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IMPACT OF FACILITIES LAYOUT METHODS ON IN-PERSON ELECTIONS: A THEORETICAL EXPLORATION

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IMPACT OF FACILITIES LAYOUT METHODS ON IN-PERSON ELECTIONS: A THEORETICAL EXPLORATION

BY

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ABSTRACT

While previous research in elections has utilized systems engineering methods to address the issue of long lines, this work has primarily focused on the development of resource allocation methods through basic queuing theory and simulation modeling. While resource allocation plays a critical role in addressing long lines, little work has observed the effect of the physical environment on the system.

The purpose of this work was to explore the effect of layout (i.e., the layout of voting equipment and path directionality) on voting system performance (i.e., average voter travel distance and average voter time-in-system) at different turnout levels in a theoretical voting system. For the purposes of this research, a two-step voting system was modeled and a rectangular room of 1,000 sqft was used as the theoretical polling location. Facilities layout planning and computational analysis utilizing discrete event simulation was performed on the systems at varying levels of turnout. The results of the simulation were then statistically compared using *t*-tests with a Bonferroni corrected alpha for pairwise comparisons.

The results indicate that layout and path directionality have a significant effect on average voter travel distance, regardless of turnout, and the Perimeter layout results in the smallest average travel distance and the shortest average time-in-system. However, as voter turnout increases, the effect of layout on time-in-system becomes overshadowed by the time voters spend in queue. It was also found that path directionality has a significant impact on average voter travel distance, and which path directionality is most efficient is dependent upon the layout method used. Contrarily, path directionality was not found to have a significant effect on the average time-in-system. This work exemplifies that layout is a critical aspect to consider in the design of future elections and provides valuable insight for election

administrators and future researchers into the efficiency of various layout methods and path directionalities.

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I would like to express my gratitude for my Major Professor, Dr. Gretchen Macht, who made this work possible. Had it not been for her guidance throughout this process and the confidence she had in my abilities, this work would not have been possible. I would also like to thank her for introducing me to the world of systems engineering and for demonstrating that we can in fact have a great impact on the world around us if we commit ourselves to it. You have certainly changed the course of my professional career and my life, and for that I am extremely grateful. I would also like to thank my committee members for their time and support along the way.

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Finally, I am incredibly grateful for my mom and dad for their love and support over the past year and for believing in me since the beginning. Thank you for listening, providing guidance, and pushing me to always keep learning and growing.

PREFACE

This paper is written in manuscript format for publication in *Stochastic Systems*. Formatting requirements, based on the INFORMS version of the journal, dictate that the submission can be no longer than 35 pages, double or single spaced, with 1" margins and 11 point font. The abstract describing the main results can be no longer than 200 words and a maximum of five keywords are allowed.

At the moment of the defense, this paper has not yet been submitted to the journal for review. Based on the feedback from the Thesis Committee, this manuscript is projected to be submitted prior to the end of the summer.

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Abstract

Motivated by the limited current literature exploring the effects of facilities layout planning in voting systems, this work aims to observe the effects of layout and path directionality on voting system performance. A two-step voting system is considered and a 1,000 sqft room is modeled under various layout and path directionality conditions. Discrete event simulation is used for a computational simulation analysis using the Bonferroni Approach to Multiple Comparisons to determine differences in average voter travel distance and average voter time-in-system. The results indicate that layout method and path directionality have a significant effect on average voter travel distance, with the perimeter layout with a unidirectional path being the most efficient. For the average time-in-system, layout had an effect at some turnout levels and between some layout methods; however, path directionality had no significant effect. Similar to average travel distance, the perimeter layout generally resulted in the most efficient time-in-system. This work exemplifies the critical role that layout plays in the performance of elections and presents valuable insight into ways in which layout can be utilized to design more efficient election systems.

Keywords: facility layout planning, discrete event simulation, election systems, voter turnout

Introduction

Recently, researchers have started to focus on in-person voting systems from a systems engineering perspective to explore causes and propose solutions to the issue of long lines. From queuing theory to simulation to optimization, industrial and systems engineering techniques can assist in the efficacy and efficiency of the election system. While methods in layout optimization and discrete event simulation (DES) have been researched and developed over the last 30 years, these tools are not typically used in planning facilities outside of manufacturing. Election administrators typically use manuals or best practices (US Department of Justice, 2016; US Department of Justice, 2010; US Election Assistance Commission, 2007; ACE Electoral Knowledge Network. n.d.), their "Rules of Thumb," and personal experience to arrange and recommend layouts of in-person polling locations (Stewart, 2015a, p. 13). When the results of these estimations are insufficient, they can cause irreparable harm to the election system by causing delays and long lines that lead to voter disenfranchisement (King, 2019; Stewart & Ansolabehere, 2015; Claassen et al., 2012). These traditionally accepted methods are commonly applied in polling place set up, where they do impact the flow of voters and the overall time to vote.

Although creating simulations from scratch is often complex and resource-intensive, these models' complexity and robust nature can provide critical information for election preparation. Voting systems are inherently stochastic as randomness is present in multiple aspects of the system (e.g., voter arrival times, voter processing, voter choice of check-in station, ballot marking station). Simulation-related works have been conducted on queuing theory basics in election systems by investigating voter wait times and lines at polls to identify the causes of the delays (e.g., Allen & Bernshteyn, 2006; Stewart, 2015a). Nevertheless, a limited amount of DES is utilized in election research even though it allows for comprehensive stochastic system modeling. The application of the DES in the literature representing processes spans the globe, evaluating elections in Hong Kong (Au et al., 2018), Nigeria (Olabisi & Chukwunoso, 2012; Ganiyu et al., 2016), and the United States (Yang et al., 2014; Allen, 2011; Allen et al., 2020; Bernardo et al., under review). Even when DES is an appropriate method for capturing voting system variability, the literature does not consider the actual in-person polling location capacity and layout inside that location as a constraint.

This paper explores the relationship between facility layout planning and voting system performance through discrete event simulation. Computational simulation analysis for theoretical facility layout methods was performed to determine whether there is a relationship between the layout of a polling location and voting system performance. This analysis is executed by generating a set of theoretical voting systems and observing the effects of facility layout method and voter path directionality on voter time-in-system and voter travel distance. Focusing on the relationship between the defined conditions, this work does not attempt to determine an optimal layout strategy. Instead, this work aims to identify relationships between layout and performance and indicate which systems provide the best performance metrics. The following research questions are proposed:

1) Does the layout method have a significant impact on voter time-in-system and voter travel distance for various levels of voter turnout; if so, which is the most efficient?
2) Does the voter path directionality have a significant effect on voter time-in-system and voter travel distance for various levels of voter turnout; if so, which is the most efficient?

Voting Systems & Systems Engineering

The right to vote is the bedrock of democracy. Millions of people across the United States exercise their right to vote in elections. In the November 2020 General Election, nearly 159.8 million ballots were cast (United States Election Project, 2020), and therefore, this process must be executed in a manner that upholds voter accessibility. However, ensuring that millions of voters can cast their ballots efficiently has often been challenging as many Americans experience long lines when voting (United States Presidential Commission on Election Administration, 2014; Ansolabehere & Shaw, 2016).

Researchers have begun to address the issue of long lines from a systems engineering perspective. For example, various queuing theory methods have been applied to provide more sufficient resource allocation estimates to understand and quantify lines or wait times. This work has aimed to improve voting system performance by optimizing allocation and quantity decision making (Belenky, 2007; Allen & Bernshteyn, 2006; Stewart & Ansolabehere, 2015; Edelstein, 2006; Edelstein & Edelstein, 2010; Yang et al., 2014). Stewart and Ansolabehere (2015) state that queuing theory is a promising tool for addressing long lines. However, this research is limited in that it does not consider the variability in processing times and arrival rates within the system. Edelstein and Edelstein (2010) also used computer queuing simulations to develop state-specific resource allocation models. Edelstein (2006) recognized that a lack of adequate resource allocation resulted in long lines. The work further presented a ratio of voters to voting equipment, but the data used significantly generalizes the voting process. Overall, resource allocation methods using queueing theory may be able to better predict the number of resources that a polling location needs to decrease the occurrence of long lines compared to "Rules-of-Thumb" methods. However, queuing theory generalizes voting systems to the point that it may limit applicability to large-scale decision-making. Furthermore, these studies do not consider the effect of the physical space or the layout of equipment on resource allocation or voting system performance.

Yang et al. (2015) and Allen et al. (2020) developed optimization models that improved upon the initial voting queuing theory research. These models allowed for the modeling of variation in voter turnout and voting machine availability throughout the day and, therefore, more accurately represent actual voting systems. These models were shown to allocate resources in a way that significantly reduced the average voter time-in-system and the number of voters that wait in long lines (Yang et al., 2015), but they still fail to consider physical space characteristics and the layout of equipment as variables that may affect the system. Yang et al. (2014) developed queuing models and simulation models to optimally allocate resources. The steady-state queuing models, while simple, again do not adequately capture the variation inherent in the system. The simulation models account for variability and are therefore more representative and comprehensive of systems. They do not, however, consider the physical characteristics of the space or the layout of voting equipment.

When considering the inherent stochasticity within processing times, arrival rates, and the selection of possible routes, voting systems become more complex. Therefore, it is essential to capture the effects of independent variables while accounting for variability and stochasticity in the system. Discrete event simulation (DES) has the capability of modeling such systems. DES has been used extensively in other applications such as hospital layout planning (Gibson & Lease, 2007; Arnold et al., 2012; Lather, 2019). Gibson and Lease (2007) demonstrated that DES is effective in analyzing the effects of different layouts and processes. For example, traveling routes were determined by the patient's clinical state and, therefore, lead to stochasticity within the paths being modeled by DES (Arnold et al., 2012). From a general systems perspective, voting systems are similar to hospitals in this way. However, this aspect of path directionality is a relatively new perspective in election systems, especially in the previous DES models (Bernardo et al., 2020). Voter travel paths in voting systems are both selected and dependent upon the availability of stations, hence, capturing this stochasticity is vital in accurately modeling the system. Demonstrated through its applications in other systems, DES is an appropriate approach for modeling and analyzing the layout of voting systems.

Other researchers have used DES to model voting systems (Allen, 2011; Au et al., 2018; Allen & Bernshteyn, 2006; Olabisis & Chukwunoso, 2012; Bernardo et al., 2020). Allen (2011) demonstrates that DES modeling is an appropriate tool for modeling the variability within voting systems and accurately modeling the system and provides guidance on creating such models. However, they do not consider the physical space or the layout of equipment as a variable. Olabisis & Chukwunoso (2012) used DES to demonstrate that voting system performance can be improved by increasing the length of the Election Day and decreasing the time voters spend casting their ballot. Au et al. (2018) further demonstrate that DES can aid in addressing the issue of long lines. The authors claim to consider the layout design of the facility by varying the number of resources at each step within the system. Thus, they explore the effect of resource allocation on system performance rather than the effect of layout on actual system performance. However, Bernardo et al. (2020) utilize DES to explore the effects of layout and operational changes on the performance of a Los Angeles vote center. This work found that the positioning of departments and voter paths has a significant impact on voter time-in-system. This implies that further research observing the effects of layout and path directionality is needed. What is proposed in this research differs from the Bernardo et al. (2020) work in that it considers the layout of each station, path directionality, and the effects of these factors at varying turnout levels.

While the current literature exploring resource allocation is undoubtedly an important area of research in the voting systems domain, it is significantly limited as it overlooks the physical environment. Understanding the constraints of the physical system is beneficial in designing efficient in-person voting systems. For example, while election administrators have suggested that the positioning of voting equipment and individual stations may have an effect on voter flow, there is little literature that observes the impact of voting equipment layout and facility characteristics on voter flow directly; similarly, no known works have been done regarding the limitations imposed by voting system layout and physical characteristics on voting system performance in general.

Facilities Layout Planning (FLP) refers to the positioning of departments in relation to one another and the arrangement of individual components within each of a system's departments (Russell & Taylor, 2012; Pérez-Gosende et al., 2021). Layout is an essential aspect of system operations that can significantly affect the system performance and assist in achieving a safe, efficient flow of entities through the system (Russell & Taylor, 2012, p. 26). FLP is conducted to make a system more effective (e.g., eliminate bottlenecks, maximize space and labor utilization, minimize transportation and handling costs) and has been implemented in many different service and fabrication systems (Pérez-Gosende et al., 2021), including hospitals (Chraibi et al., 2018; Halawa et al., 2020; Helber et al., 2016; Moatari-Kazerouni et al., 2014; Benitez et al., 2018), manufacturing plants (Das, 1993; Viskup et al., 2019), and construction facilities (Farmakis & Chassiakos, 2018; Kaveh et al., 2016). In addition, research in FLP has proven that the consideration and improvement of physical space increase the efficiency and performance of various systems. However, the applicability of FLP to in-person voting systems has yet to be explored. Therefore, this work aims to address a critical gap in the literature of exploring how FLP can be used for in-person polling locations.

There are currently no national standards for polling location layout beyond the general guidelines surrounding the Americans with Disabilities Act of 1990 (ADA) (US Department of Justice, 2016; US Election Assistance Commission, 2007). In some jurisdictions, election officials create polling location layout diagrams that are used in the setup process. In contrast, other counties leave the poll workers or setup crews responsible for those decisions. This may be, in part, due to a lack of systems understanding and the assumption that physical characteristics do not impact system performance or the perceived necessity based on their jurisdictional needs. In other cases, limited resources, funds, and time may prevent election administrators from effectively incorporating polling location layouts in election planning.

Regardless, the physical space is a critical factor in planning voting systems, yet it is rarely recognized in the design and evaluation processes (Stewart & Ansolabehere, 2015). Acknowledging that facilities are inherently limited and associated with various constraints due to their size and shape is necessary for designing polling location layouts for successful elections.

This research builds on the little existing literature exploring layout in elections to explore the impact of layout and path directionality on voting system performance.

Methods and Assumptions

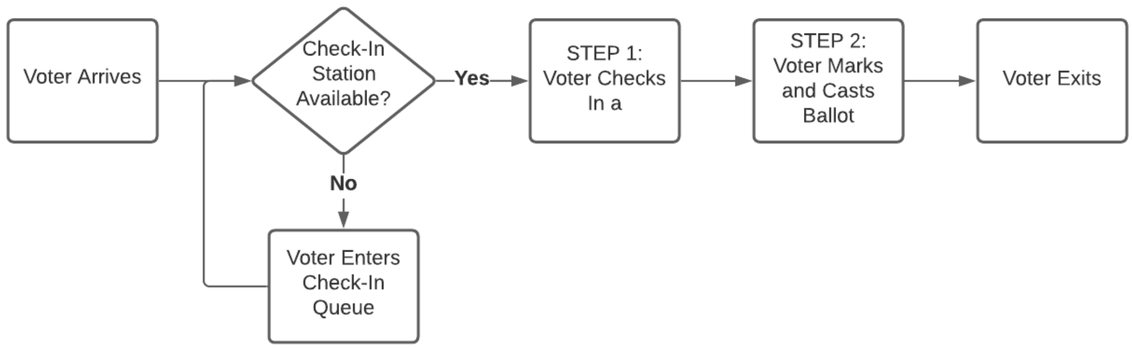
Conceptual Modeling

The models used in this analysis are theoretical and represent a two-step voting system. The two-step voting system is the simplest of the voting systems regarding the number of processes used in US elections. It consists of (i) a check-in process and (ii) a one-step ballot marking and ballot casting process. In this system, a voter arrives and enters the queue for check-in. When voters arrive at check-in, they are assisted by a poll worker and checked into the system by an electronic pollbook. When the voters have finished checking in, they move to a ballot marking and casting device (BMCD).[1] In this system, queues cannot build between check-in and the BMCDs; therefore, if all BMCDs are occupied, the voter must wait at the check-in station until a BMCD becomes available. After casting the ballot at the BMCD, the voter travels to the exit door and exits the system. The process flow chart for the system is shown in Figure 1.

[1]Traditionally, the term in the literature is a ballot marking device (BMD). However, with most BMDs, this means that there is another processing step immediately following where a voter casts their ballot. With this particular system, the voter can do both steps of ballot marking and casting at the same station, hence the use of this terminology.

Figure 1.

Process Flow Chart for a Two-Step Voting System



Additional processes that may occur in some voting systems, such as provisional voting,[2] vote by mail ballot drop-off,[3] and the "I Voted" sticker pick-up process,[4] were not considered.

Two independent variables were considered in this analysis: the directionality of the voter path and the layout of the voting equipment. The dependent variables (i.e., the performance metrics) that were monitored were: (i) voter time-in-system (TIS) and (ii) voter travel distance (TD). An additional variable, voter turnout, is included in the analysis at six different levels to observe how the dependent variables change within each level of turnout. Therefore, comparisons are not performed between levels of voter turnout but within the different layout scenarios.

