, we gathered voter turnout data from the 2022 November midterm election. Through an Open Records Request with the Office of the Georgia Secretary of State, we retrieved a dataset containing the hourly voter check-in counts at 2,427 polling locations across all 159 counties within the State of Georgia. However, in this pilot study, and given the runtime limitations of our simulation that we will discuss further in this paper, we primarily focused on the 249 polling locations within Fulton County.

Fulton County is Georgia's most populous county, with over 1 million residents and 750,000 registered voters, comprising more than 10% of the registered voters in the state (U.S. Census Bureau 2022). Fulton County has experienced historical issues with long voting times and overcrowded voting locations (Fowler 2020). Different counties may hold slightly different elections with varying ballot lengths, but we assume the ballot lengths within the county to be comparable to the rest of Georgia as most races are at the state level. Li et al. (2013) found that ballot length in Central Florida elections had a significant impact on the time voters spent in the voting system, so for this paper we attempt to eliminate this variable by examining locations only within Fulton County. Because of the size of the county and the necessity for voter optimization in the region, our data analysis focuses on identifying and evaluating how average and worst-case voter waiting times could improve for voting locations within Fulton County.

2.2 Patterns in Voter Arrival Times

Previous research regarding election system research has mostly relied on metrics like voting machine allocation, poll closing time, or voter throughput to measure the success of simulation optimization on improving election lines (Li et al. 2013; Wang et al. 2015). However, there has been a gap in research examining the effect that different patterns of voter arrival times might have on voter queue length throughout the day. Our simulation uses real, hourly voter arrival patterns from the 2022 midterm election in Georgia across the spectrum of voter arrival patterns discussed here.

We have identified two main types of voter arrival behaviors: one that is uniform throughout the day and another with a more concentrated morning rush. Figure 1 illustrates a voting location with an approximately uniform distribution of voter arrivals. Throughput at this precinct remains relatively steady over the course of election day. Figure 1 also shows a location where a large proportion of voters enter the queue in the morning (between the hours of 7:00am and 10:00am). At this location, there are significant peaks of voter arrivals early in the morning, and especially at the hours of 7:00am and 10:00am. However, the rest of the day outside of the morning hours sees a significantly lower arrival of voters.

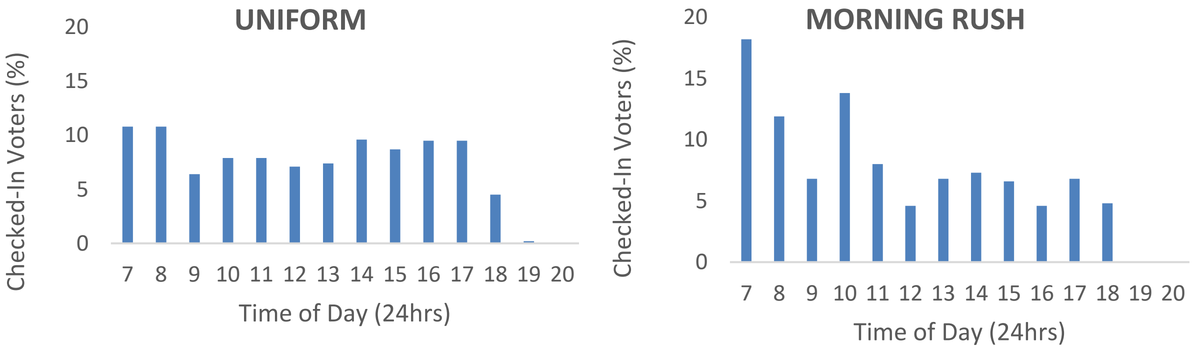

Figure 1: Chart of voter arrival times throughout the day at locations with uniform and morning rush arrivals. The uniform chart uses data from Shakerag Elementary School, and the morning rush chart uses data from Morningside Presbyterian Church.

Considering the different types of voter arrival patterns, our research aims to find an optimal allocation of voting equipment which considers how machines are utilized throughout the day based on the peak times voters arrive. In finding a representative sample of voting locations to test our simulation with, we had to come up with a numerical measure to test the strength of a rush during the day. Here, we use a measure which divides the greatest number of voters observed in a single hour by the average of voters checked in. We will call this measure the peak/average ratio in future references. Thus, a higher peak/average ratio corresponds to a location with many voters entering a location in a single hour compared to the average hour, and a lower ratio would correspond to a more uniform distribution of voters throughout the day. Figure 2 shows a correlation between the peak/average ratio and election day (ED) voter turnout. Voting locations with highly irregular or peaked voter turnouts also tend to be locations which experience low voter turnout. For this and future references to ED turnout, we define it as the number of voters who arrived at a specific location to vote on election day divided by the total number of registered voters assigned to this given voting location. Figure 2 also visualizes the number of registered voters as the size of each bubble, with larger bubbles corresponding to a greater number of voters registered to a specific voting location.

