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Improving access to voting with optimized matchings

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ABSTRACT

Research on political representation has traditionally focused on the design of electoral systems. Yet there is evidence that voting costs result in lower turnout and undermine voters' confidence in the electoral system. Election administrators can selectively manipulate participation costs for different individuals and groups, leading to biased electoral outcomes. Quantifying the costs of voting and designing fair, transparent and efficient rules for voter assignment to polling stations are important for theoretical and practical reasons. Using analytical models, we quantify the differential costs of participation faced by voters, which we measure in terms of distance to polling stations and wait times to cast a vote. To estimate the model parameters, we use real-world data on the 2013 midterm elections in Argentina. The assignment produced by our model cut average voting time by more than 27%, underscoring the inefficiencies of the current method of alphabetical assignment. Our strategy generates better estimates of the role of geographical and temporal conditions on electoral outcomes.

1. Introduction

Scholarly work on political representation mainly focuses on problems associated with electoral system and ballot design. However, the location and administration of polling stations have sizable effects on electoral outcomes (Alvarez et al., 2008, p. 248). Hurdles to participation increase the opportunity costs of voting, which results in lower turnout (Dyck and Gimpel, 2005) and undermines confidence in the electoral system (Claassen et al., 2008). There is now robust evidence that distance to polling stations and waiting in line to vote impose real costs on voters and discourage political participation (Dyck and Gimpel, 2005; Stewart III and Ansolabehere, 2015). Yet voting costs are not evenly distributed across the electorate. In the US, for instance, racial minorities tend to experience longer voting times than white voters (Stewart III, 2012), and urban voters travel less but wait longer to vote (Stewart III and Ansolabehere, 2015). Hence varying voting costs results in disenfranchisement, affecting political representation. As Lijphart (1997, p. 2) eloquently puts it: "low voter turnout means unequal and socioeconomically biased turnout."

These insights have piqued academic interest in issues associated with electoral administration. Decisions by authorities in charge of planning and administering elections affect the distance and wait time faced by different groups of voters (Haspel and Knotts, 2005, p. 560). These choices could be subjected to opportunistic political manipulation by those authorities, facilitating access to the ballot of their supporters and making it more difficult for their opponents to cast a vote (Nagler, 1991; Brady and McNulty, 2011). Given existing evidence that the costs of voting vary significantly across individuals of different socioeconomic status, matching voters to polling stations has become a politically salient and controversial problem (Stewart III, 2012; Herron and Smith, 2016).

Providing electoral administrators with transparent rules for voter assignment and resource allocation has important implications for the functioning of the electoral process, the fundamental pillar of democratic governance.[1] The usual recommendation to reduce voting costs is to better allocate resources across polling stations. However, electoral authorities lack a clear benchmark on how to allocate those resources in an efficient, objective and fair way. Our paper aims at filling that void.

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[1] "The use of automated districting procedures is at least able to ensure that systematic distortions of the electoral outcome are avoided, and, denying political parties the opportunity to manipulate districts, they can be very useful to provide fair district maps." (Ricca et al., 2013, p. 250).

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Employing tools of mathematical programming, we develop a modeling strategy for optimal voter assignment to polling stations, reducing voting costs as defined by the total time needed to vote (sum of travel and wait times).

The main differences between our approach and previous studies that apply quantitative methods to electoral problems are twofold: first, we consider the relocation of polling stations together with the assignment of voters to polling places; and, second, we focus on the combination of travel and waiting time as a measure of the total time needed to vote. While similar approaches have been considered in the past, earlier work did not address the problems of assigning polling stations and voters to polling places simultaneously. Allen and Bernshteyn (2006) define regression models to predict voter turnout; based on queueing theory results, they propose a simple heuristic for redistributing polling stations between a set of precincts with the aim of minimizing the maximum expected wait time among those precincts. Orford et al. (2011) consider statistical models of voter turnout and perform a correlation study between distances to polling stations, among other variables, to assess the effect of polling stations' locations. Yang et al. (2013) analyze the problem of redistributing polling stations between a set of precincts, but unlike our method they apply an "equity" criterion defined as the difference between the maximum and minimum expected waiting times among those precincts. Herron and Smith (2016) develop a simulation model that can be used to analyze the effect of different numbers of stations within the same polling place. By explicitly considering distances between voters' residences and polling stations, we can compute a reliable estimate of the travel time of each voter. As mentioned earlier, we also account for waiting time at the voting station, as estimated by a queueing theory model.