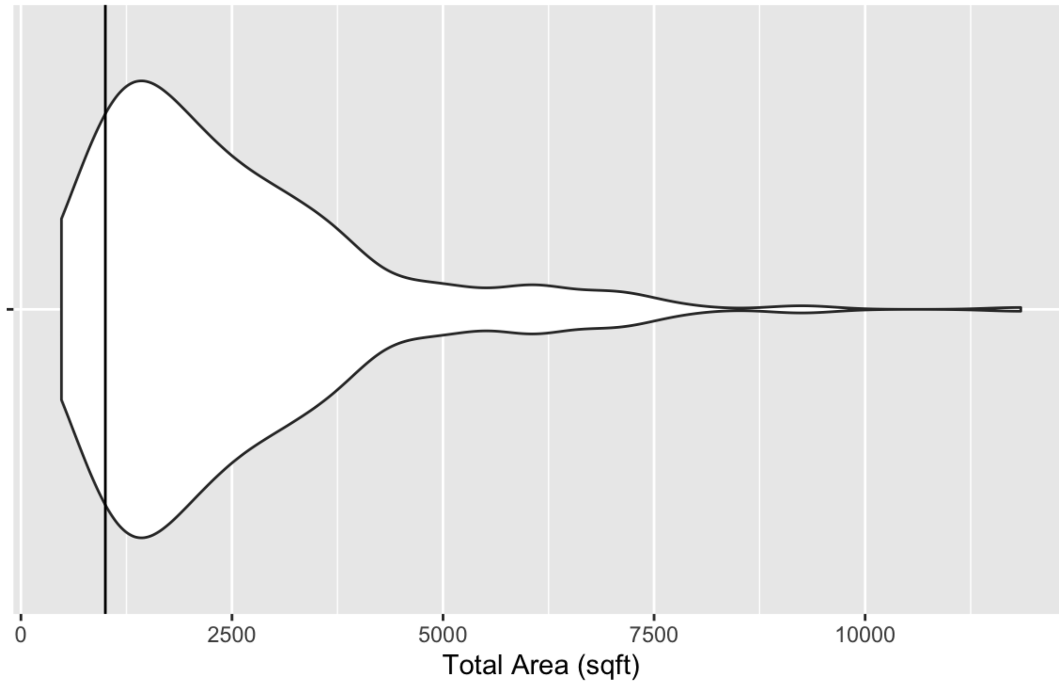
Room Size. Polling locations are held in a myriad of locations across the country (Stewart, 2013a; Stewart, 2013b; Stewart, 2015b; Stewart, 2017; Stewart, 2020). Consequently, there is no one facility with a consistent room size utilized for all polling locations; instead, numerous facilities and rooms with varying sizes and physical characteristics are used to hold elections. The

[2]Provisional voting and the inclusion of errors and backtracking were incorporated into processing times at each station and were therefore not considered separate processes within the system.
[3]Vote by mail ballot drop-off processes, in some locations, are completely independent of in-person voting (i.e., they have separate entrances, separate queues, and do not interact with the in-person voting system to any extent).
[4]The sticker pick-up process was not modeled in the system because it was assumed to have negligible effect on the system.

range of potential areas of rooms within commercial, public, and government facilities is extensive, and, therefore, it is important to understand the effects that facility layout has on a range of different room sizes. Standard offices, for example, have a total area that ranges between 210 and 250 sqft (Kansas Department of Administration, n.d.). On the other hand, high school gymnasiums often have much larger areas that can surpass 7,000 sqft (Department of Defense Education Activity, 2012).

As this is one of the first studies observing the effects of layout on system performance, the room size was held constant, and a smaller room of 1,000 sqft was used to model the theoretical system. In a preliminary analysis (see Appendix A) performed on the size of polling locations available to URI VOTES, it was found that a 1,000 sqft room fell into the area range of commonly used facility types (i.e., churches, community centers, government buildings, libraries, police/fire stations, schools, senior centers, and other facilities), and eight of twelve room types (i.e., cafeterias, cafetoriums, classrooms, community rooms, foyers, halls, meeting rooms, multipurpose rooms, and other rooms). A violin plot showing the area of 378 actual polling locations is shown in Figure 2 and demonstrates that 1,000 sqft is representative of polling locations that are used.

Figure 2.
Violin Plot of Total Polling Location Areas



In addition, assumptions were made to standardize the space: the room shape is rectangular with dimensions (e.g., columns, internal walls, or permanent furniture or room fixtures) of 25 ft by 40 ft, and it has no obstructions or physical features that must be considered in the layout of the voting equipment.

Layout Methods. While there are ADA and Election Assistance Commission (EAC) guidelines to ensure accessibility and voter privacy,[5] few comprehensive guidelines or methods exist for the layout and placement of voting equipment (US Department of Justice, 2016; US Department of

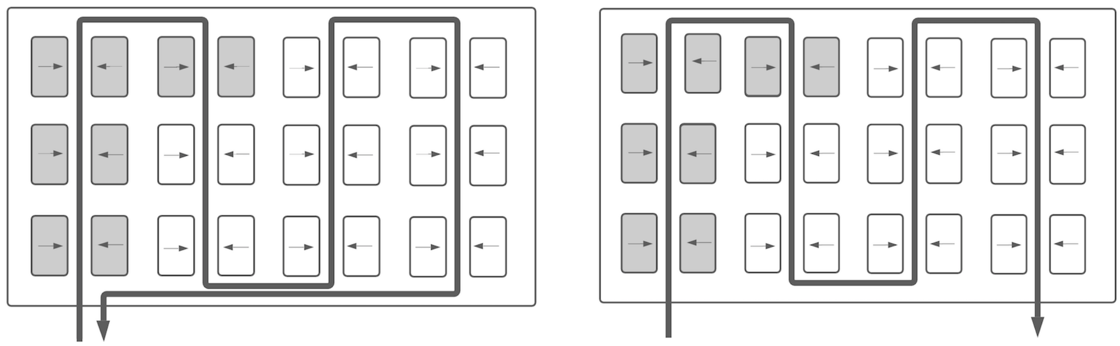
[5]ADA guidelines specify the minimum distance requirements for path widths. The 2010 ADA Accessibility Guidelines for Title II and III state in section 403.5.1 that "the clear width of walking surfaces shall be 36 inches (915 mm) minimum" and this width may be "reduced to 32 inches (815 mm) minimum for a length of 24 inches (610 mm) maximum". In addition, as stated in section 304.3.2, "turning space shall be a T-shaped space within a 60 inch (1525 mm) square minimum with arms and base 36 inches (915 mm) wide minimum" (US Department of Justice, 2010).

Justice, 2010; US Election Assistance Commission, 2007; ACE Electoral Knowledge Network. n.d.). To ensure easy access to the equipment, all paths were designed to be ADA compliant. Therefore, three facility layout methods were defined and explored: 1) serpentine method, 2) aisle method, and 3) perimeter method.

The *Serpentine* layout method is commonly used in facility layout planning (Botsali & Peters, 2005; Zijlstra & Mobach, 2011); however, it is unclear if, in practice, this method has been applied to voting. Adapted to a voting system, the voter path winds in an "S" shape through the polling facility, and stations are positioned on the left and right sides of the path (Figure 3). The check-in stations (grey rectangles) come first along the voter path (line) and are followed by the BMCDs (white rectangles).[6] It is assumed in this specific layout that the voters follow the path and choose any available station. The voter follows any marked path and takes a 90-degree turn to either enter or exit the station. For the cyclical Serpentine layout, the TD range possible is between 109.7 ft to 118.0 ft, whereas the unidirectional Serpentine layout's TD range is 86.3 ft to 95.4 ft.

[6]All process stations, regardless of check-in or BCMDs, are illustrated as rectangles for simplicity of demonstrating the facility layout method.

Figure 3.
Serpentine Layout Method for Locations With Path Directionality

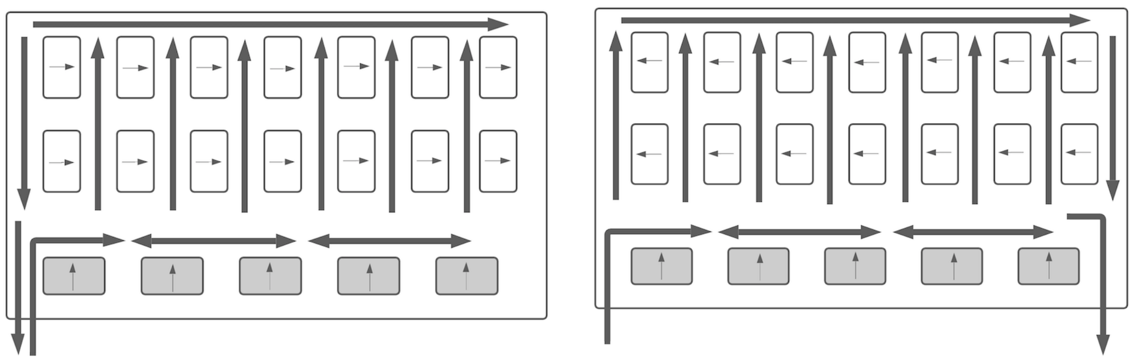


(a) Cyclical Serpentine Layout Method *(b)* Unidirectional Serpentine Layout Method

Note: A black arrowed line illustrates the voter path. Rectangles represent stations for processes (i.e., check-in, BCMD). The arrows on the stations indicate the direction that the station faces (i.e., the arrows face the path indicating that the voting equipment faces in towards the path and can be accessed directly from the path).

The second layout method considered is the *Aisle* method, similar to layouts used in retail stores. Research regarding retail facility layouts often focuses on the block structure design and location of aisles to maximize profits for a store (Li, 2011). The application of this method, however, has also been observed in polling locations. In this method, a row of check-in stations along a wall and blocks of BMCDs are perpendicular to the row of check-in stations. Thus, there are multiple rows of BMCDs, and all of the stations face the same direction. From the BMCD, the voter path continues to the wall opposite the check-in stations and then moves towards the exit, as shown in Figure 4. The voter follows any marked path in this layout and takes a 90-degree turn to either enter or exit the station. In the cyclical Aisle layout, the minimum possible TD is 89.5 ft and the maximum possible TD is 134.9 ft with the unidirectional Aisle layout between 92.4 ft and 170.6 ft.

Figure 4.
Aisle Layout Method for Locations With Path Directionality



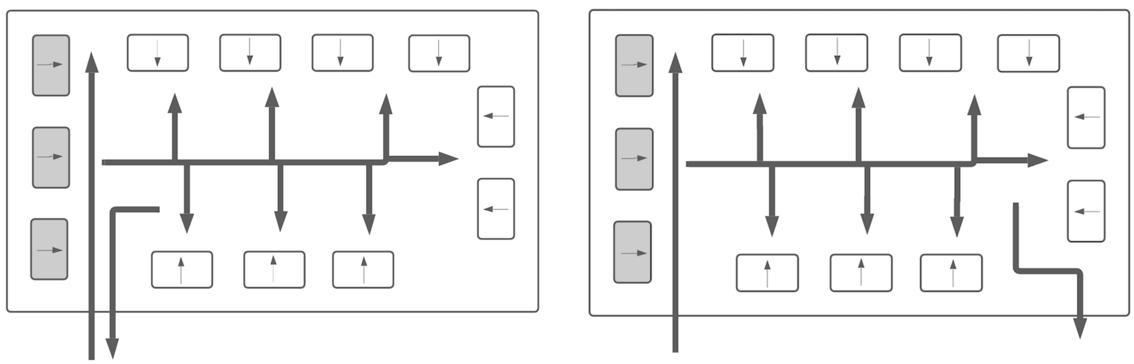
(a) Cyclical Aisle Layout Method *(b)* Unidirectional Aisle Layout Method

Note: A black line illustrates the voter path. Rectangles represent stations for processes (i.e., check-in, BCMD). Arrows on the stations indicate the direction that the station faces (i.e., the arrows face the path indicating that the voting equipment faces in towards the path and can be accessed directly from the path).

The final layout method is the *Perimeter* layout method, a method observed by the URI VOTES team in polling locations. This method was adapted from the loop flow layout pattern with an outer loop, a commonly used layout method in manufacturing systems (Tompkins et al., 2010; Ho & Moodie, 1998; Sinriech, 1995). There are centralized routes for entities to follow in this method, and stations are positioned on the outside of the loop (Tompkins et al., 2010). Shown in Figure 5, all check-in stations and BMCDs are positioned along the walls and face toward the center of the room. No equipment is placed in the center of the room. It is assumed that the equipment is first placed along the left wall, then along the walls in a clockwise direction. Even if there is enough space along the walls to locate check-in stations and BMCDs greater than 3’ apart, they are only placed 3’ apart to maintain consistency in the layout method. It is also assumed in this method that the voters travel freely from any check-in station to any BMCD and take the most direct path to that BMCD station and the most direct route to the exit that any other station does not obstruct. For the cyclical Perimeter layout, the minimum possible TD is 34.0 ft and the maximum possible TD is 91.7 ft. For the unidirectional Perimeter layout the minimum possible TD is 42.9 ft and the maximum possible TD is 80.5 ft.

Figure 5.

Perimeter Layout Method for Locations With Path Directionality



(a) Cyclical Perimeter Layout Method *(b)* Unidirectional Perimeter Layout Method

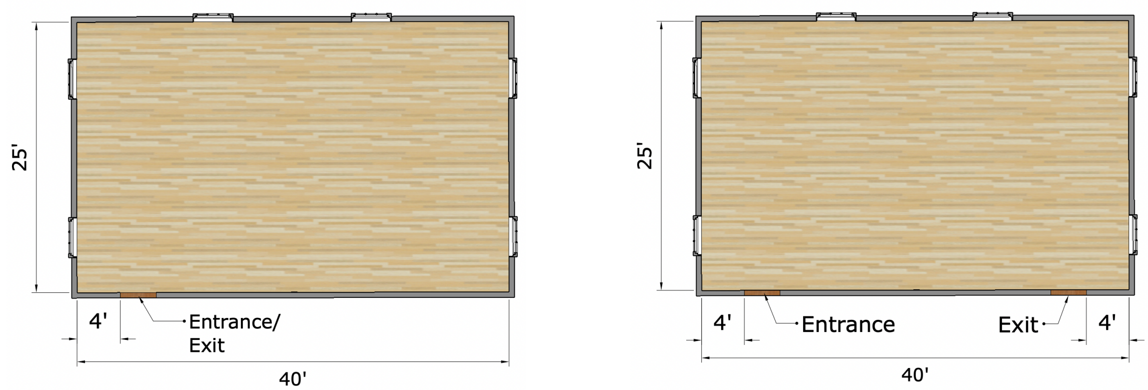
Note: A black line illustrates the voter path. Rectangles represent stations for processes (i.e., check-in, BCMD). Also, not all possible voter paths are shown in the drawing. Instead, the arrows on the stations indicate the direction that the station faces (i.e., the arrows face the path indicating that the voting equipment faces in towards the path and can be accessed directly from the path).

Path Directionality. Each of the three layouts was modeled with varying path directionalities: 1) a cyclical path and 2) a unidirectional path. In the *cyclical path*, the voter enters and exits through the same door. In the *unidirectional path*, the voter enters through one door that is the designated entrance and exits through a different door designated as the exit.

The layout of the polling location and the voter path depends on the location of the entrance and exit. The placement of the doors was kept consistent throughout all of the systems. In the models utilizing the cyclical path, the door was located along the 'front' long wall, 4 ft away from the shorter left wall (e.g., Figure 6a). For the models utilizing the unidirectional path, both the entrance and exit doors were located on the same long wall; the entrance door was located 4 ft from the short left wall, and the exit door located 4 ft from the right short wall (e.g., Figure 6b).

Figure 6.

Location Dimensions



(a) 1,000 sqft Room with One Door *(b)* 1,000 sqft Room with Two Doors

Voter Turnout. While voter turnout is not considered in this analysis as an independent variable, it is included as a control variable. Voter turnout varies greatly either due to the inherent variability in the percentage of voters that turn out to vote or due to the considerable variation across the US in the number of voters assigned to a given in-person polling location (Webb, 2014). Therefore, understanding how systems behave at different levels of turnout is essential. A total of six turnouts are tested in each of the systems: {500, 1000, 1500, 2000, 2500, 3000}. A turnout level of 500 was chosen to represent systems under relatively low voter turnout. A turnout level of 3,000 was chosen to represent systems with a relatively high voter turnout because some locations define 3,000 as the maximum number of voters assigned to that in-person polling location (RI Gen L § 17-11-1, 2012).