Using the scatterplot shown in Figure 2, we chose 20 different voting locations in our study which exhibited varying degrees of rushes throughout the day, from uniform to heavily rushed arrivals, and varying ED voter turnouts. To find a representative sample of 20 locations, we chose approximately 5 locations from each quadrant split by the Average lines in Figure 2. After choosing 5 locations from each quadrant, we verified that the voter arrival times of all these locations showed a wide range of possible voter behaviors. In this paper we further attempt to use this peak/average ratio as an indicator for finding locations which span the range of concentrated arrivals.

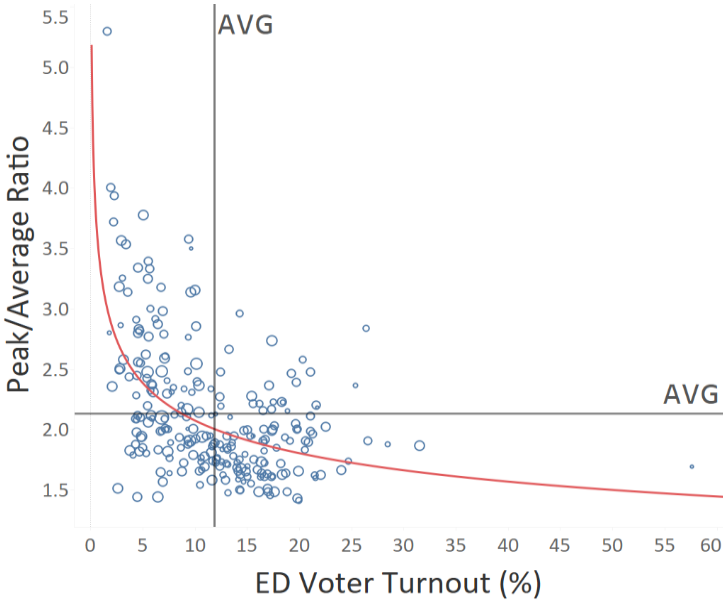

Figure 2: 2022 election day (ED) voter turnout versus the peak/average ratio determined at each voting location. The size of the bubble corresponds to the number of registered voters at a given location. The vertical and horizontal lines correspond to the average ED voter turnout and peak/average ratio among all locations.

2.3 Demographic Variability among Voting Locations

Examining how different demographic groups are impacted by changes in the election system is critical for ensuring that no specific group of voters are disenfranchised in the electoral process. This section will focus on identifying and analyzing demographic diversity within Fulton County to demonstrate the possible drawbacks of a simple proportionality-based voting equipment allocation rule in accounting for voter diversity. Further, our simulation relies primarily on turnout data from the 2022 midterm election, so this section will also discuss how demographic disparities in turnout are related to the necessity in creating a robust election system simulation.

Demographic data and diversity among voting locations is important when determining equity in the voting system because voter turnout is sensitive to many different factors, including geographic location and demographics (Cantoni and Pons 2022). Measures such as race, age, access to transportation, and party affiliation have been shown to be correlated with voter turnout in recent years (de Benedictis-Kessner and Palmer 2017; Barber and Holbein 2022; Pew Research Center 2023). Other factors like household income also show distinct voter turnout trends, with high-income individuals tending to vote at a higher rate than low-income individuals (Laurison and Rastogi 2023).

Amy (2021) explains how the population of the State of Georgia has grown much more urban and diverse in recent years. Even within Fulton County, Georgia's most populous county, there exists significant differences in demographic makeup in the area. Using data from the 2022 American Community Survey administered by the US Census Bureau, we analyze and compare demographic measures along census tracts. Further, we have used this census tract data to match specific demographic makeups with each voting location within Fulton County.

Fulton County is an exceptionally diverse county racially, with approximately 45% of residents identifying as Black or African American and 44.2% identifying as White alone (U.S. Census Bureau 2022) However, as of 2022, approximately 64 percent of voting locations within Fulton County reside in a census tract containing more than 70 percent of residents belonging to one race alone (U.S. Census Bureau 2022).