Our modeling framework allows us to quantify the costs of voting, as given by the two components of voting time, under different voter assignment scenarios. First, we develop a benchmark model to match voters to polling stations that satisfies fundamental principles of efficiency and objectivity. We use this benchmark to quantify the costs of participation under the voter allocation rule in Argentina. The current election design assigns voters to polling places within a territorial subunit of the broader electoral district in alphabetical order. While seemingly innocuous, this alphabetical assignment rule does not internalize the varying voting costs—resulting from travel distance to polling stations and wait times—for different voters within those subunits.

Using voter-to-polling-station assignment data in one territorial subunit of the city of Buenos Aires, we document large differences in total voting time when the current electoral system is compared to the optimized assignment. We find that minor changes in voter assignment to polling stations resulting from our model lead to sizable variation in the expected costs of voting, as measured by travel and wait times. On average, the assignment that results from the benchmark model reduces the average total voting time by more than 27% with respect to the current official assignment. We also develop alternative models that either vary the capacity of polling places, relocate polling stations, or both. For each of these alternatives, we compare the resulting total voting time to the assignments used in Argentina, and discuss the expected impact on voting outcomes. The reductions in travel and wait times arising from the implementation of our linear programming approach are significant. There is ample evidence that even small changes in total voting time can have a significant impact on participation rates (McNulty et al., 2009) and on perceptions about the legitimacy of the electoral process (Spencer and Markovits, 2010; Gerber et al., 2013). Although the efficiency gains could have significant effect in elections like those in Argentina where voting is mandatory, the gains are likely to be even more important under different electoral rules, in particular where voting is not mandatory.[2] Assessing the impact of implementing more efficient voter assignment rules on electoral outcomes—including turnout and representation—under different electoral rules is a potentially fruitful and important area for a more rigorous empirical evaluation.

The rest of this paper is divided into six sections. Section 2 places our contribution in the context of the extant literature; Section 3 describes the current official assignment process of voters to polling stations used in Argentinean elections and the matching problem variants that will be solved; Section 4 introduces the proposed voter-matching models, beginning with the benchmark assignment version, which we use to document the extra participation costs experienced by voters under the current system; Section 5 discusses the methodologies for obtaining and processing the data on queues and waiting times at the polling places and the voters' geographical location data; Section 6 implements the models and analyzes the results; and finally, Section 7 presents our closing comments and conclusions.

2. Related literature

Voting is one of the central features of democratic governance. In theory the individual decision to vote is affected by expected benefits and costs of turning out (Downs, 1957; Riker and Ordeshook, 1968; Aldrich, 1993). The rational voter hypothesis has been criticized because it fails to explain the levels of voting. Since the probability of casting a decisive vote is negligible, any small cost of participation would lead to abstention.[3] However, we do observe that many individuals vote systematically, suggesting that political participation is not solely based on self interest (Palfrey and Rosenthal, 1983, 1985; Aldrich, 1993; Green et al., 1994).[4] In any event, the rational voter model provides important insights that explain participation at the margin (Aldrich, 1993; Blais et al., 2000; Bhatti, 2012). The choice to participate in an election varies across voters according to individual characteristics, including interest and motivation. Hence, even in highly salient elections, a large number of potential voters abstain, indicating that civic-mindedness is far from universal and that voting costs could affect political participation. Hurdles to participation also play an important role in other major perspectives on the individual and group level determinants of voting (Gomez et al., 2007).[5] In all of these perspectives, distance to polling stations and wait time increase the opportunity costs of voting, resulting in lower turnout (Dyck and

[2] Mandatory voting is likely to result in higher turnout rates (Singh, 2011, 2015; Carlin and Love, 2013). Yet, as documented in the literature on election management, holding motivation to vote and constraints constant (including the expected cost of not voting), the reduction in participation costs should result in a higher likelihood of voting. We discuss this conjecture further in footnote 2 below. Anecdotally, we observe stark differences in turnout rates in primary, midterm and presidential elections in Argentina, USA and elsewhere. The Chilean case presents an interesting example: turnout rates dropped substantially (from about 85% to 40%) after Chile moved from mandatory voting for all voters who registered voluntarily, to voluntary voting with universal registration (Contreras et al., 2016).