Assumptions. There are few precedents regarding polling location layout currently in place; therefore, assumptions regarding the setup and the analysis of the theoretical systems were made. Assumptions are, but not limited to, the following:

1. BMCDs are modeled as electronic ballot marking devices with the dimensions of 3' by 2.15'.
2. Check-in stations are modeled as 6' by 2.5' tables, with one check-in station per table.
3. A 3' by 4' space in front of both the check-in stations and BMCDs is included in the stations to account for the space a voter occupies to comply with the ADA guidelines (US Department of Justice, 2016).
4. There is at least 4' between the check-in stations and the walls to ensure poll workers have the space to move and operate.
5. There is a minimum of 3' between check-in stations and between BMCDs to provide voter privacy.
6. BMCDs can be positioned against walls.
7. The voter always travels to check-in first, then to a BMCD.
8. Voter paths are designed to be at least 3' wide to comply with ADA guidelines but may narrow to 32" over a length no greater than 2' (US Department of Justice, 2016).
9. Paths to check-in and BMCD stations were drawn to the center of the 3' by 4' voter space in front of the check-in and BMCD stations defined above.
10. While voter paths may overlap, they are unidirectional; thus, the voter must follow the path from the entrance through to the exit.
11. Voters do not have to walk-by or pass through BMCDs to access the check-in stations.
12. Voters are serviced on a first-come-first-serve basis, meaning that they are served in the order in which they enter the check-in queue.
13. No queue can form between steps/stations, such as between check-in and BMCDs (Los Angeles County Registrar-Recorder/County Clerk, 2020).

14. Voter travel path begins at the entry door and ends at the exit door; therefore, the only TD considered in this analysis occurs within the polling location.
15. Voters randomly choose any available station.[7]

Model Inputs

While these are theoretical models, they were designed using actual processing times collected from a two-step voting system during a pre-Covid-19 election in the 2020 Presidential Preference Primaries (i.e., Los Angeles County). First, the check-in processing times were pulled from electronic poll books and the ballot marking and casting processing times were observed and collected (see the section on Data Collection). Second, the data were cleaned to remove unrealistic processing times on the lower bound and fit for a statistical distribution. Lastly, the resource allocation within all designed systems is fixed to maintain potential service capabilities.

Data Collection. The primary tools used to collect the data were the URI VOTES Voting System Timers (a Microsoft Excel add-on) (URI VOTES, 2021). These are programmed timers that allow the observer to track multiple voters simultaneously and store the processing times in a tabular format. In addition, all data collection observers were trained to use a standardized method for initiating the start and end of a process to decrease errors. The observer started the timer the moment when the voter arrived at the check-in or BMCD station, and ended the timer the moment the voter began exiting the station. Potential errors include variation due to observations, observation types, and the data collector's process of demarcating the beginning and end of an observation. To mitigate the likelihood of errors, the Voting System Timers are designed to remove the last observation if the data collector recognizes a mistake. No personal identifiers were collected during this process.

[7]While there has been no research regarding how voters choose a check-in station or a BMCD station, some research on how people choose stations in other applications (e.g., bathroom stalls, products from shelves) does exist (Christenfeld, 1995).

Data Processing. The data were cleaned and processed using *R* statistical software. Distributions were fit to the raw data after the bottom 2.5th quantile was removed to ensure that errors in observed processing times were eliminated. Removing the bottom 2.5th quantile eliminated processing times of zero; processing times of zero would mean that the voter was able to complete either the check-in or BMCD processes in zero seconds, which is not possible. Similarly, processes times of a few seconds were also not possible and were likely errors caused by the observer marking false time recordings and were, therefore, removed. Processing times on the upper tail were not removed because these are accurately recorded processing times that represent variation within the processing times and indicate delays; however, the causes for these tail observations were not denoted. The verification of the observed processing times on the upper tail was accurately recorded by directly discussing it with the URI VOTES data collectors.

Processing Times. Cleaned check-in data fit a lognormal distribution with a log mean of 0.73319 and a log standard deviation of 0.53558. Cleaned BMCD data fit a lognormal distribution with a log mean of 1.6996 and a log standard deviation of 0.4845. The cleaned processing time data for the check-in and BMCD processing times are shown in Table 1. The applicability of the lognormal distribution was reinforced because the data contained all positive values, had a small mean and relatively large variance (Crow & Shimizu, 1987). The goodness-of-fit statistics and plots justifying the fit of the distributions are provided in Appendix B.

Table 1.
Cleaned Processing Time Data Descriptive Statistics

	N	Mean	St. Dev.	Minimum	Q_{25}	Median	Q_{75}	Maximum
Check-In	2570	2.454	1.910	0.667	1.417	1.833	2.716	20.533
BMCD	1171	6.1795	3.529	1.417	4.117	5.500	7.300	48.467

Walking Speed. While there is no apparent research in the elections simulations that utilizes a variable walking speed for voters, research in other fields has applied methods such as modeling walking speed as a random variable. For example, research using simulation in healthcare layout problems applied uniform distributions to the walking speeds of patients and medical staff (Lather, 2019). A similar approach was used in this study to model the variability in voter walking speed.

For Americans at or over the age of 18, 8.3% have ambulatory disabilities (US Census Bureau, 2019). There is limited data specifically concerning the percentage of voters that have ambulatory disabilities. Therefore, for this study, it was assumed that the percentage of Americans over the age of 18 was the percentage of voters with ambulatory disabilities. Considering little data exists on the walking speed of voters, and more specifically voters with ambulatory disabilities, a triangular distribution was used to model the walking speeds of those voters with ambulatory disabilities using the minimum of 0.1 m/s, maximum of 1.77 m/s, and mean of 1 m/s (Shi et al., 2008).

For the remaining percentage of voters without ambulatory disabilities, the average walking speed was further broken down by age group (i.e., 18-29, 30-39, 40-49, 50-59, 60-69, 70-79, 80+) and sex (i.e., male and female) (US Census Bureau, 2021). The Bohannon & Andrews (2011) meta-analysis with a sample size of over 23,000 individuals was used to determine the average walking speeds for each sex within each age group. Table 2 provides the average walking speed for each of the groups (i.e., age and sex) described above.

Table 2.
Walking Speed of Non-Ambulatory Disabled Voters by Age and Sex (US Census Bureau, 2021; Bohannon & Andrews, 2011)

Age	Average Speed			
	Proportion of Total Voters (%)	Average Speed (m/s)	Proportion of Total Voters (%)	Average Speed (m/s)
	Females		Males	
18-29	8.65	1.341	7.81	1.358
30-39	8.37	1.337	7.46	1.433
40-49	7.88	1.390	7.07	1.434
50-59	9.18	1.313	8.30	1.433
60-69	9.57	1.241	8.48	1.339
70-79	6.43	1.132	5.48	1.262
80+	3.05	0.943	2.26	0.968

Resource Allocation. The ratio of check-in stations to BMCDs was 1:3. This ratio was observed at the polling locations that utilized a two-step voting system and was held consistent throughout all models. To determine the number of check-in stations and BMCDs, the maximum number of resources that could be fit into the 1,000 sqft room under each of the layout methods using both cyclical and unidirectional paths was calculated while following the guidelines listed above. Each of the models resulted in the same number of maximum resources that could fit into the space; therefore, three check-in stations and nine BMCDs were used in all models. Not only was this decided for baseline comparison, but maximum equipment fit in the space to ensure maximum capabilities.

Model Coding

All layout models (n = 6) were created in SketchUp®. First, the base models for the empty rooms were created. Then, the three check-in stations and the nine BCMD objects were placed based on the facilities layout method; details of the objects and dimensions are in Appendix C. The assumptions outlined in the Layout Methods section of Conceptual Modeling were used to generate each of the layout models. Layouts for each of the systems are provided in Appendix D.

Simio™ simulation software was used to simulate the outcomes of each hypothetical system. A *source* with a bimodal arrival rate adapted from Yang, Fry, and Kelton (2009) was used to supply entities (i.e., voters) with a walking speed that followed a nested discrete distribution. From the *source* (i.e., **Src**), voters traveled on a *path* (i.e., **Src_CI_Input_Path**) to a *transfer node* (i.e., **CheckIn_InputN**) before randomly selecting any available check-in station. Each of the check-in stations were modeled as an individual *server* (i.e., **CheckIn1**, **CheckIn2**, and **CheckIn3**). To prevent any voters from traveling to an occupied check-in server or a queue building at any one check-in server, the input buffers to the check-in servers were set to zero, and the selection weight of each of the paths was only set to one if there was availability at that station; otherwise, it was set to zero. If the sum of voters travelling to the desired check-in station and the number of voters currently being processed at that station was less than one; on the contrary, the selection weight was set to zero if a voter was either on the path to the desired check-in station, or a voter was being served at the desired check-in station. Additionally, an *add-on process* (i.e., **CheckInProcess**) that set the capacity of the transfer node (i.e., **CheckIn_InputN**) to either one or zero depending on the number of voters being serviced at the check-in stations was called upon entities entering and exiting the *transfer node* and upon exiting the check-in servers.[8]

Each of the check-in servers had an initial capacity of one and a processing time that was randomly selected from a lognormal distribution (Random.Lognormal(0.7332,0.5356,2) minutes) to simulate the variability in check-in processing times.[9] In addition, an add-on process specific to each server was triggered to prevent a queue from building between check-in and the BMCD

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[8]This add-on process summed the total number of voters on paths to any check-in station and the total number of voters currently being serviced across all check-in servers. When this value was greater than the capacity of check-in, three, then the current traveler capacity of the transfer node leading to check-in (i.e., **CheckIn_InputN**) was set to zero; in other cases, it was set to one to continue to allow voters to travel to check-in.

[9]Stream 2 was used to ensure that the randomness in the processing time was held consistent across all simulations and replications within simulations to reduce variability across scenarios.

stations.[10] Entities then traveled via connectors to a transfer node that had an initial traveler capacity of one to ensure that voters leaving a check-in server traveled to a BMCD server on a first-come-first-serve basis.

Another add-on process that decided if the sum of voters traveling on any path to any BMCD and the voters at all BMCD servers was less than the BMCD capacity was used. If yes, then entities continued along the path to a BMCD station; if not, then entities were held. The outbound routing logic was determined by link weight similarly to check-in, and the same process of randomly selecting any available BMCD was used. Each of the BMCDs were modeled as individual servers with a random processing time following a lognormal distribution `Random.Lognormal(1.6996,0.4845,2)`. Paths were created from each BMCD server to the *sink* (i.e., **Snk**) to model the voter walking from the BMCD to the exit and exiting the system. A tally statistic (i.e., **TotalTravelDistance**) was calculated when the voter entered the sink. The layout model from SketchUp® was imported in Simio™, and the paths were laid over the layout, ensuring all paths were true to scale. An individual simulation file was created for each of the different combinations tested ($n = 6$).

The total voter turnout was a variable input to model the systems. A separate scenario was run for each level of voter turnout ({500, 1000, 1500, 2000, 2500, 3000} voters). The responses that were tracked within Simio™ were average TIS and average total TD by a voter within the system. Using the Banks et al. (2010) equation for calculating the number of replications needed under specified error allowances ($\epsilon = 1$ foot, $\epsilon = 2$ seconds) for all possible scenarios ($n = 72$), the maximum number of replications with a Bonferroni corrected alpha of 0.00333 (i.e.,

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[10]If the number of voters at the nodes following the check-in servers was one, then the capacity of that check-in server became zero; if the number of voters was zero, then the check-in server capacity was set to one.

α_{ij}=0.05/15=0.00333 for all pairwise comparisons, where the number of comparisons C=15, and the number of systems K=6) was determined to be approximately 1450 replications.

Verification and Validation

These models were adapted from previous simulations built by the URI VOTES team and were verified by simulation experts on the URI VOTES team. Additionally, previous simulations were verified by the Los Angeles County Registrar-Recorder/County Clerk and the Rhode Island Board of Elections to ensure that the model logic was coded accurately.

Because the systems explored in this study are theoretical, it is not possible to compare the resulting TIS to observed values for the same system. However, it is possible to compare the resulting TIS values from Simio™ to actual voting systems described in literature and reported in the news. While there is little literature providing data on the average TIS at low turnout levels, at high turnouts the resulting TIS of nearly six hours were comparable to those witnessed in real elections (Fowler, 2020).

Experimental Design

This research aims to explore whether the layout of the voting equipment and path directionality have an effect on voting systems' performance. It is hypothesized that the layout and path directionality does have a significant effect on voting system performance. DES modeling was used to monitor the effects of the various systems on the performance metrics. The results were statistically compared using the Bonferroni Approach to Multiple Systems Comparison (Banks et al., 2010, p. 476-477). The multiple system comparisons Bonferroni approach was used to create pairwise comparisons between each system (i.e., α_{ij}=0.05/15=0.00333 for all pairwise comparisons, where the number of comparisons C=15, and the number of systems K=6) (Banks et al., 2010, p. 477). Simio™ outputs the mean value and the half-width across all replications for each scenario within each system, and these values were used to calculate a confidence interval for the average voter TIS and average voter TD with 99.67% confidence. A t-test was used to compare the means of the systems within each turnout level to determine if they were statistically different. A complete output for all performance metrics for all systems at each turnout level are provided in Appendix E.

Results

Voter Travel Distance

The confidence intervals with the Bonferroni corrected alpha (α_{ij}=0.00333) for the minimum, maximum, and average total voter TD at all turnout levels are shown in Table 3. The table shows that all systems have confidence intervals around the mean TD that do not overlap. The significant differences are presented in detail below.

Table 3.
Simulated Voter Travel Distance

Turnout	Layout Method	Path Directionality	Average TD (ft) 99.6% CI	Avg TD St. Dev.	Minimum TD (ft)	Maximum TD (ft)
500	Aisle	Cyclical	(116.807, 116.875)	0.446	89.501	134.875
500	Aisle	Unidirectional	(121.447, 121.555)	0.297	92.356	170.604
500	Perimeter	Cyclical	(70.791, 70.85)	0.279	34.022	91.732
500	Perimeter	Unidirectional	(59.706, 59.744)	0.280	42.946	80.446
500	Serpentine	Cyclical	(111.477, 111.486)	0.273	109.711	118.045
500	Serpentine	Unidirectional	(89.226, 89.234)	0.269	86.253	95.44
1000	Aisle	Cyclical	(116.796, 116.842)	0.699	89.501	134.875
1000	Aisle	Unidirectional	(121.367, 121.433)	0.426	92.356	170.604
1000	Perimeter	Cyclical	(70.788, 70.823)	0.404	34.022	91.732
1000	Perimeter	Unidirectional	(59.707, 59.729)	0.409	42.946	80.446
1000	Serpentine	Cyclical	(111.481, 111.486)	0.416	109.711	118.045
1000	Serpentine	Unidirectional	(89.231, 89.237)	0.409	86.253	95.44
1500	Aisle	Cyclical	(116.802, 116.845)	0.386	89.501	134.875
1500	Aisle	Unidirectional	(121.339, 121.402)	0.230	92.356	170.604
1500	Perimeter	Cyclical	(70.779, 70.813)	0.218	34.022	91.732
1500	Perimeter	Unidirectional	(59.705, 59.727)	0.208	42.946	80.446
1500	Serpentine	Cyclical	(111.48, 111.486)	0.213	109.711	118.045
1500	Serpentine	Unidirectional	(89.23, 89.236)	0.212	86.253	95.44
2000	Aisle	Cyclical	(116.784, 116.828)	0.245	89.501	134.875
2000	Aisle	Unidirectional	(121.348, 121.411)	0.144	92.356	170.604
2000	Perimeter	Cyclical	(70.78, 70.812)	0.142	34.022	91.732
2000	Perimeter	Unidirectional	(59.699, 59.72)	0.140	42.946	80.446
2000	Serpentine	Cyclical	(111.481, 111.486)	0.141	109.711	118.045
2000	Serpentine	Unidirectional	(89.23, 89.236)	0.145	86.253	95.44
2500	Aisle	Cyclical	(116.801, 116.843)	0.056	89.501	134.875
2500	Aisle	Unidirectional	(121.346, 121.41)	0.036	92.356	170.604
2500	Perimeter	Cyclical	(70.779, 70.812)	0.034	34.022	91.732
2500	Perimeter	Unidirectional	(59.7, 59.722)	0.034	42.946	80.446
2500	Serpentine	Cyclical	(111.482, 111.488)	0.035	109.711	118.045
2500	Serpentine	Unidirectional	(89.23, 89.236)	0.034	86.253	95.44
3000	Aisle	Cyclical	(116.784, 116.825)	0.058	89.501	134.875
3000	Aisle	Unidirectional	(121.346, 121.409)	0.037	92.356	170.604
3000	Perimeter	Cyclical	(70.784, 70.817)	0.035	34.022	91.732
3000	Perimeter	Unidirectional	(59.703, 59.725)	0.035	42.946	80.446
3000	Serpentine	Cyclical	(111.48, 111.485)	0.036	109.711	118.045
3000	Serpentine	Unidirectional	(89.23, 89.235)	0.035	86.253	95.44

Layout Methods. When the path directionality is held constant, the effect of the layout on the total average voter TD can be explored. The differences in total average voter TD in feet by layout method for each path directionality is shown in Table 4.