Given this discrepancy between individual precinct demographics and county-level demographics, as well as varying turnout from precinct to precinct, there is a need to find a system of resource allocation that is more robust and efficient in the face of these differences. Currently, voting machines are generally allocated to each precinct according to the registered voter population (GA Code § 21-2-367 2022). Allowances in Georgia law does permit allocations which do not strictly follow the rule of one voting booth per 250 electors. Because of this permission in the State code, we propose an approach which can create better equity and efficiency than a simple proportional rule based on averages.

3 OVERVIEW OF SIMULATION MODEL

3.1 Description of Model

3.1.1 Model Logic

Our simulation seeks to model 20 real precincts in the state of Georgia, specifically selected to encompass the full range of precinct behavior. Each voter is a simulated entity that must first check-in at the precinct with a human, fill out their ballot at a ballot marking device and lastly place their vote into a scanner to be counted. Service and arrival times at each step of the process are generated using random variables. The number of poll-pad devices, ballot marking devices and even scanners are input parameters for the model and can be changed at each precinct. The source of variability from precinct to precinct comes from the arrival patterns of voters, which are modeled using random variables and distinct at each location. Precincts in Georgia open at 7:00 AM, and allow voters to arrive until 7:00 PM, all voters in line at 7:00 PM will be permitted to cast a ballot so long as they remain in line until doing so.

3.1.2 Input-Distributions and Data Sources

The arrival rate to each polling location is the defining feature of each precinct in our model. Our simulation treats arrivals as a non-stationary process, changing hour by hour to reflect actual voter behavior in Georgia. To capture the variability in arrival rates throughout the day and at each location, we used data obtained from the State Election Board via an Open Records Request. The dataset contained the number of arrivals to each precinct at each hour of the day on election day in 2022. Our model utilizes data from 20 different polling locations within Fulton County. Each of the hourly arrivals from these polling locations are input into our model using Simio rate tables, a feature of the Simio software that takes arrivals per unit of time as an input and then outputs random arrival times that fit the input pattern. For each simulation hour, inter-arrival times of voters are simulated using a Poisson distribution with mean λ^{-1}, where λ represents the number of voters that arrived at that precinct at a specific hour in 2022.

In Georgia, once voters arrive to a precinct, they first queue in the check-in line (Figure 3). The check-in process in Georgia is done by a poll worker using a device called a poll-pad. Voters will be asked for their Driver's License and to confirm certain information like their address and voter registration on the poll-pad. In primary elections, voters will also be asked to select which type of ballot they would like to cast (Republican, Democrat, Independent). Variability at this stage can present significant issues. Most voters will make it through the check-in process quickly, but there will be special cases that can take several minutes. Voters might arrive at an incorrect precinct, show up without being properly registered, without proper identification, among other common mistakes. Additionally, this step of the process is conducted primarily between two humans; experienced poll workers and voters will likely move through this step very quickly, while those new to voting or working the polls may take longer. To simulate the variability of this process, we have modeled the check-in time with a normal distribution of mean 2 minutes and standard deviation of 1 minute, truncated at 0 to be strictly positive.

The second step in the voting process in Georgia is the process of filling out one's ballot (Figure 3). This is typically done on an ImageCast X Ballot Marking Device (BMD), distributed by Dominion Voting Systems. Studies show that the length of time needed to cast a ballot depends largely on the length of the ballot (Li et al. 2013). Our simulation concerns itself only with Fulton County, and while in some election years there will be small differences in ballot length from precinct to precinct within the county, it is adequate to assume each ballot in Fulton County will be of relatively similar length. Additionally, voter preparation can play an important role in individual variability. Georgia offers sample ballots on its election website, and many voters use this to prepare a list of candidates and ballot measures to vote for before arriving to the precinct, while other voters will see the ballot for the first time at the BMD. To simulate this, we use a normal distribution with mean 8 minutes and standard deviation of 2 minutes truncated at 0 to be strictly positive.

The final step of the voting process is placing a printed ballot into a scanner (Figure 3). Nearly every precinct in the county will only have 1 scanner because it is the fastest step in the voting process. One quirk of scanners in Georgia is that after it fills up, it must be emptied. On Presidential election days, scanners in busy precincts can fill up 1 to 2 times on election day. Scanners can take 10 to 20 minutes to empty, and while being emptied voters will not be able to advance in the process. To model the time, it takes to scan a ballot, the uniform distribution is used with a lower bound of 30 seconds and upper bound of 60 seconds. After 250 votes are cast, the scanner will fill up and need to be emptied. The time to empty the scanner is also modeled by the uniform distribution with a lower bound of 10 minutes and upper bound of 15 minutes. In our simulation, all precincts have been given just 1 scanner.