[3] In the rational voter model the probability of voting is a function of the utility an eligible voter gets from casting her vote. We can denote the probability that individual i turns out as an increasing function of U_v, the utility she derives from voting: $\pi_i = f(U_v)$. The utility of voting, $U_v = f(pB, c)$, can be defined in terms of the material and psychological benefits B that the voter expects to receive when her candidate of choice wins the election, the probability p that her vote will be decisive, and the costs c of participating in the electoral process. The costs of voting include the resources required to acquire information about candidates and political issues, and the time it takes to cast a vote. Under general conditions, the utility of voting is increasing with the benefits B and decreasing with the cost of participation c. As the number of voters increases, the probability p of any single vote being pivotal becomes negligible. To the extent that voting is costly, a rational voter is likely to sit an election out.

[4] We can further decompose the voter benefits into selfish ones (benefits accrued directly by the voter) and social ones (indirect benefits to others that the voter internalizes). If solely motivated by selfish benefits, the individual calculus would result in a lower probability of turning out as the number of voters increases. Social benefits, on the other hand, could result in a higher probability of voting even as the number of voters goes up (see Edlin et al., 2007).

[5] These perspectives place emphasis on socio-economic status (Almond and Verba, 2015; Verba and Nie, 1987), or group level conditions affecting voter mobilization (Rosenstone and Wolfinger, 1978; Rosenstone et al., 1993).

Gimpel, 2005, p. 532).

There is now robust evidence that distance to polling stations depresses turnout in elections in the U.S. and around the world (Gimpel and Schuknecht, 2003; Haspel and Knotts, 2005; Dyck and Gimpel, 2005; Highton, 2006; McNulty et al., 2009; Spencer and Markovits, 2010; Brady and McNulty, 2011; Herron and Smith, 2016). There is also a strong relationship between proximity to polling stations and the propensity to vote in municipal elections in Denmark (Bhatti, 2012). A closely related problem that has received attention in recent years is that of queues at polling places and the consequent voter waiting times. Allen and Bernshteyn (2006) provide empirical evidence that people are deterred from voting by waiting times. Long lines can deter voters, increasing attrition through balking or reneging (Spencer and Markovits, 2010). Stewart III and Ansolabehere (2015) analyze polling place queues and their negative effects in the United States.[6] Herron and Smith (2016) refer to several problems recently experienced by voters in the U.S. and Canada, some of whom were unable to vote despite having queued for hours. Wait times also affect the voter's perception that their vote counts, undermining confidence in the electoral system (Claassen et al., 2008).

The problem of defining and modifying the boundaries of an electoral district has been tackled by a number of scholars in the field of election administration. Research in this area focuses on a wide range of issues including voter registration (Rosenstone and Wolfinger, 1978; Nagler, 1991; Herron and Smith, 2016), location of polling stations and allocation of voting machines (Knack, 1995; Highton, 2006; Wang et al., 2014), the agencies in charge of monitoring the electoral process (Herron and Smith, 2016), and voting technologies (Edelstein and Edelstein, 2010). Voting locations—schools, churches, fire stations, etc.—and the immediate surroundings of a polling place have been shown to have an impact on voting decisions and choices (Wheeler et al., 2008; Rutchick, 2010). Interest in election administration is also a response to concerns about gerrymandering or manipulation of the boundaries of an electoral district to favor a particular political party. Cain et al. (2008), for example, analyze the existence of gerrymandering in California, while Chambers and Miller (2013) introduce measures that can incorporate geographic features to assess the compactness of districts.