Table 4.

Differences in Average TD by Layout Method

Turnout (people)	System Settings	Layout Method Comparisons: Perimeter and Aisle Layouts (ft)	Serpentine and Aisle Layouts (ft)	Perimeter and Serpentine Layouts (ft)
500	Cyclical Path	46.0865***	5.4094***	40.6770***
500	Unidirectional Path	61.8038***	32.2842***	29.5196***
1,000	Cyclical Path	46.0172***	5.3267***	40.6905***
1,000	Unidirectional Path	61.7059***	32.1990***	29.5069***
1,500	Cyclical Path	46.0338***	5.3513***	40.6825***
1,500	Unidirectional Path	61.6942***	32.1865***	29.5077***
2,000	Cyclical Path	46.0511***	5.3707***	40.6804***
2,000	Unidirectional Path	61.6818***	32.1788***	29.5030***
2,500	Cyclical Path	46.0124***	5.3352***	40.6772***
2,500	Unidirectional Path	61.7101***	32.1963***	29.5138***
3,000	Cyclical Path	46.0110***	5.3445***	40.6665***
3,000	Unidirectional Path	61.6981***	32.1819***	29.5162***

Note: A positive value indicates that the total TD increased when the layout changed from the first layout listed to the second. *Significance*: * $p < 0.00333$, ** $p < 6.66E-4$, *** $p < 6.66E-5$ (Bonferroni corrected).

There are significant differences in TD between each layout method for systems utilizing both path directionalities at all voter turnouts. The systems utilizing the Perimeter layout had a significantly lower average TD than those utilizing the Aisle layout for the cyclical path and the unidirectional path. The systems utilizing the Serpentine layout also had a significantly lower average TD than those utilizing the Aisle layout method at all turnout levels for the cyclical path and the unidirectional path. At all turnout levels, the Perimeter layout systems resulted in a lower average TD than those utilizing the Serpentine layout for the cyclical path and the unidirectional path.

Path Directionality. When the layout method is held constant, the effect of the path directionality on the total average voter TD can be explored. The differences in total average voter TD in feet for each layout is shown in Table 5 for all voter turnout levels.

Table 5.

Differences in Average TD by Path Directionality

Turnout (people)	System Settings	Path Directionality Comparisons Cyclical and Unidirectional (ft)
500	Aisle Layout	4.6234***
500	Perimeter Layout	-11.0939***
500	Serpentine Layout	-22.2513***
1,000	Aisle Layout	4.6223***
1,000	Perimeter Layout	-11.0664***
1,000	Serpentine Layout	-22.2500***
1,500	Aisle Layout	4.5830***
1,500	Perimeter Layout	-11.0774***
1,500	Serpentine Layout	-22.2522***
2,000	Aisle Layout	4.5608***
2,000	Perimeter Layout	-11.0699***
2,000	Serpentine Layout	-22.2473***
2,500	Aisle Layout	4.6098***
2,500	Perimeter Layout	-11.0880***
2,500	Serpentine Layout	-22.2514***
3,000	Aisle Layout	4.5883***
3,000	Perimeter Layout	-11.0989***
3,000	Serpentine Layout	-22.2491***

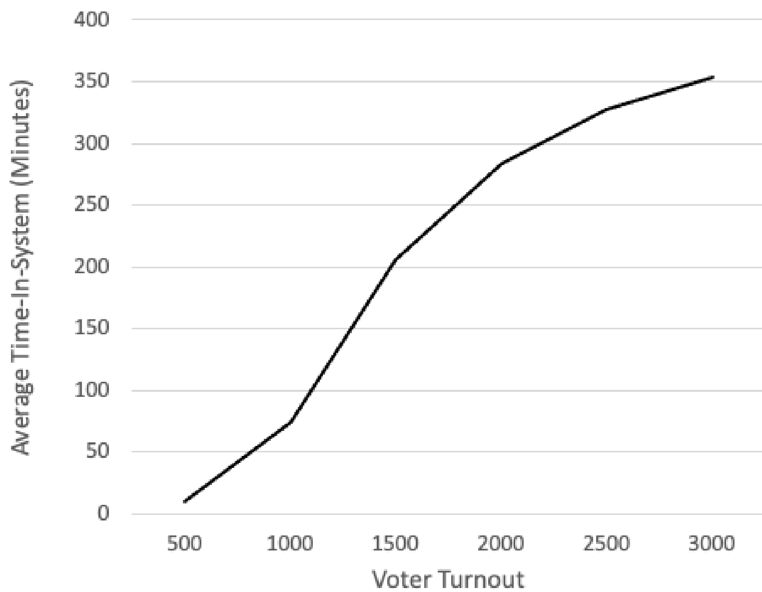
Note: A positive value indicates that the total TD increased when the path directionality changed from cyclical to unidirectional, and a negative value indicates a decrease in total TD decreased when the path directionality changed from cyclical to unidirectional. *Significance*: * $p < 0.00333$, ** $p < 6.66E\text{-}4$, *** $p < 6.66E\text{-}5$ (Bonferroni corrected).

There are significant differences between the systems utilizing the cyclical path and those utilizing the unidirectional path for all layout methods at all voter turnout levels. For the Aisle layout, the cyclical path results in a significantly lower average TD than the unidirectional path at all turnout levels. However, the systems utilizing the unidirectional path resulted in a significantly lower average TD than those utilizing the cyclical path for the Perimeter layout at all turnout levels and the Serpentine layout at all turnout levels.

Voter Time-In-System

As shown in Figure 7, the average voter TIS increased as the voter turnout increased for the Perimeter layout with a cyclical path. Each of the systems followed a similar curve to that of the Perimeter layout with a cyclical path system, as shown in Appendix F.

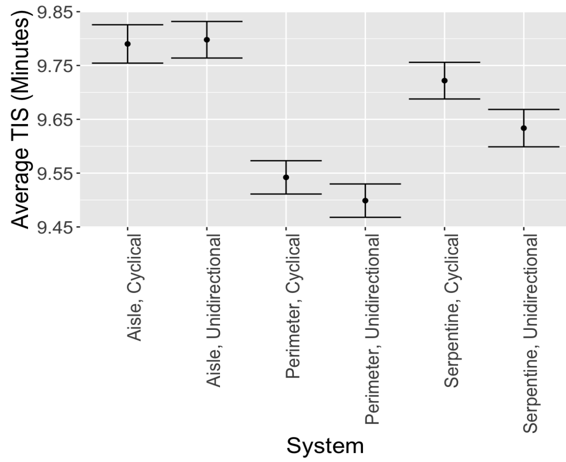
Figure 7.
Average Voter Time-In-System over Voter Turnout for the Perimeter Layout Method with a Cyclical Voter Path



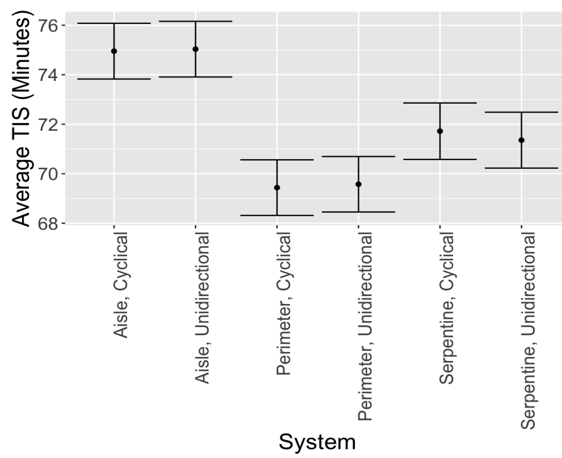
The differences in average TIS by layout method and path directionality are explored in detail at all turnout levels. The confidence intervals with the Bonferroni corrected alpha (α_{ij}=0.00333) for the average voter TIS at all turnout levels are shown in Figure 8.

Figure 8.

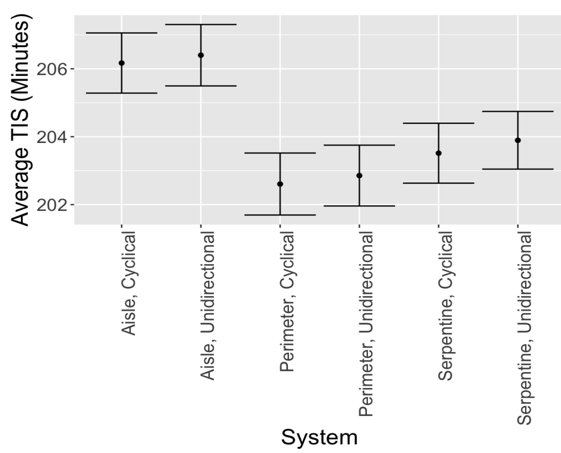
Average Voter Time-In-System



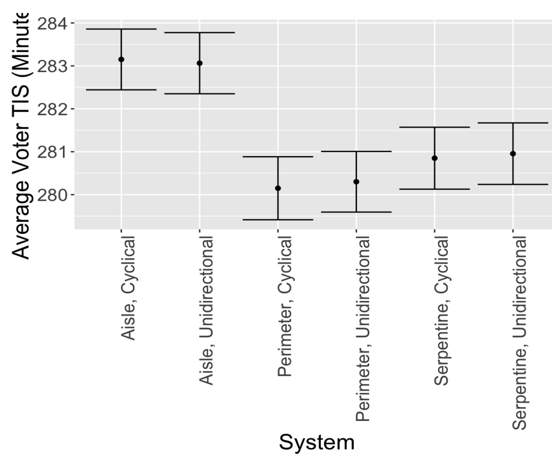
(a) 500 Voter Turnout



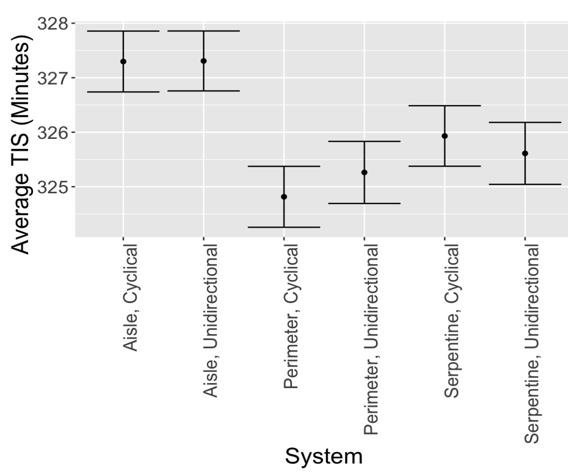
(b) 1,000 Voter Turnout



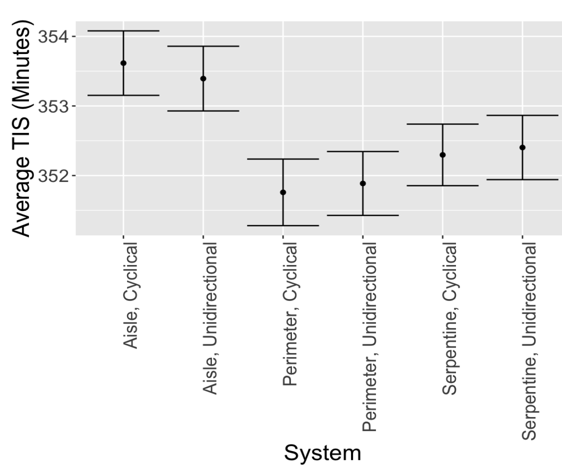
(c) 1,500 Voter Turnout



(d) 2,000 Voter Turnout



(e) 2,500 Voter Turnout



(f) 3,000 Voter Turnout

Layout Methods. When the path directionality is held constant, the effect of layout on the average voter TIS can be explored. The differences in average TIS in minutes by layout when controlling for path directionality is shown in Table 6 for all turnout levels. A positive value indicates that the total TIS increased from the first layout method to the second layout method, and a negative value indicates a decrease in total TIS decreased between the first layout method and the second.

Table 6.
Differences in Average TIS by Layout Method

Turnout (People)	System Settings	Layout Method Comparisons: Perimeter and Aisle Layouts (min)	Serpentine and Aisle Layouts (min)	Perimeter and Serpentine Layouts (min)
500	Cyclical Path	0.2480***	0.0682	0.1797***
500	Unidirectional Path	0.2990***	0.1642***	0.1348***
1,000	Cyclical Path	4.8622***	3.2247***	1.6374*
1,000	Unidirectional Path	3.7896***	3.0468***	0.7427
1,500	Cyclical Path	2.6647***	1.4792**	1.1855*
1,500	Unidirectional Path	3.4814***	2.8899***	0.5915
2,000	Cyclical Path	2.6934***	1.9596***	0.7338
2,000	Unidirectional Path	2.4998***	2.0780***	0.4218
2,500	Cyclical Path	2.4816***	1.7590***	0.7226
2,500	Unidirectional Path	2.5288***	1.4665***	1.0623**
3,000	Cyclical Path	1.8572***	1.3189*	0.5383
3,000	Unidirectional Path	1.5069**	0.9901	0.5168

Note: A positive value indicates that the total TIS increased from the first listed layout method to the second. *Significance*: * $p < 0.00333$, ** $p <$ 6.66E-4, *** $p <$ 6.66E-5 (Bonferroni corrected).

There are significant differences in TIS between the Aisle and Perimeter layouts at all voter turnouts. The systems utilizing the Perimeter layout had a significantly lower average TIS than those utilizing the Aisle layout for the cyclical path and the unidirectional path. The Serpentine layout systems also had a significantly lower average TIS than those utilizing the Aisle layout method for the cyclical path at all turnout levels except 500 voters and for the unidirectional path at all turnout levels except 3,000 voters. The systems utilizing the Perimeter layout resulted in a lower average TIS than those utilizing the Serpentine layout for the cyclical path at low turnout levels (i.e., 500 voters, 1,000 voters, and 1,500 voters), and for the unidirectional path at some turnout levels (i.e., 500 voters and 2,500 voters).

Path Directionality. When the layout method is held constant, path directionality on the average voter TIS can be explored. The differences in average TIS in minutes by path directionality for each system when controlling for layout are shown in Table 7.

Table 7.
Differences in Total Average Voter TIS by Path Directionality

Turnout (People)	System Settings	Path Directionality Comparisons: Cyclical and Unidirectional (min)
500	Aisle Layout	0.0078
500	Perimeter Layout	-0.0432
500	Serpentine Layout	0.0882
1,000	Aisle Layout	-0.7265364
1,000	Perimeter Layout	0.3460842
1,000	Serpentine Layout	-0.548637
1,500	Aisle Layout	0.3757344
1,500	Perimeter Layout	-0.4409232
1,500	Serpentine Layout	-1.0349538
2,000	Aisle Layout	0.1569
2,000	Perimeter Layout	0.3505
2,000	Serpentine Layout	0.0385
2,500	Aisle Layout	-0.1720
2,500	Perimeter Layout	-0.2192
2,500	Serpentine Layout	0.1205
3,000	Aisle Layout	-0.2227
3,000	Perimeter Layout	0.1276
3,000	Serpentine Layout	0.1061

Note: A positive value indicates that the total TIS increased when the path directionality changed from cyclical to unidirectional, and a negative value indicates a decrease in total TIS decreased when the path directionality changed from cyclical to unidirectional. *Significance*: * $p < 0.00333$, ** $p < 6.66E-4$, *** $p < 6.66E-5$ (Bonferroni corrected).

There were no significant differences in average TIS between the cyclical and unidirectional paths for any of the layout methods at any turnout level.

Discussion

The average voter TD was shown to vary significantly by layout method and path directionality. However, the confidence intervals on the average total voter TD were relatively narrow because there are a defined number of possible paths that the voter can take. The only variation in path length was the randomness in the voters' selection of check-in station and BMCD station. Therefore, because there were a set number of 27 paths that the voters could take, it was possible to determine the average voter TD with little variance.

As the turnout increased, the demand for resources also increased, but the number of resources remained the same resulting in increases in average TIS. All of the systems were able to process low levels of turnout. However, as the results showed, even at 1,000 voters, the average TIS of the voters increased to durations over one hour demonstrating that long lines may occur in any of these systems when the turnout approaches 1,000 voters.

The average voter TIS is dependent on the average voter TD and the walking speed. While the system is stochastic, the variation in processing times was controlled for by the application of common random numbers in the simulation. Therefore, the resultant significant increases in average TIS are dependent on the voter TD and the walking speed. This is also shown in the plots of the confidence intervals for the average TD (i.e., Figure 5) and the average TIS (i.e., Figure 7). The plots follow the same shape, demonstrating that there is a positive relationship between average TD and average TIS.