Figure 3: Steps in the Georgia voting system.

For the check-in step, our simulation treats all poll workers as clerks checking in voters with a poll pad, and does not consider the impact managers, or other supplementary types of employees might have on this step. For assistance with BMDs and emptying the scanners, our model assumes there are supplementary poll workers present to handle these tasks, and that check-in proceeds uninterrupted.

3.1.3 Implementation in Simio

Our model was constructed entirely within Simio. Voters at each precinct are distinct model entities corresponding to their specific precinct. This allows for performance statistics, such as time in system, to be calculated independently at each polling place. Additionally, each step of the process is implemented with a simple server object, connected by simple connectors. Input-distributions are stored as data objects, and each server references the input-distribution corresponding to its step of the voting process. Voter arrivals are modeled using a source object, and all 20 source objects reference a unique rate table that contains the 2022 election day data that corresponds to that specific precinct.

One of the key advantages of implementing our simulation in Simio is the experiment feature, which enables users to quickly and easily edit input parameters and run repeated replications of the simulation for each set of the parameters. Since we are modeling 20 precincts, each with a specific number of poll-pads and ballot marking devices, our model has 40 input parameters. To properly capitalize on this, the capacity of each server in our Simulation is an integer valued property. When running the optimization add-ons included with Simio, this allows the software to explore the feasible region encompassed by all 40 parameters.

When selecting precincts, as discussed earlier, we were very intentional to ensure a broad range of voter behavior would be included in our model. 9 of the 20 precincts experience at least 2 times as many voters than on average during their peak hour, while the other 11 precincts follow distributions that are less concentrated (Table 1). Tracey Wyatt Community Center, Ponce de Leon Library and Etris Community Center are among the more concentrated precincts while Hoyt Smith, Esther Jackson and Abbots Hill demonstrate arrival patterns that are more uniform throughout the course of the day.

3.2 Selected Precincts

Table 1: The 20 simulated precincts with measures of size, turnout and concentration of arrivals.

Precinct Name	Registered Voters	Election Day Turnout	Turnout %	Peak/Avg Ratio
Shakerag Elementary	3673	623	0.17	1.51
Cathedral of St Phillip	3391	653	0.19	2.46
Esther Jackson Elem.	2858	539	0.19	1.48
Tracey Wyatt Comm.	2832	45	0.02	5.3
Morningside Pres.	5808	589	0.1	2.54
Lang-Carson Community	3277	691	0.21	2.48
Hoyt Smith Center	3769	746	0.2	1.43
Omrewood Park Pres.	4416	1391	0.31	1.87
Peachtree Rd. Utd.	8671	592	0.07	2.1
Etris Community	4430	223	0.05	3.77
Ponce de Leon Library	2577	369	0.14	2.96
Mtn. Park Community	460	265	0.58	1.69
Little 5 Point Community	1768	467	0.26	2.84
Lebanon Baptist Church	2945	782	0.27	1.9
C. H. Gullat Elementary	4427	258	0.06	2.12
Ison Springs Elementary	5418	351	0.06	1.44
Peachtree Pres. Church	5282	391	0.07	1.82
Abbots Hill Elementary	2170	374	0.17	1.46
Dad’s Garage Theatre	3169	686	0.22	2.2
Sandy Springs Church	2571	159	0.06	2.91

In addition to variation in voter pattern, we also sought out variability in size and voter turnout. Mountain Park Community only serves 460 registered voters, while Peachtree Road United Method serves 8761 registered voters. On election day in 2022, Mountain Park saw a 58% turnout while the significantly larger Ormewood faced a turnout of 31% of registered voters. These were among the higher turnouts in the state, while precincts such as Tracey Wyatt and Etris Community Center only saw turnouts of 2-5%.