On a related problem associated with the administration of voting resources, scholars have used simulations to balance the assignments to voting machines across polling stations using equity and efficiency considerations (Yang et al., 2009, 2014; Wang et al., 2014). Yang et al. (2015) apply a robust optimization approach to the voting machine allocation problem aimed at reducing the number of voters experiencing extremely long waiting times. The numerical results reported in these studies are derived from data for the 2008 U.S. election in Franklin County, Ohio. Despite these contributions, a recent review of the empirical literature on voting in the U.S. by Ansolabehere and Shaw (2016) concludes that we have limited knowledge on how resource allocation affects voting costs and the quality of the voting experience. Moreover, while political districting and voting machine assignment problems in the aforementioned literature are important, the problem of matching voters to polling stations given predefined districts and resource allocations has received much less attention. This is an important oversight, especially when considering democracies in developing countries, which have limited access to resources and technology. In these settings elections usually take place on a single day, voters are assigned beforehand to a single location, and voting and tallying votes is conducted manually.

[6] The 2008 Survey of the Performance of American Elections (SPAE) reports that 11% of non-voters were discouraged by long wait times. The number for 2012 was 14.5% (Pettigrew, 2013). During the 2008 presidential election 2% of individuals who arrived at polling stations reneged due to long wait times (Spencer and Markovits, 2010).

The previous discussion underscores the importance of designing mechanisms assigning voters to polling stations that fulfill two basic criteria: first, the mechanism should be globally efficient, increasing the incentives to participate in the electoral process; and, second, the mechanism should reflect objective criteria such as geography and wait times that are less susceptible to political manipulation. Analytical models can help in designing optimal assignments that fulfill these criteria.[7] Our contribution is twofold: First, we use well a established analytical framework, specifically mathematical programming and queuing theory, to address the problem of efficiently assigning voters to polling stations[8]; and second, we perform an empirical analysis using real data from the 2013 national election in Argentina, for which we are able to document unnecessary obstacles to participation faced by Argentine voters.

Naturally, the problem of minimizing voting costs, including the location of polling places and allocation of resources to polling places (polling stations, voting machines, capacities), interacts with political districting, ballot design and other attributes of the electoral system. We take the electoral system, districting and resources as given and focus on the minimization of travel time, which we achieve by optimizing the assignment of voters to polling places. To attain our ultimate goal, which is to optimize total voting time, we also consider the allocation of resources as a lever to control wait time at the polling station.

3. Measuring voting costs

The approach we propose employs mathematical programming to assign voters to polling stations. Our method relies on a *matching problem* whose formulation and resolution strategies are already well established (Nemhauser and Wolsey, 1988). We use this model to quantify the costs of participation—measured in terms of travel and wait times—using real data on voters in one electoral subunit within the broader electoral district of the Autonomous City of Buenos Aires (CABA), Argentina, during the 2013 national midterm elections. Voting in Argentina's national elections is mandatory, but in a typical electoral cycle at least one-fifth of the electorate does not turn out to vote.[9] The country is divided into twenty-four electoral districts, one for each of the 23 provinces plus CABA. District magnitude ranges between 2 and 35, according to the population of the province.[10] All eligible voters are automatically added to the electoral rolls and they must cast their ballots at polling stations (*mesas electorales*), one or more of which are set up for the purpose in a single polling place. Typically, polling stations are located in educational establishments within the territorial subunits; hereafter we will refer to the latter as *polling places* or schools. Voters are assigned to polling places within the district they live in. Votes are cast for province-wide party lists and the seats in the National Congress are allocated proportionally to the lists using the D'Hondt formula. We take the electoral system as a given, focusing our analysis on the method of voter assignment to polling stations.

[7] The use of optimization in issues of election administration has been investigated since the 1970s (Garfinkel and Nemhauser, 1970), and is receiving stronger attention in recent years (Tasnádi, 2011; Ricca et al., 2013; Kalcsics, 2015).

[8] See Lenzi (2013) who develops a similar strategy and obtains preliminary results for Pergamino, an electoral district in Argentina.

[9] Voting is mandatory for citizens aged 18–70. Unexcused abstention can result in fines of $50 to $150 and other administrative penalties, such as denial of certain government services for a period of one year or compulsory community service for up to three years. In practice, penalties for not voting are often set aside and even rescinded by blanket amnesties which are usually passed before the beginning of the following electoral cycle. In any event, while mandatory voting can create a sense of obligation to vote, differential voting costs have the potential to affect individual incentives to participate.