Layout Method. At all levels of turnout, the layout method significantly impacts the total average voter TD. To address research question 1, the Perimeter layout resulted in a significantly lower TD than the Aisle layout regardless of path directionality. This suggests that the Perimeter layout may be more efficient than the Aisle layout. The Perimeter layout also results in a significantly smaller average TD than the Serpentine layout; this was shown to be true for all systems regardless of path directionality. Therefore, the Perimeter layout is always more efficient with regard to average voter TD than the Serpentine layout. Lastly, the Serpentine layout resulted in a significantly lower average TD than the Aisle layout for all systems regardless of path directionality. This indicates that in small rectangular polling locations of 1,000 sqft with no obstructions, regardless of the path directionality, the most efficient layout concerning total voter TD is the Perimeter layout. The second most efficient is the Serpentine layout, and the least efficient is the Aisle layout.

These findings are important because they demonstrate that voters may be required to travel different distances to vote depending on the layout chosen. This is especially important when considering voters with ambulatory disabilities. The Perimeter layout allows voters to choose from any random available stations and allows them to take the most direct route to the chosen station. On the contrary, the Aisle and Serpentine layouts restrict the voter path and require the voter to travel a greater distance.

To address research question 1, the Perimeter layout results in a shorter average TIS than the Aisle layout for all turnout levels, indicating that the Perimeter layout method is always more efficient concerning TIS than the Aisle layout method in small rectangular polling locations of 1,000 sqft with no obstructions. The Perimeter layout method also results in a lower average TIS than the Serpentine layout method for small locations with one door. However, the Serpentine layout method is more efficient with regard to average TIS than the Aisle layout for small locations with two doors.

The pattern of significance displayed at low levels of turnout was not present at high levels of turnouts. Instead, the Perimeter layout method resulted in lower average TIS for small rooms with one door at high levels of turnout. However, in large rooms, the Aisle layout was significantly more efficient than the Serpentine layout in terms of average TIS. This demonstrates that as turnout increases, the effect of layout on average TIS varies; some layout methods are more efficient in average TIS at low turnout levels, and other layout methods are more efficient at higher turnout levels. In other words, there is no one size fits all solution when it comes to choosing the most efficient layout with regard to average TIS. This exemplifies that layout can have a significant effect on average TIS, a finding that is supported by Bernardo et al. (2020). Although resource allocation is a critical factor to consider in the design of elections, the layout of equipment should also be considered for it can significantly decrease the time that voters spend in the system.

Path Directionality. To address research question 2, at all levels of turnout, the cyclical path is more efficient for the Aisle layout, and the unidirectional path is more efficient for the Perimeter and Serpentine layout with respect to the average TD. Therefore, the most efficient path directionality is dependent on the layout method in use. This indicates that path directionality also plays an essential role in the total distance that a voter will have to travel, and for each of the layouts, a path directionality can be chosen that best assists voters with ambulatory disabilities.

Each of the layouts has an inherently different path length because the positioning of the equipment varies. The path directionality also impacts the path lengths because the path either leads from the BMCD stations back towards the entrance door or to a separate exit door on the opposite side of the room. The results of this study show that the most efficient of the six systems observed, with regard to average TD, is the Perimeter layout with a unidirectional path.

To address research question 2, there was no significant effect of the path directionality on the average TIS at both low turnouts and high turnouts. Therefore, the path directionality or the number of separate entrances and exits does not alone significantly affect the average TIS. However, it is important to note that this is only necessarily in these hypothetical systems under the assumptions that were made for the positioning of the doors. Further work observing whether other potential voter path directionality and door placements significantly affect the average voter TIS is needed to draw more general conclusions. However, as mentioned before, it can make a difference in combination with other factors.

Conclusion

Previous voting system research has overlooked the constraints imposed by the physical space and the layout on the voting system as well as the effects on system performance. This is among the first studies of its kind that merges facilities layout planning with discrete event simulation to understand how voting systems are affected by the layout of equipment and path directionality. Discrete event simulation was proven to be a valuable tool in the analysis of the physical polling location characteristics and equipment layout on the voting system performance. This study found that the layout and path directionality significantly affect the average total voter travel distance. On the other hand, for the average time-in-system, the layout was found to be significant in some systems, and the path directionality was not found to be significant. Understanding how these variables affect the system is important in choosing the best design for a polling location that minimizes the average travel distance or the average time-in-system.

Further research is needed to determine whether the conclusions that were drawn in this study for the two-step system are also applicable in other voting systems (e.g., three-step and five-step voting systems). In addition, as mentioned previously, this analysis only considered one room size and assumed that the room was free of any obstructions. However, many polling locations have permanent fixtures (e.g., columns and interior walls) and furniture that further constrain the layout of the equipment. There also are a limitless number of rooms of varying dimensions and sizes that are used as polling locations. Thus, a separate analysis is needed to explore layout within rooms with different physical characteristics to determine the effects of layout in polling locations other than the one modeled in this study. Furthermore, in not varying the size of the room, the number of resources in all systems remained the same. By varying the size of the room, however, it would be possible to determine if different layout strategies affect the total number of resources within a polling location. This is important in optimizing space usage and increasing the number of voters processed through the system. Therefore, future research may include rooms of varying sizes and varying resources. Moreover, only three layout methods were considered in this study. There are a multitude of other potential layout methods that are currently in use in polling locations, or are used in other service systems and may be applied to voting systems. Whether or not the layout is intuitive and facilitates a smooth voting experience was outside the scope of this work, yet would provide valuable insight into whether or not the layouts would be realistic to implement.

Further research in this field is needed to develop a better understanding of how the physical characteristics of a polling location and the layout of voting equipment can be adapted to different in-person voting systems; this may potentially allow election officials and election administrators to select a polling location design that is optimal for their given system. This work does provide valuable insight into the impact on the role that layout and path directionality have on voting system performance and can be utilized by election administrators in the planning of more efficient elections. Overall, this work provides a foundation for future research examining how the physical characteristics of the polling location and the layout of voting equipment affect voting system performance. Voting is the foundation upon which democracy is built; therefore, ensuring that the process is executed in an efficient and effective manner is crucial, and implementing strategic layout designs into in-person voting systems can assist in that process.

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Appendix

Appendix A:

In 2018, a total of 230,871 polling places were used in the United States General election. Less than one percent of those polling locations were located at election offices themselves (National Conference of State Legislatures, 2020, p. 7). Most polling locations are public facilities (i.e., schools, government offices, police/fire stations, and libraries) and civic centers (i.e., churches, community centers, and senior centers) that are temporarily converted into polling places. However, a small percentage of voters (less than 4%) also vote in private businesses and stores (Stewart, 2013a; Stewart, 2013b; Stewart 2015; Stewart, 2017; Stewart, 2020). This demonstrates that a wide range of different facilities are used for elections across the country, and therefore, understanding the capabilities and limitations of different types of facilities used for elections is critical in preparing for a successful election.

Data from 2008 to 2016 categorizing facility types used in elections demonstrates twelve categories shown in Table 1 (Stewart, 2013a; Stewart, 2013b; Stewart 2015; Stewart, 2017; Stewart, 2020). These facility types are representative of polling locations across the entire United States. The data available for facilities used in the 2020 General election is currently limited and categorizes facilities types into six distinct categories (i.e., school buildings, other government offices, churches, community centers, libraries, and other). The data available in the 2020 survey does not categorize the facility types in the same amount of detail as previous years, as not all traditional building types were available due to the pandemic. Therefore, the other categories listed in Table 1 (i.e., police/fire station, senior center, store/shopping mall, private business, private home, and unknown) that were distinguished between in previous years all fall into the 2020 "Other" category. This research is concerned with non-Covid-19 voting systems, and therefore, the changes in polling facility type usage from 2018 to 2020 is assumed to primarily be attributed to the Covid-19 pandemic, and are not considered significant for this research.

Table A.1
Facility Type Usage For U.S. Elections Between 2008 and 2020 (Stewart, 2013a, Stewart, 2013b; Stewart 2015; Stewart, 2017; Stewart, 2020)

Facility Type	2008	2012	2014	2016	2020	Average Usage
School Building	28.2%	28.0%	27.9%	23.4%	15.0%	24.5%
Government Office	19.7%	18.3%	18.0%	18.9%	23.0%	19.58%
Church	15.7%	16.0%	17.0%	17.2%	14.0%	15.98%
Community Center	14.9%	15.5%	15.7%	16.1%	21.0%	16.64%
Police/Fire Station	6.1%	6.0%	5.4%	6.2%	-	5.93%
Library	3.3%	4.2%	4.1%	5.8%	10.0%	5.48%
Other	5.6%	5.6%	5.5%	5.6%	17.0%	7.86%
Senior Center	3.0%	2.8%	2.9%	3.6%	-	3.08%
Store/Shopping Mall	2.1%	2.1%	2.0%	1.9%	-	2.03%
Private Business	1.1%	1.1%	1.1%	1.4%	-	1.18%
Private Home	0.2%	0.0%	0.0%	0.0%	-	0.05%
Unknown	0.0%	0.0%	0.4%	0.0%	-	0.10%

Trends in the frequency of use for each facility type within the United States remained relatively consistent between 2008 and 2016, as shown in Table 1. However, trends in usage between different facility types during this time period are not consistent throughout the country's different regions (i.e., South, West, Northeast, Midwest). Between 2008 and 2018, public facilities, particularly schools, were generally used more in the Northeast, and churches were used more in the South, West, and Midwest (Stewart 2013a; Stewart, 2013b; Stewart 2015; Stewart, 2017). This is, in part, because each state has unique laws governing what facilities can be used as polling locations, with some states specifying the required use of schools, certain public buildings, and other specific types of locations (e.g., tax-exempt buildings) and the prohibited use of others (e.g., buildings that sell alcohol, private residents of running candidates) (National Conference of State Legislatures, 2020).

Each polling location is inherently different regarding its shape, size, and other physical features such as permanent furniture and fixtures. The table above does categorize the polling locations by facility type, but it does not further categorize the facilities into specific room categories. Some polling locations are in rooms that are generally open spaces (e.g., gymnasiums, community rooms, cafeterias), whereas others have obstructions that must be considered in the layout design process (e.g., courthouse rooms, fire halls).

Rather than selecting three different facilities from the list above, three general facilities of varying sizes will be modeled in order to better understand how the dimensions of the physical space impacts the overall system. In order to identify common room types, a list of 378 polling locations from Rhode Island was used. This list included the polling location name, which most often consisted of the facility name and the room name, and the total square footage of the room. The average, minimum, and maximum total area for each of the facility types are listed in Table 2. Some locations did not include the room type or facility name and are not included in the table. Figure 2 plots the total area for each of the common facility types. The table and plot demonstrate that there are large ranges of areas associated with most of the facility types.

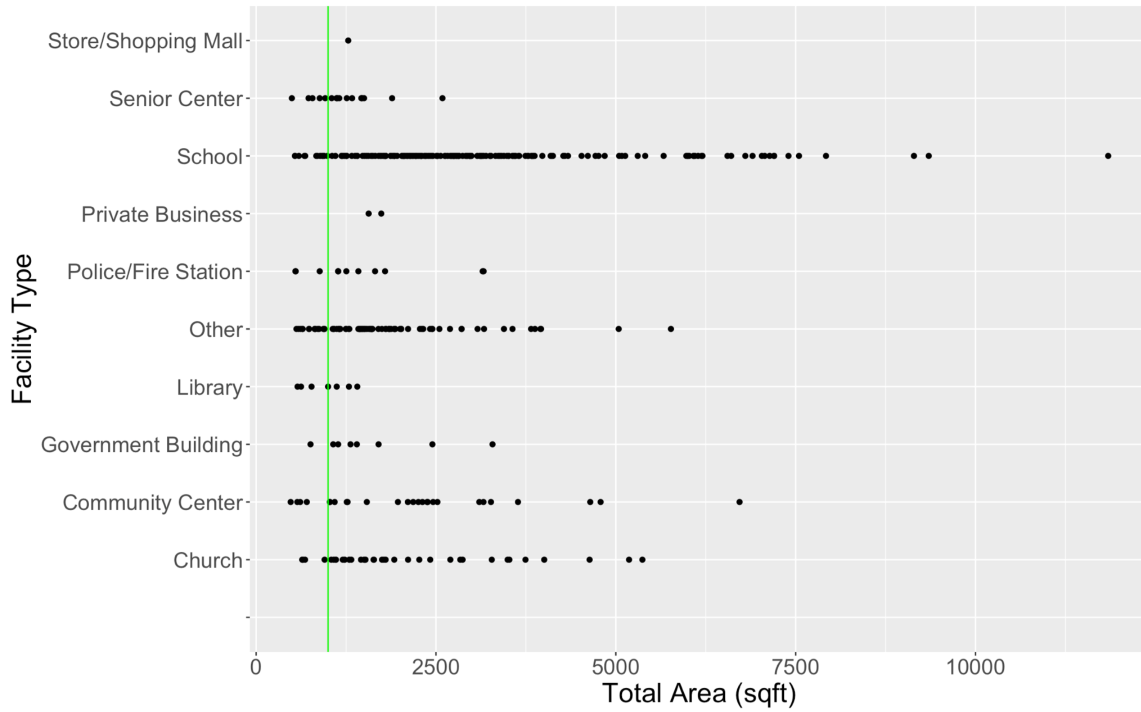
Table A.2

Average, Minimum, and Maximum Area by Facility Type

Facility Type	Average (sqft)	Minimum (sqft)	Maximum (sqft)	Count
School Building	3223	540	11844	185
Government Office	1640	756	3286	8
Church	2048	640	5369	40
Community Center	2287	480	6720	26
Police/Fire Station	1517	546	3162	11
Library	969	575	1406	7
Other	1821	560	5766	82
Senior Center	1238	496	2590	16
Store/Shopping Mall	1280	1280	1280	1
Private Business	1652	1564	1739	2

Figure A.1:

Range of Total Area by Facility Type

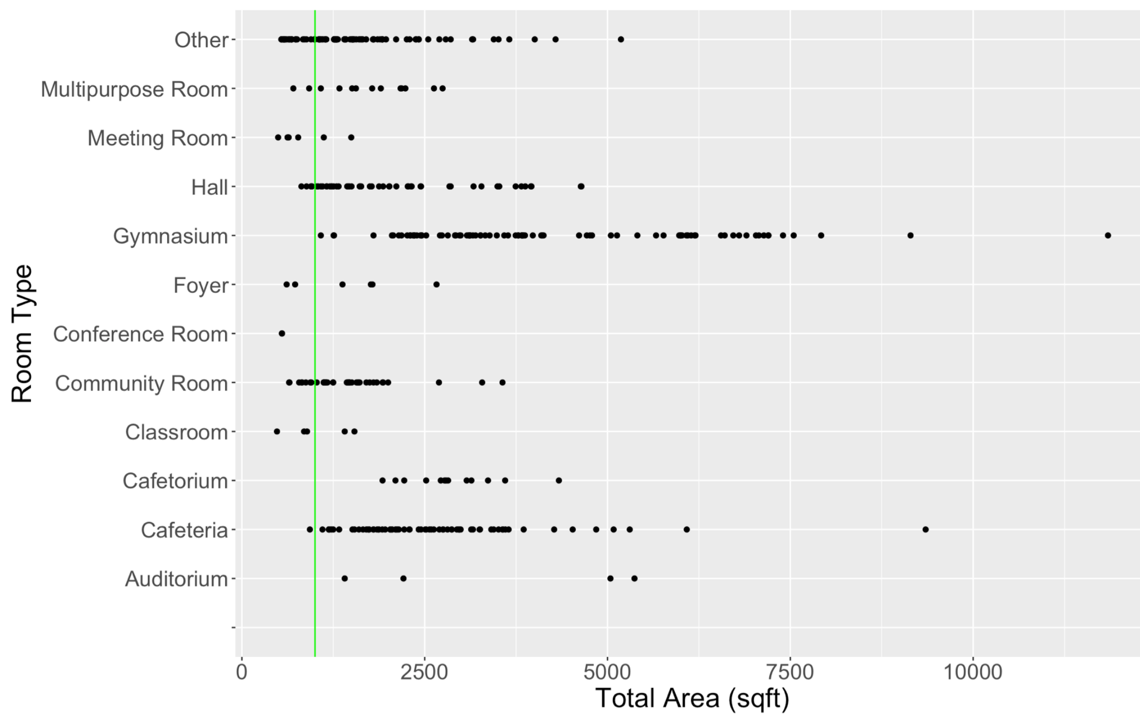


In addition to variation in area based on facility type, total area and the dimensions of a room are likely to vary from room to room within a facility. For example, there are multiple types of rooms within a school building (e.g., gymnasiums, cafeterias, cafetoriums, classrooms, multipurpose rooms, libraries, and labs) that range greatly in total area. While there is no data currently available providing the room type usage for elections across the United States, it was possible to determine the room type for the 378 Rhode Island polling locations. The average, minimum, and maximum total area for each of the polling locations in Rhode Island is listed in Table 3 by room type. Figure 3 also illustrates each of the individual polling location areas in Rhode Island by room type.