3.3 Allocation Methods

3.3.1 Current Allocation Under Georgia Law

GA Code § 21-2-367 (2022) strongly advises that each precinct have at least one ballot marking device per 250 registered voters. While Georgia law is not as specific for poll worker requirements, poll workers are also granted in proportion the number of registered voters serviced by a precinct. Based on historic allocations, we elected to grant poll workers at ratio of 1 for every 4 groups of 250 registered voters, rounded to the nearest whole. Using this allocation pattern for the 20 precincts we have elected to simulate 306 total ballot marking devices will be used throughout the system, in addition to 55 poll workers. These quantities will be used as constraints on the alternative allocation patterns explored in our research.

3.3.2 Optimal Allocation

One focus of our research is the search for an optimal allocation of a finite amount of election resources. Optimal in this sense, however, is tricky to define. One could seek to simply minimize the average time in system for an arbitrary voter on election day, but this may lead to a scenario that neglects smaller precincts with smaller effects on the mean. To counteract this, we propose an objective function that also considers the maximum wait time experienced by any voter on election day. Since the maximum weight time experienced by any voter will necessarily be greater than the average wait time experienced by an arbitrary voter, we choose to scale the average wait time by a factor of six. This brings the two quantities to similar magnitudes and ensures the maximal weight time does not dominate optimality. This results in the following optimization problem:

Minimize

$$z = 6\sum_{i=1}^{20} \frac{\sum_{\mathrm{n}} W_{(i,n)}\left(c_{i,1},c_{i,2}\right)}{N_i} + \sum_{i=1}^{20} Max\left(W_{(i,n)}\left(c_{i,1},c_{i,2}\right)\right) \tag{1}$$

Subject To

$$\sum_{i=1}^{20} c_{i,1} \leq 55 \tag{2}$$

$$\sum_{i=1}^{20} c_{i,2} \leq 306 \tag{3}$$

Where $W_{(i,n)}\left(c_{i,1},_{i,2}\right)$ is the wait time experienced by the nth voter at the ith precinct as a function of $c_{i,1}$, the number of poll-pads allocated to precinct *i*, and $c_{i,2}$, the number of ballot marking devices allocated to precinct *i*. N_i corresponds to the number of voters at precinct *i*, and lastly, $Max\left(W_{(i,n)}\left(c_{i,1},c_{i,2}\right)\right)$ is the maximum wait time experienced by a voter at precinct *i*. The two constraints ensure that no more resources are used than the minimum requirements of Georgia law. The optimization problem is more complex than it initially appears, because both W and N are functions of random variables, making simulation optimization useful in finding a solution near optimality.

Simio users have access to add-in processes that can aid in simulation optimization. Opt Quest is one of these and is used to generate scenarios with varying controls; examining the feasible region in search of a scenario that optimizes with respect to a user-specified parameter. We set up an Opt Quest experiment, with our two constraints and objective function. Opt Quest was allowed to create up to 600 unique scenarios, replicating each scenario 6 times.

At the conclusion of the Opt Quest run, subsect selection was used to winnow the 600 feasible scenarios. Subset selection divides each scenario into one of two categories, potentially the best, or not the best. At the 95% confidence level, subset selection rejects all scenarios for which there is strong evidence that they are not optimal. As is typical of hypothesis testing, failure to reject a scenario simply means that there is not strong enough evidence to reject it, not that it is optimal.

Lastly, to further narrow down candidate scenarios, the KN method is used. The KN method simulates the remaining scenarios until, with 95% confidence, it is sure that at least one of the remaining scenarios is the best, or within the indifference parameter δ from the best scenario. For our purposes, the indifference parameter was set to 12 minutes. After 50 replications, 17 scenarios were still selected by KN, we chose to continue analysis on the scenario with the lowest average time in system across the 50 replications.

3.3.3 Heuristic Allocation

Simulation is computationally expensive, and even with just 20 precincts, running Opt Quest and KN to fruition was incredibly challenging. Elections in the United States only occur at most a few times a year, and typically only 1 or 2 of the elections that will occur during a given year will strain the system. With enough preparation time, it is possible election administrators could use simulations built on historic data to allocate equipment, but it certainly would be challenging. For that reason, we choose to also evaluate simple heuristic allocations against the current allocation under Georgia law.

The needs of a precinct are related to the number of registered voters serviced by it, but registered voters alone cannot provide the whole picture. For instance, a precinct that services many registered voters may be in an area that historically has low turnout. A precinct with only a few registered voters may be in an area where economic factors drive voters to show up to the precinct either very early in the morning or very late in the evening. To capture concentration of voters as well as quantity of voters, each precinct was assigned a score using the following equation:

$$z = c\,\frac{\text{Maximum Arrivals per Hour}}{\mathit{Average\ Arrivals\ per\ Hour}} + \frac{\mathit{Number\ of\ Registered\ Voters}}{250} \tag{4}$$

Where *c* is a scalar parameter that weighs the Peak/Avg Ratio. With a score *z* assigned to each precinct, the proportion of equipment allocated to a precinct is correlated to the proportion of its score to the sum-total of all precinct's scores. This heuristic was evaluated with five different values for c: 1,2,3,5 and 10. To be in line with current practices in Fulton County, no precinct was permitted to have fewer than 2 poll-pads. The performance of the heuristic for each weight will be compared to performance of the current allocation of equipment.

4 RESULTS

4.1 Optimal Allocation

4.1.1 Performance of Optimal Allocation

Overall, simulation optimization was able to vastly improve upon the allocation currently employed by Georgia law. Average time in system experienced by an arbitrary voter decreased by 18%, from about 50 minutes to 41 minutes. Ten of the twenty precincts experienced a local decrease in average time in system, with Mountain Park Community seeing the most drastic decrease from 2 hours and 47 minutes to just 11 minutes (Table 2).

Table 2: Inputs and mean performance measures for 3 simulated allocations across 50 replications. Here "TIS" refers to time in system. "PPs" and "BMDs" refer to the number of poll pads and ballot marking devices at a precinct. "H4" refers to the fourth, and highest preforming, heuristic (c=5).

Precinct Name	Curr. Max TIS (Hours)	Curr. Avg TIS (Hours)	Opt. Max TIS (Hours)	Opt. Avg TIS (Hours)	Curr. PPs	Curr. BMDs	Opt. PPs	Opt. BMDs	H4 PPs	H4 BMDs
Shakerag Elementary	.533	.221	.701	.319	3	15	2	12	2	12
Cathedral of St Phillip	1.368	.64	.76	.305	2	14	3	15	3	16
Esther Jackson Elementary	.551	.235	.49	.203	2	12	2	11	3	16
Tracey Wyatt Community	.26	.18	.262	.181	2	12	5	26	2	16
Morningside Pres. Church	.671	.3	.675	.302	4	24	2	29	3	48
Lang-Carson Community	1.584	.92	1.703	.999	2	14	3	15	2	8
Hoyt Smith Center	.609	.255	1.382	.791	3	16	2	12	2	8
Omrewood Park Pres.	5.589	3.405	5.576	3.365	3	18	3	15	5	32

Peachtree Rd. Untd-Method.	.548	.231	.828	.353	6	35	4	22	2	8
Etris Community	.323	.192	.411	.217	3	18	4	22	2	8
Ponce de Leon Library	.613	.248	.441	.201	2	11	3	16	3	20
Mountain Park Community	4.984	2.788	.381	.185	2	2	2	8	3	12
Little 5 Point Community	1.029	.472	1.046	.466	2	8	2	14	2	8
Lebanon Baptist Church	2.258	1.465	.811	.389	2	12	2	12	3	12
C. H. Gullat Elementary	.391	.188	.386	.192	3	18	3	16	2	12
Ison Springs Elementary	.450	.188	.444	.189	4	22	3	15	3	12
Peachtree Pres. Church	.462	.193	.445	.206	4	22	3	16	2	8
Abbots Hill Elementary	.468	.199	.419	.189	2	9	2	9	3	12
Dad's Garage Theatre	1.426	.811	.644	.27	2	13	2	14	3	20
Sandy Springs Christian Ch.	.306	.187	.288	.182	2	11	3	16	5	12
System Wide	**5.666**	**.838**	**5.576**	**.687**	**55**	**306**	**55**	**300**	**55**	**306**