Table A.3:
Average, Minimum, and Maximum Area by Room Type

Room Type	Average (sqft)	Minimum (sqft)	Maximum (sqft)	Count
Auditorium	3506	1406	5369	4
Cafeteria	2666	930	9350	71
Cafetorium	2876	1924	4335	13
Classroom	1033	480	1539	5
Community Room	1464	646	3564	39
Conference Room	548	546	550	2
Foyer	1488	612	2662	6
Gymnasium	4311	1080	11844	85
Hall	2095	814	4644	50
Meeting Room	858	496	1496	6
Multipurpose Room	1750	704	2745	13
Other	1619	540	5184	84

Figure A.2
Range of Total Area by Room Type



The vertical line in Figures 2 and 3 mark the total area of each of the 1,000 sqft general polling facilities. The 1,000 sqft location has a total area that falls into the area range of 8 of commonly used facility types (i.e., churches, community centers, government buildings, libraries, police/fire stations, schools, senior centers, and other facilities), and 8 room types (i.e., cafeterias, cafetoriums, classrooms, community rooms, foyers, halls, meeting rooms, multipurpose rooms, and other rooms). This location is representative of smaller locations that are used as polling locations and is modeled as an open, rectangular room with the dimensions of 40’ by 25’.

Appendix B: Data Cleaning and Processing

Figure B.1

Raw Check-In Processing Time Histogram in Minutes

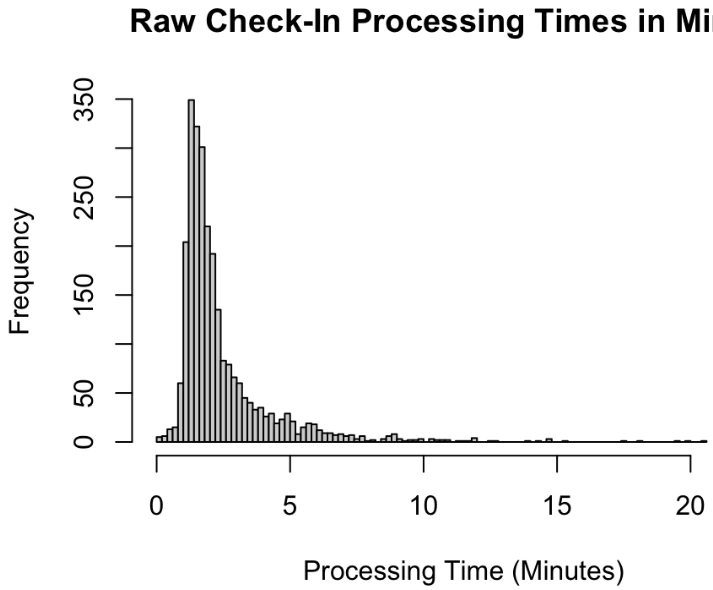


Table B.1

Goodness of Fit Maximum Likelihood Estimates for Raw Check-In Processing Time Distributions

Statistic/Criteria	Weibull Distribution	Lognormal Distribution	Gamma Distribution
Kolmogorov-Smirnov statistic	0.1619684	0.0983163	0.1440675
Cramer-von Mises statistic	23.6702310	8.4132439	17.7023483
Anderson-Darling statistic	134.7999482	48.8768186	96.1943107
Akaike's Information Criterion	9111.493	8227.849	8648.172
Bayesian Information Criterion	9123.217	8239.574	8659.89

Figure B.2

Goodness of Fit Plots for Raw Check-In Processing Times

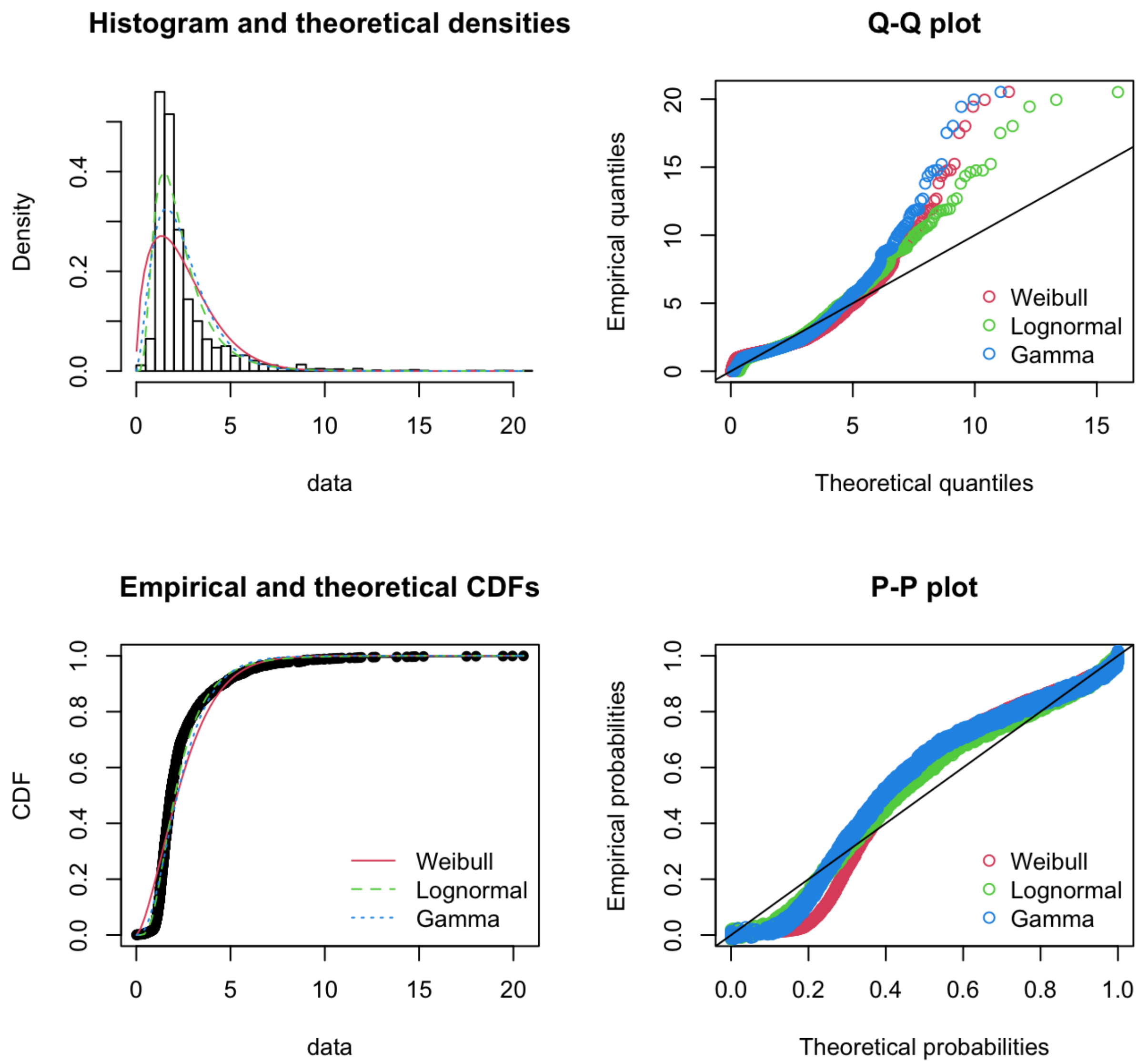


Table B.2

Goodness of Fit Maximum Likelihood Estimates for Cleaned Check-In Processing Time Distributions

Statistic/Criteria	Weibull Distribution	Lognormal Distribution	Gamma Distribution
Kolmogorov-Smirnov statistic	0.1654426	0.1067134	0.1502834
Cramer-von Mises statistic	24.7751038	9.5194730	19.1952211
Anderson-Darling statistic	142.8390475	54.5833456	104.9689774
Akaike's Information Criterion	9012.942	7856.562	8487.480
Bayesian Information Criterion	9024.645	7868.265	8499.183

Figure B.3

Goodness of Fit Plots for Cleaned Check-In Processing Times

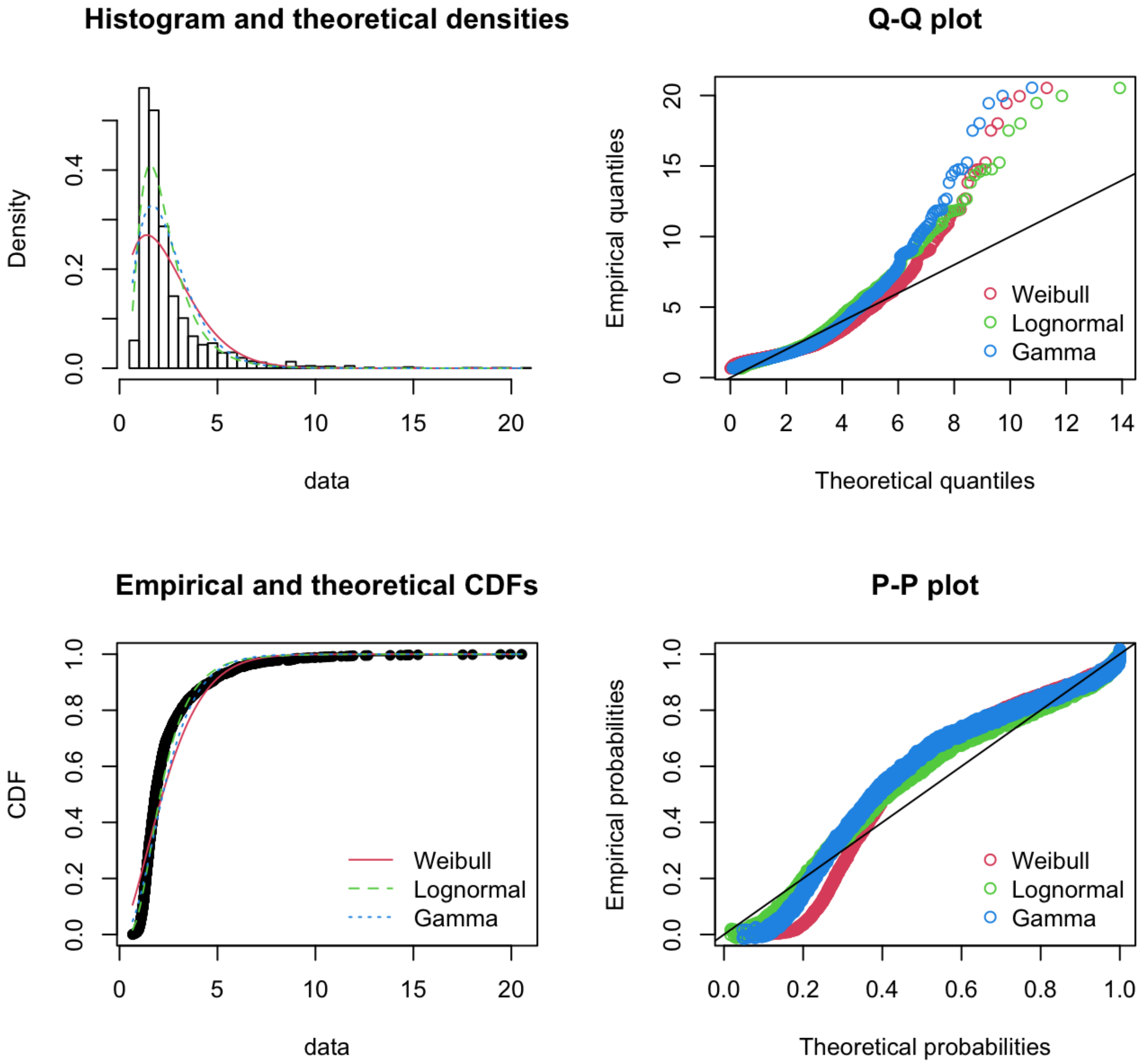


Figure B.4

Raw Ballot Marking and Casting Processing Time Histogram in Minutes

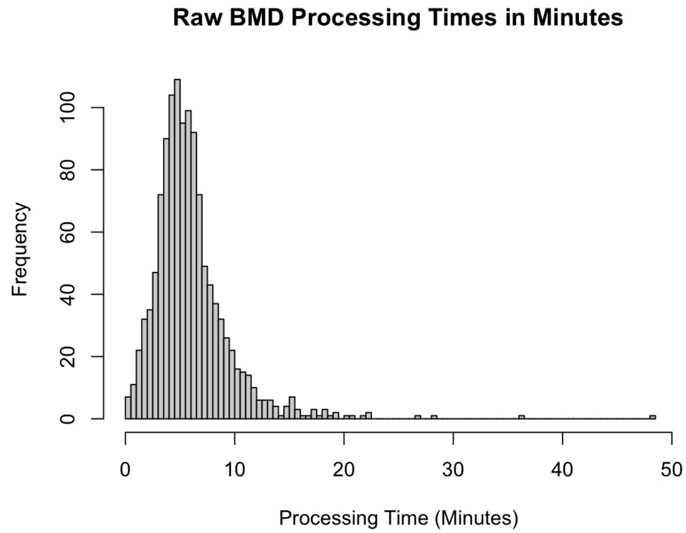


Table B.3

Goodness of Fit Maximum Likelihood Estimates for Raw Ballot Marking and Casting Processing Time Distributions

Statistic/Criteria	Weibull Distribution	Lognormal Distribution	Gamma Distribution
Kolmogorov-Smirnov statistic	0.08320952	0.08140273	0.05604987
Cramer-von Mises statistic	3.46179498	2.39216490	1.30793179
Anderson-Darling statistic	20.67112113	14.15317563	7.67899400
Akaike's Information Criterion	6161.379	6138.743	6041.792
Bayesian Information Criterion	6171.574	6148.938	6051.987

Figure B.5

Goodness of Fit Plots for Raw Ballot Marking and Casting Processing Times

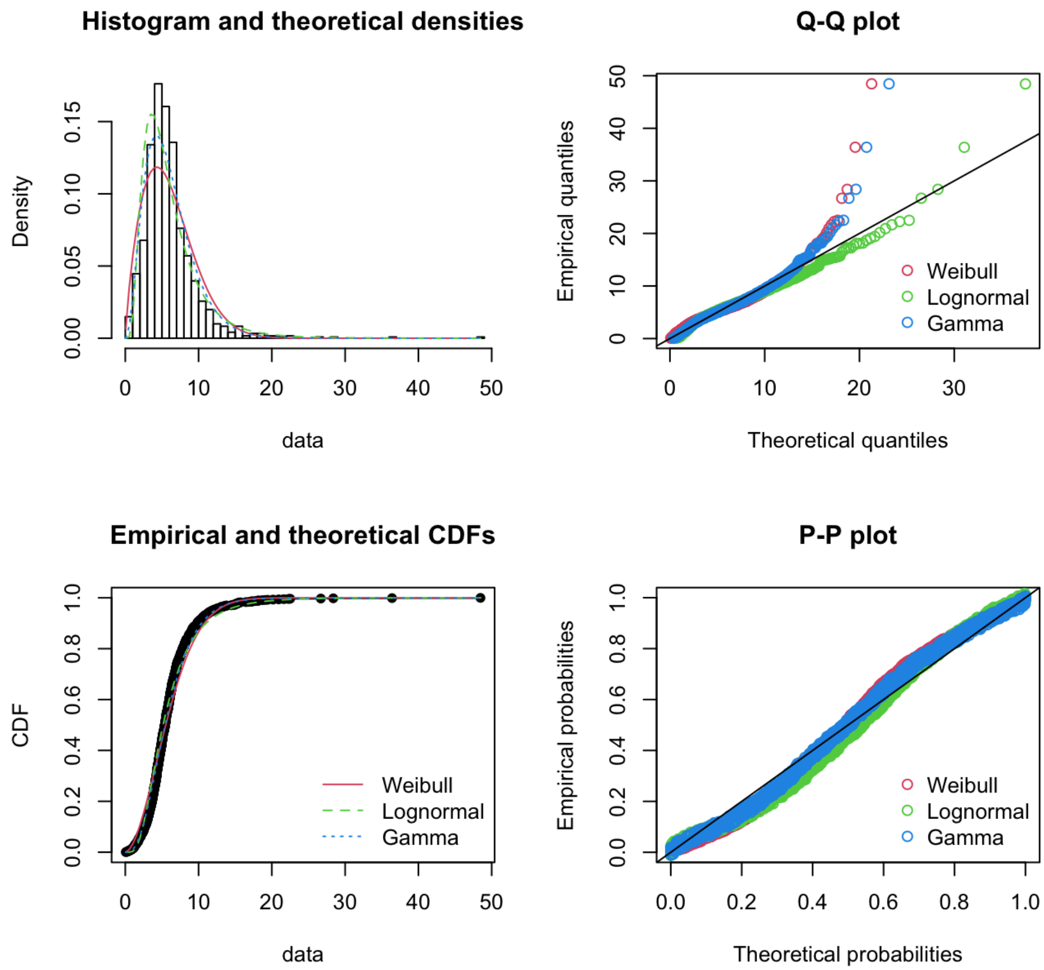


Table B.4

Goodness of Fit Maximum Likelihood Estimates for Cleaned Ballot Marking and Casting Processing Time Distributions