Lebanon Baptist and C. H. Gullat recorded a decrease by about a factor of four while average wait time was cut in half at Saint Phillip. Despite the high magnitudes of decrease in average time in system, the highest magnitude of increase experienced by any precinct was an increase by a factor of .678 at Hoyt Smith (Table 2). For variables designated as response variables in an experiment, Simio generates a SMORE plot (Simio Measure of Risk and Error) showing the 95% confidence interval for that variable. We designated mean average time in system to be a response variable, and from the SMORE plot were able to reject the null hypothesis that the opt quest and current allocation means were equivalent, with 95% confidence. To evaluate the feasibility of a heuristic that models the optimal allocation, linear regression was used to look for correlations between the number of ballot marking devices allocated to a precinct at optimality and other known variables. R_i, the number of groups of 250 registered voters serviced by each precinct, had only a weakly positive correlation to the number of ballot marking devices given to each precinct at optimality (Table 3). This is particularly interesting, because this is the quantity the state primarily uses to allocate ballot marking devices. On the other hand, P_i, the ratio of arrivals during the peak hour to average arrivals, had a slightly stronger positive correlation to the number of BMDs given to each precinct at optimality than R_i. While neither correlation is particularly strong, this suggests that the arrival pattern does have some impact on the needs of a precinct. Additionally, it supports that there are other variables impacting a precinct's needs outside of concentration and number of registered voters. One likely suspect would be turnout, as well as the number of election day voters, but because turnout is so volatile it would be a challenge to accurately forecast it at each individual precinct.

4.1.2 Correlation of Optimal Allocation to Known Variables

To evaluate the feasibility of a heuristic that models the optimal allocation, linear regression was used to look for correlations between the number of ballot marking devices allocated to a precinct at optimality and other known variables. Ri, the number of groups of 250 registered voters serviced by each precinct, had only a weakly positive correlation to the number of ballot marking devices given to each precinct at optimality (Table 3). This is particularly interesting, because this is the quantity the state primarily uses to allocate ballot marking devices. On the other hand, Pi, the ratio of arrivals during the peak hour to average arrivals, had a slightly stronger positive correlation to the number of BMDs given to each precinct at optimality than Ri. While neither correlation is particularly strong, this suggests that the arrival pattern does have some impact on the needs of a precinct. Additionally, it supports that there are other variables impacting a precinct's needs outside of concentration and number of registered voters. One likely suspect would be turnout, as well as the number of election day voters, but because turnout is so volatile it would be a challenge to accurately forecast it at each individual precinct.

Table 3: Linear regression models for correlation of allocated ballot marking devices at optimality to other variables.

Linear Regression Model	β_0	β_1	β_2	p-value of β_1	p-value of β_2
$Y_i \sim \beta_0 + \beta_1 R_i$	11.7	.214	-	.661	-
$Y_i \sim \beta_0 + \beta_1 P_i$	13.6	.622	-	.257	-
$Y_i \sim \beta_0 + \beta_1 R_i + \beta_2 P_i$	9.80	.768	.223	.311	.669

4.2 Heuristic Allocation

Of the 5 heuristics simulated, heuristic 4 stood out the most regarding improvement upon the current allocation. Average time in system experienced by an arbitrary voter decreased by 8 percent and once again 10 out of 20 precincts experienced a decrease in average time in system, at much greater magnitudes than increases at any precinct (Table 4). That this heuristic was able to improve upon the current allocation at all suggests that there is a relationship between the needs of a precinct and the concentration of voter arrivals at said precinct. From Simio's SMORE plots, the hypothesis that the mean average time in system of heuristic 4 is equivalent to the current scenario can be rejected with 95% confidence.

Table 4: Mean performance measures for the 5 heuristics across 50 replications.

	Heuristic 1	Heuristic 2	Heuristic 3	Heuristic 4	Heuristic 5
Scale of Peak/Avg Ratio	1	2	3	5	10
Avg TIS (Hours)	.803	.829	.810	.768	.781
Max TIS (Hours)	5.69	5.64	5.73	5.73	5.63

5 CONCLUSIONS

Our simulation suggests that solely allocating resources according to registered voters is not the most equitable, nor efficient way to do so. Through optimization of the election system using simulations, it can be demonstrated that alternative allocations lower the average time spent in system by an arbitrary voter without depriving other precincts of the resources they need (Table 2). Not only that, but at optimality, there is not a strong correlation between the number of registered voters serviced by a precinct and the number of ballot marking devices allocated to that precinct (Table 3). Heuristic allocations that consider alternative variables, like concentration of arrivals, also have the potential to improve on the current allocation method which relies heavily on registered voter counts (Table 4). Considering how voter turnout can be impacted by a large variety of different variables, our simulation may be useful in building a more robust allocation method which can consider factors beyond simply registered voter counts.

Further experiments examining the efficiency and equity of election resource allocation would ideally focus on broadening the scope of data examined. Currently, our simulation is limited to just 20 precincts in Fulton County which is a mostly urban region. However, the State of Georgia encompasses a variety of regions including suburban, rural, costal, and mountainous. Voters in each of these areas are likely to follow patterns entirely distinct from those in Fulton County, thus expanding the model to cover the entire state could reveal even more about inequity and variability in voting systems. Additionally, examining voter arrival data from a wider range of election years could reveal insights about the repetition and predictability of voting patterns in precincts. By expanding the scope of the simulation, and the data used to build it, it is entirely possible that better heuristics for allocating election equipment could emerge, drawn from patterns of optimal allocations in the state as a whole.

REFERENCES

Alexander, A. and G. Fields. 2022. "Effect of Georgia's Voting Law Unclear, Despite High Turnout". *AP News*. https://apnews.com/article/2022-midterm-elections-georgia-state-government-89b374bfafdba5b673a46b240a5e3e1f, accessed 12th April 2024.

Amy, J. 2021. "Georgia Gets More Urban and Diverse as White Residents Dip". *AP News*. https://apnews.com/article/georgiacensus-2020-234b0a23975b19f682cf37a2517ee364, accessed 12th April 2024.

Barber M. and J. B. Holbein. 2022. "400 Million Voting Records Show Profound Racial and Geographic Disparities in Voter Turnout in the United States". *PLOS ONE* 17(6):1-13.

Bertsimas, D., V. F. Farias, and N. Trichakis. 2012. "On the Efficiency-Fairness Trade-off". *Management Science* 58(12): 2234–2250.

Cantoni, E., and V. Pons. 2022. "Does Context Outweigh Individual Characteristics in Driving Voting Behavior? Evidence from Relocations within the United States." *American Economic Review* 112(4): 1226-72.

de Benedictis-Kessner, J. and M. Palmer. 2023. "Driving Turnout: the Effect of Car Ownership on Electoral Participation". *Political Science Research and Methods* 11(3): 654-662.

Fabina, J. 2023. "Voter Registration in 2022 Highest in 20 Years for Congressional Elections". *United States Census Bureau*. https://www.census.gov/library/stories/2023/05/high-registration-and-early-voting-in-2022-midterm-elections.html, accessed 10th April 2024.

Fowler, S. 2020. "Why do Nonwhite Georgia Voters Have to Wait in Line for Hours? Too Few Polling Places". *NPR*. https://www.npr.org/2020/10/17/924527679/why-do-nonwhite-georgia-voters-have-to-wait-in-line-for-hours-too-fewpolling-pl, accessed 12th April 2024.

GA Code § 21-2-367 2022. https://law.justia.com/codes/georgia/2022/title-21/chapter-2/article-9/part-4/section-21-2-367/, accessed 21st August 2024.

Laurison, D., and A. Rastogi. 2023. "Income Inequality in U.S. Voting: A Visualization". *Socius* 9.

Li, J., T. T. Allen, and K. Akah. 2013. "Could Simulation Optimization have Prevented 2012 Central Florida Election Lines?." In *2013 Winter Simulation Conference (WSC)*, 2088-2096 https://doi.org/10.1109/WSC.2013.6721586.

MIT Election Data and Science Lab. 2020. "EPI Full Reproduction Files 2008-2022". https://elections.mit.edu/#/data/map?view=state-profile&state=GA&year=2020, accessed 21st August 2024.

U.S. Census Bureau. 2022. *American Community Survey*. https://www.census.gov/programs-surveys/acs/data.html, accessed 12th April 2024.

Wang, X., M. Yang, and M. J. Fry. 2015. "Efficiency and Equity Tradeoffs in Voting Machine Allocation Problems". *Journal of the Operational Research Society* 66(8): 1363-1369

AUTHOR BIOGRAPHIES

BROCK SPENCE is an undergraduate student in the H. Milton Stewart School of Industrial and Systems Engineering at the Georgia Instute of Technology. His studies are concentrated in Operations Research. His email address is brockspence@gatech.edu.

ALEXANDER CAÑEDO is an undergraduate student in the H. Milton Stewart School of Industrial and Systems Engineering at the Georgia Institute of Technology. His email address is acanedo3@gatech.edu.

DIMA NAZZAL is a Principal Academic Professional in the H. Milton Stewart School of Industrial and Systems Engineering at the Georgia Institute of Technology. Her research focuses on modeling, design, and control of discrete event logistics systems, including healthcare delivery systems, manufacturing systems, and distribution systems. She currently serves as the Chair of the Faculty Executive Board at the Georgia Institute of Technology. Her email address is dima.nazzal@gatech.edu and her website is https://sites.gatech.edu/dima-nazzal/.