Statistic/Criteria	Weibull Distribution	Lognormal Distribution	Gamma Distribution
Kolmogorov-Smirnov statistic	0.09375509	0.0324706	0.06230426
Cramer-von Mises statistic	4.21536174	0.3179665	1.15366815
Anderson-Darling statistic	Inf	1.9778479	6.69675410
Akaike's Information Criterion	5922.499	5610.469	5698.335
Bayesian Information Criterion	5932.630	5620.600	5708.466

Figure B.6

Goodness of Fit Plots for Cleaned Ballot Marking and Casting Processing Times

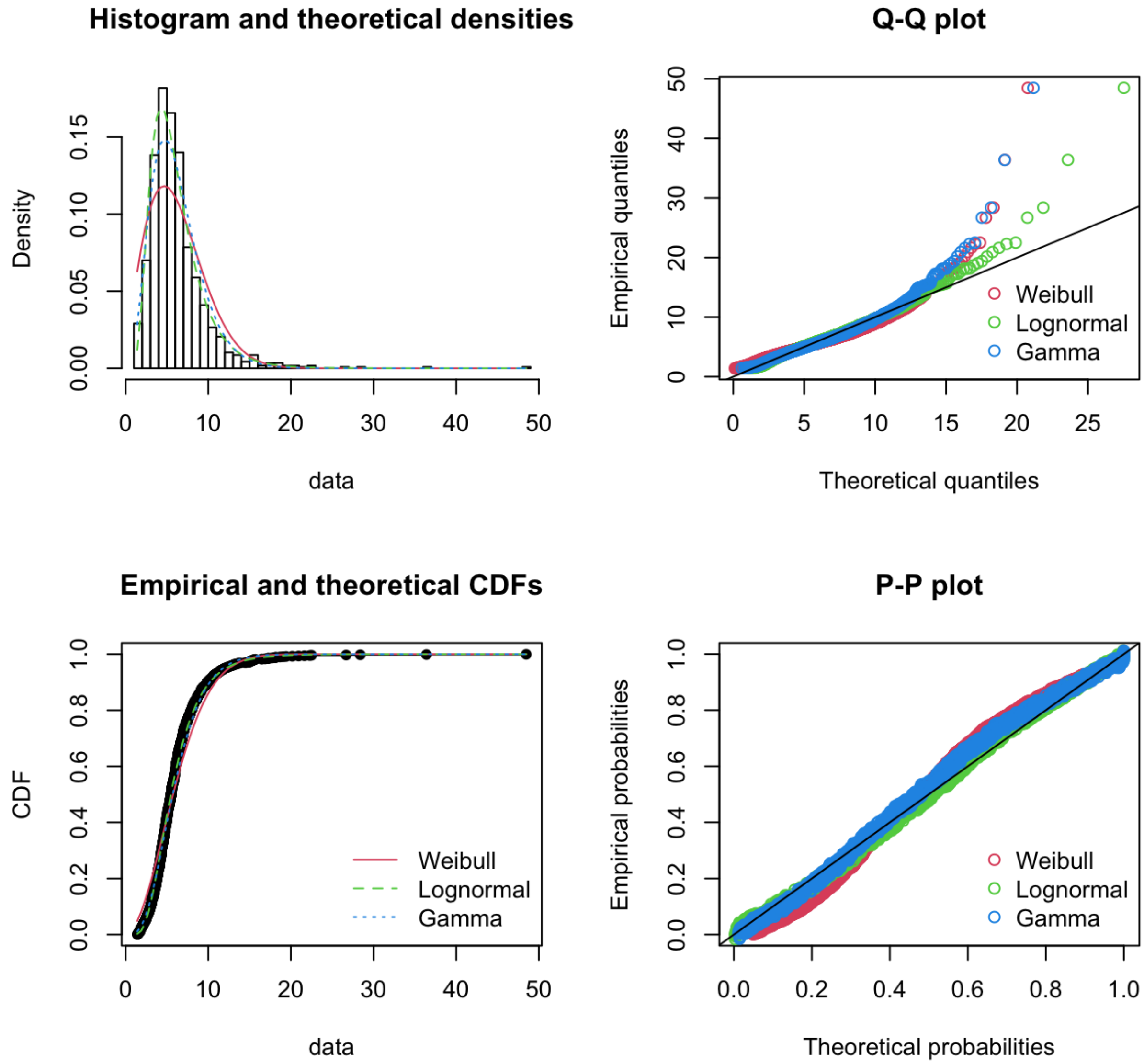


Table B.5

Raw Processing Time Data Statistics

	N	Mean	St. Dev.	Minimum	Q_{25}	Median	Q_{75}	Maximum
Check-In	2597	2.454	1.912	0.0167	1.400	1.833	2.700	20.533
Ballot Marking & Casting	1209	6.0145	3.592	0.0667	3.933	5.400	7.183	48.467

Figure B.7
Cleaned Check-In Processing Times in Minutes

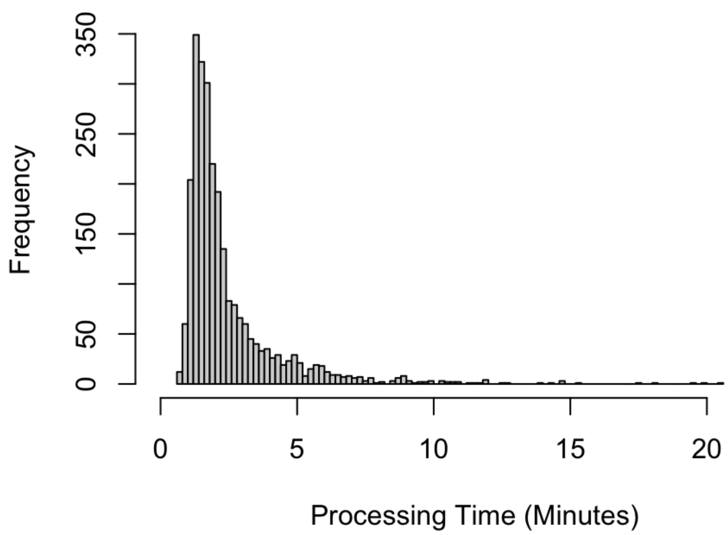
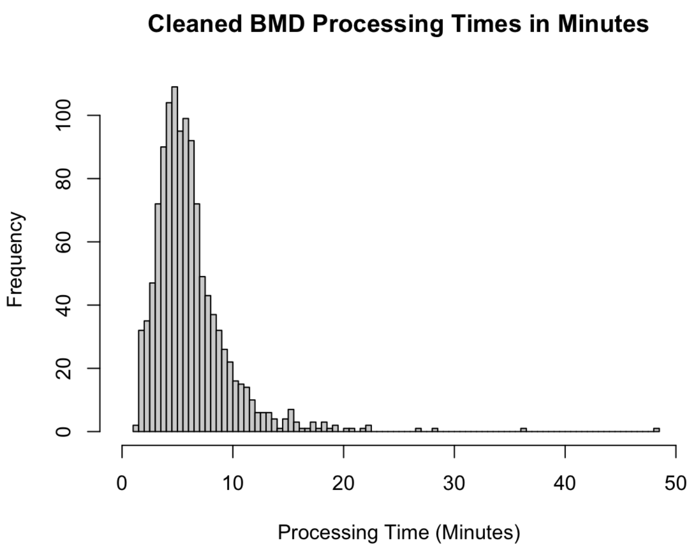


Figure B.8
Cleaned Ballot Marking and Casting Processing Times in Minutes



Appendix C: SketchUp Models for Voting Equipment

Figure C.1:
SketchUp Objects with Dimensions for Check-In Station

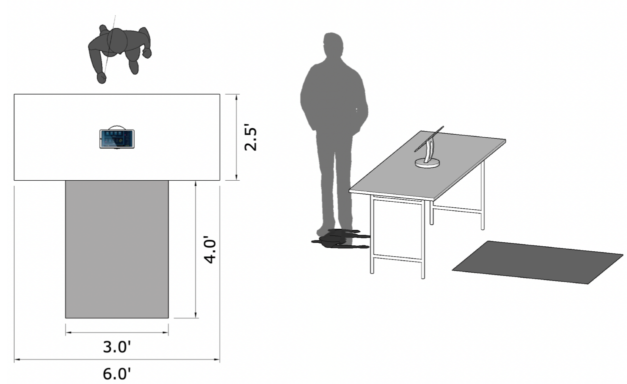
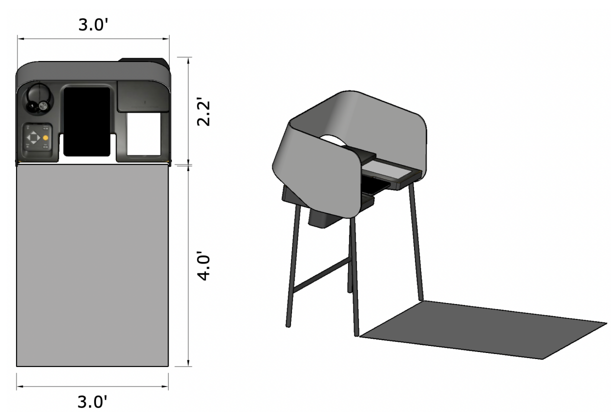


Figure C.2:
SketchUp Objects with Dimensions for Ballot Marking and Casting Station



Appendix D: Layout Diagrams

Figure D.1

Aisle Layout with Cyclical Path

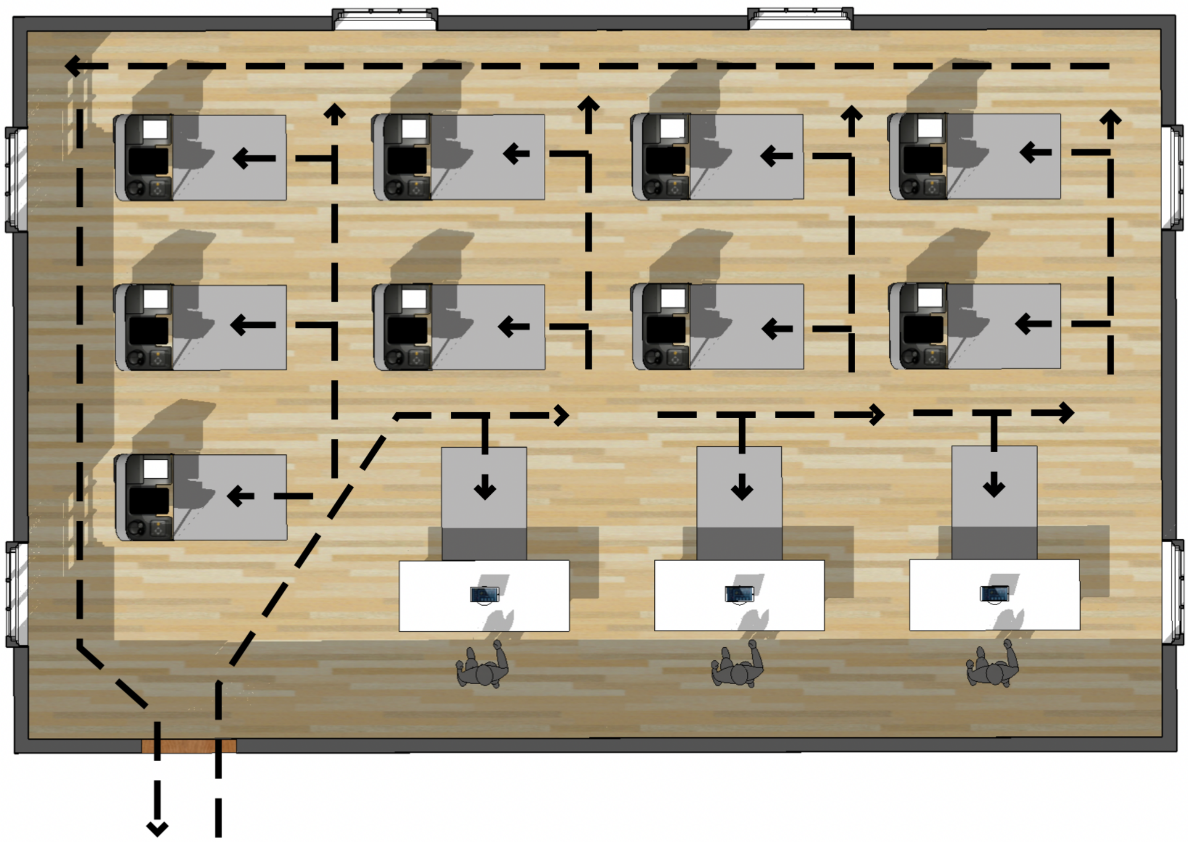


Figure D.2

Aisle Layout with Unidirectional Path

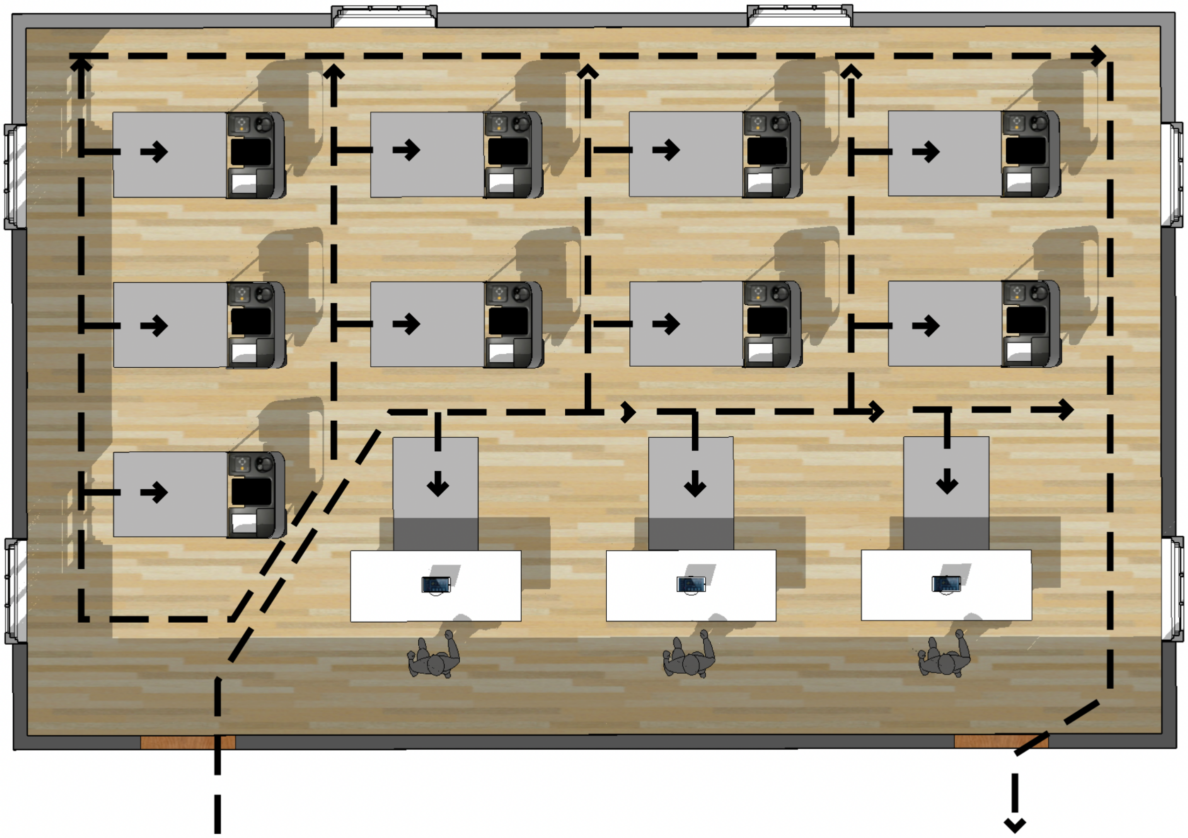


Figure C.3

Perimeter Layout with Cyclical Path

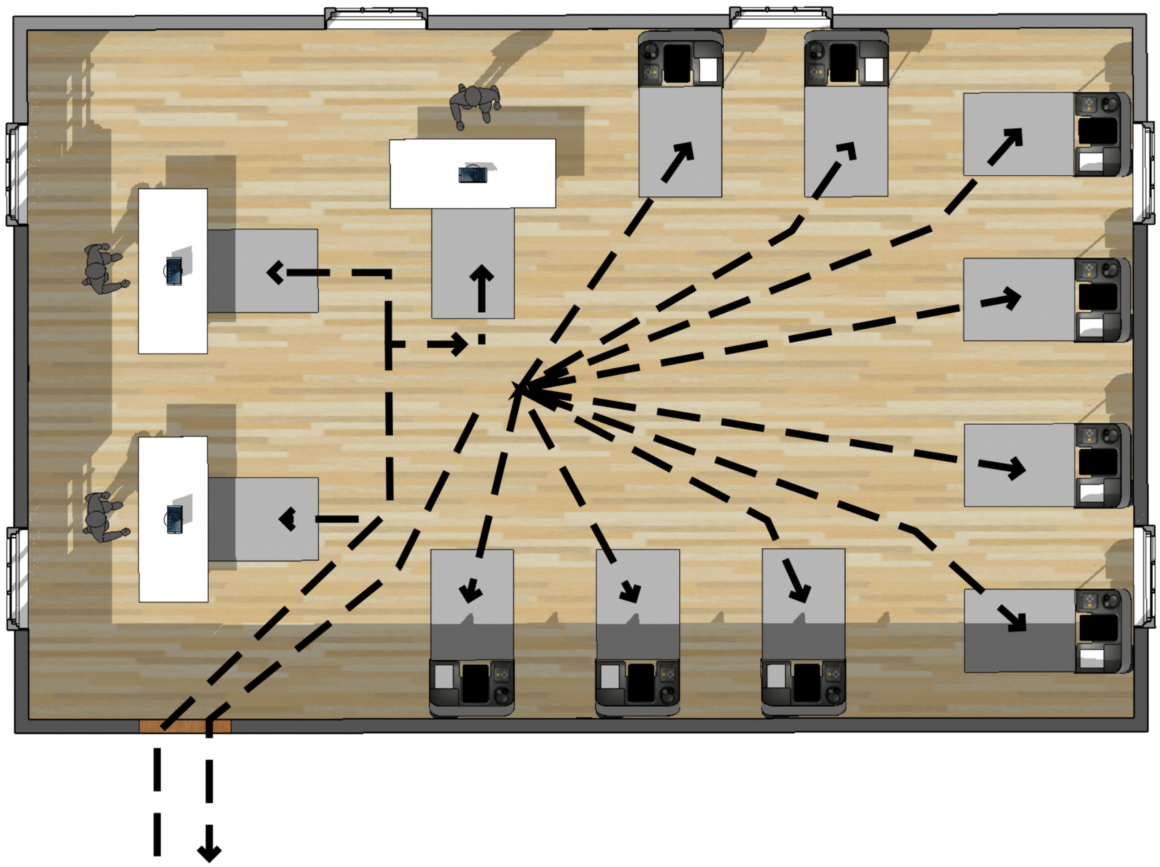


Figure D.4

Perimeter Layout with Unidirectional Path

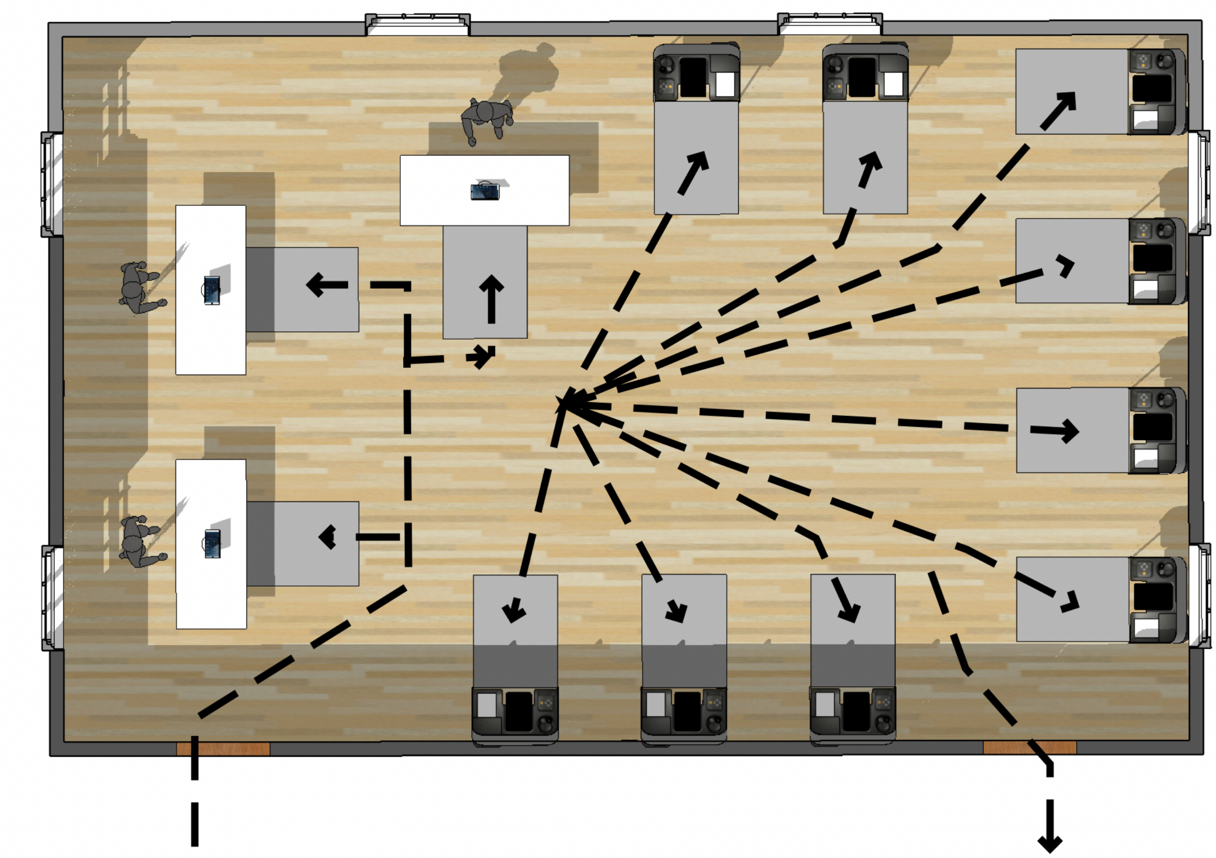


Figure D.5

Serpentine Layout with Cyclical Path

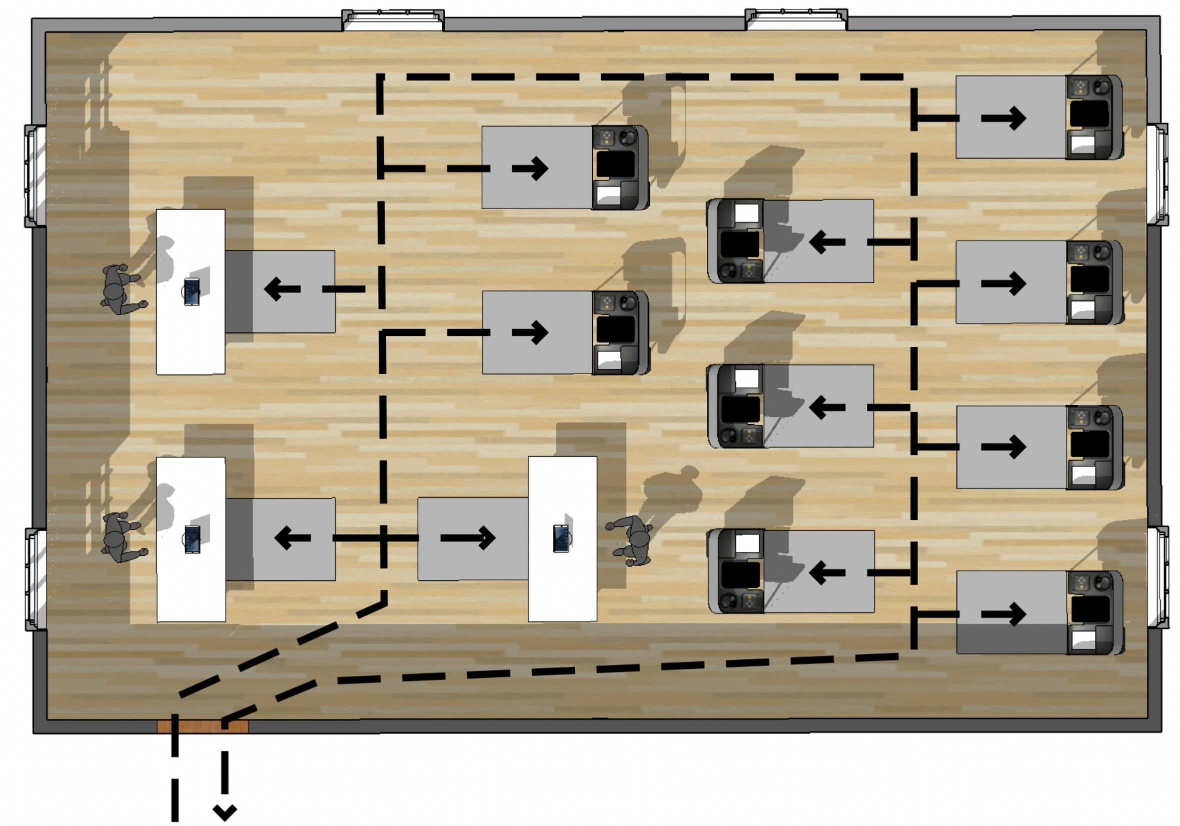
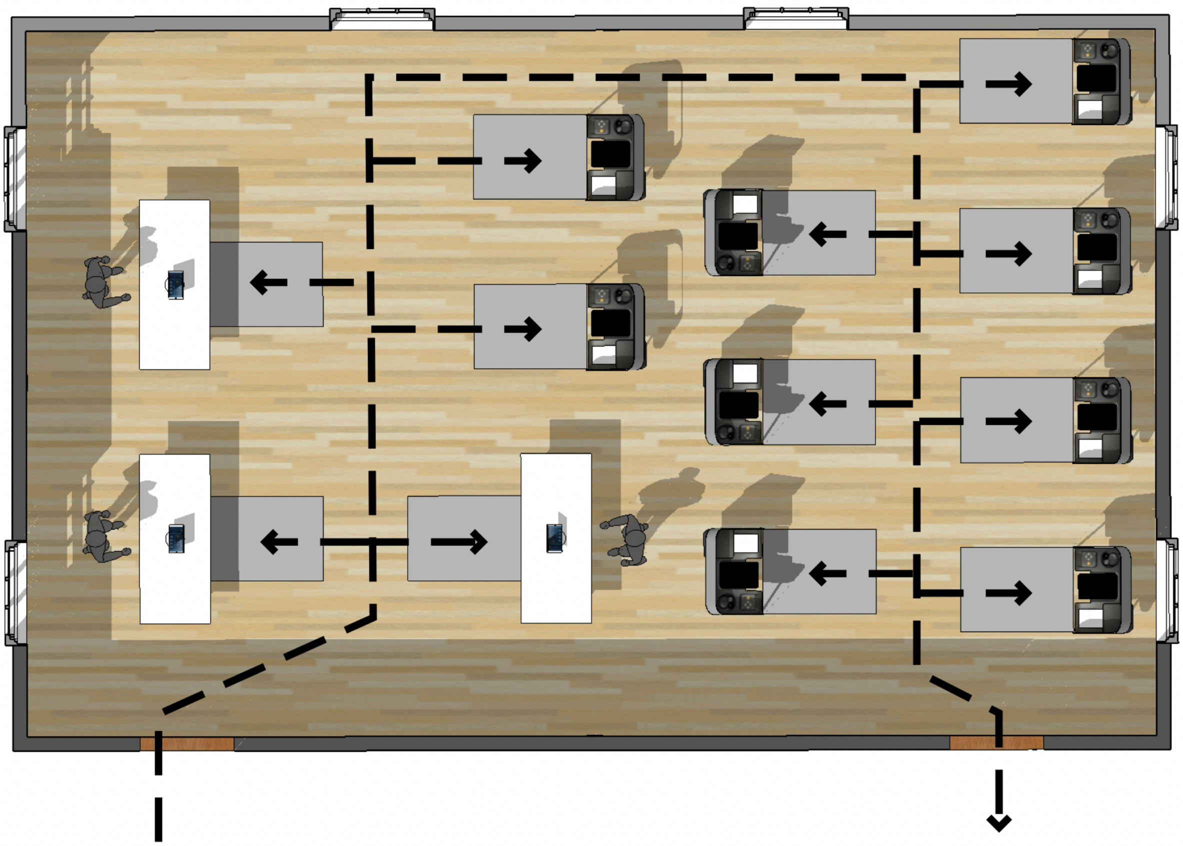


Figure D.6

Serpentine Layout with Unidirectional Path



Appendix E: Results

Table E.1

Performance Metrics for All Systems at All Voter Turnout Levels

Layout Method	Path Directionality	Turnout	Average TIS (minutes) 99.6% CI	Average TD (feet) 99.6% CI
Aisle	Cyclical	500	(9.754, 9.826)	(116.807, 116.875)
Aisle	Unidirectional	500	(9.764, 9.832)	(121.447, 121.555)
Perimeter	Cyclical	500	(9.511, 9.573)	(70.791, 70.85)
Perimeter	Unidirectional	500	(9.468, 9.53)	(59.706, 59.744)
Serpentine	Cyclical	500	(9.688, 9.756)	(111.477, 111.486)
Serpentine	Unidirectional	500	(9.599, 9.668)	(89.226, 89.234)
Aisle	Cyclical	1000	(73.826, 76.078)	(116.796, 116.842)
Aisle	Unidirectional	1000	(73.91, 76.158)	(121.367, 121.433)
Perimeter	Cyclical	1000	(68.315, 70.562)	(70.788, 70.823)
Perimeter	Unidirectional	1000	(68.454, 70.696)	(59.707, 59.729)
Serpentine	Cyclical	1000	(70.578, 72.859)	(111.481, 111.486)
Serpentine	Unidirectional	1000	(70.227, 72.486)	(89.231, 89.237)
Aisle	Cyclical	1500	(205.284, 207.056)	(116.802, 116.845)
Aisle	Unidirectional	1500	(205.496, 207.304)	(121.339, 121.402)
Perimeter	Cyclical	1500	(201.694, 203.519)	(70.779, 70.813)
Perimeter	Unidirectional	1500	(201.96, 203.751)	(59.705, 59.727)
Serpentine	Cyclical	1500	(202.632, 204.397)	(111.48, 111.486)
Serpentine	Unidirectional	1500	(203.045, 204.744)	(89.23, 89.236)
Aisle	Cyclical	2000	(282.442, 283.858)	(116.784, 116.828)
Aisle	Unidirectional	2000	(282.35, 283.775)	(121.348, 121.411)
Perimeter	Cyclical	2000	(279.415, 280.883)	(70.78, 70.812)
Perimeter	Unidirectional	2000	(279.594, 281.006)	(59.699, 59.72)
Serpentine	Cyclical	2000	(280.128, 281.571)	(111.481, 111.486)
Serpentine	Unidirectional	2000	(280.238, 281.671)	(89.23, 89.236)
Aisle	Cyclical	2500	(326.739, 327.856)	(116.801, 116.843)
Aisle	Unidirectional	2500	(326.758, 327.858)	(121.346, 121.41)
Perimeter	Cyclical	2500	(324.257, 325.374)	(70.779, 70.812)
Perimeter	Unidirectional	2500	(324.693, 325.832)	(59.7, 59.722)
Serpentine	Cyclical	2500	(325.376, 326.486)	(111.482, 111.488)
Serpentine	Unidirectional	2500	(325.044, 326.18)	(89.23, 89.236)
Aisle	Cyclical	3000	(353.153, 354.079)	(116.784, 116.825)
Aisle	Unidirectional	3000	(352.928, 353.858)	(121.346, 121.409)
Perimeter	Cyclical	3000	(351.28, 352.237)	(70.784, 70.817)
Perimeter	Unidirectional	3000	(351.427, 352.345)	(59.703, 59.725)
Serpentine	Cyclical	3000	(351.855, 352.739)	(111.48, 111.485)
Serpentine	Unidirectional	3000	(351.941, 352.865)	(89.23, 89.235)

Appendix F: Confidence Interval Plots for Average Voter TIS

Figure F.1

Average Voter Time-In-System for Each System at All Turnout Levels