[10] The average district magnitude in Argentina is 5.34. CABA has a district magnitude of 12 or 13, depending on the electoral cycle; it is the second largest in the country after the province of Buenos Aires (not to be confused with the Autonomous City of Buenos Aires), which has a district magnitude of 35.

Under the current National Elections Code (Argentine Law, 1983), the assignment of voters to specific polling stations within subunits of the electoral district, and therefore schools, is performed alphabetically; that is, essentially in a random order.[11] Although electoral subdivisions usually are relatively small in area, the assignments are often not geographically efficient, resulting in higher travel and wait times for the average voter. There is room, therefore, for an alternative mechanism in which the matching of two voters to schools can be interchanged in such a way that the travel distances to their polling stations would be shortened. Also, changes could be made to the current distribution of polling stations and their (legally defined) voter capacity that would reduce the time voters spend queuing at polling stations once they arrive at their assigned school. With this in mind, the purpose of this study is to develop an efficient and fair voter assignment strategy that minimizes distances to polling stations and waiting times, and to put into perspective the costs of voting under the current assignment mechanism compared to the optimized assignment.

We begin our analysis by measuring the time each voter requires to walk from their residence to their assigned school and back. Next, we investigate the dynamics of the voting process at the polling station and compute queue waiting times. We obtained voter data for the 11th *Comuna* (administrative district) of the City of Buenos Aires.[12] District 11 is representative of an average urban district in Argentina.[13] It is partitioned into 11 electoral divisions numbered 113 to 123, configured as shown on the map in Fig. 1.

Each voter in the district is assigned to a polling station in a school. The locations of schools designated as polling places are indicated by red stars in Fig. 1. The information gathered also includes the addresses of schools and voters. Under the current system each polling station has a maximum capacity of 350 voters.[14] Table 1 reports the turnout rates for the polling stations within the 11 electoral divisions in the district. The table shows that while the average turnout rate is similar, there is considerable variation in turnout per polling station for each electoral division. Most importantly, although voting is mandatory not everybody votes in practice.

The real-world data we collected enabled us to rigorously analyze travel and wait times for different voters, which are a function of the current electoral rules. We compare this to the travel and wait times for the assignments generated by our models. We begin by describing the voter assignment problem.

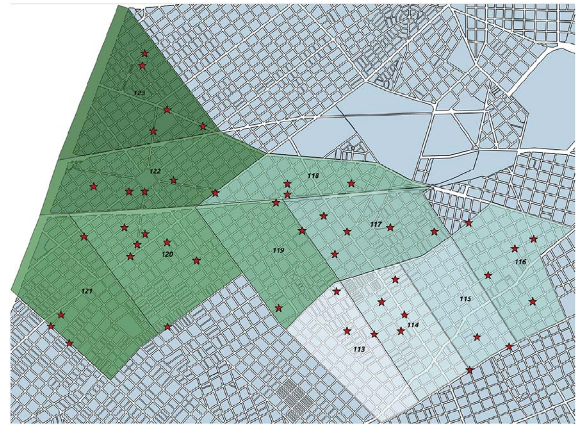

Fig. 1. Partition of the 11th Comuna of Buenos Aires into electoral divisions. Red stars indicate schools designated as polling places. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Turnout per polling station.

Electoral Division	Mean	Std. Dev.	Median	Min	Max
113	0.79	0.03	0.79	0.74	0.86
114	0.78	0.03	0.78	0.69	0.83
115	0.78	0.02	0.78	0.73	0.82
116	0.78	0.03	0.79	0.70	0.84
117	0.79	0.02	0.79	0.73	0.84
118	0.79	0.03	0.79	0.71	0.88
120	0.79	0.03	0.79	0.73	0.85
121	0.80	0.04	0.80	0.61	0.89
122	0.77	0.05	0.78	0.53	0.84
123	0.79	0.05	0.80	0.49	0.84
119	0.78	0.09	0.80	0.14	0.84

3.1. The polling place voter assignment problem

The National Elections Directorate, an agency of the Argentinean Ministry of the Interior and Transport, is the entity in charge of scheduling, organizing and carrying out all activities related to national elections. Among other tasks it is responsible for matching voters to polling stations, and therefore to the schools, that is, the polling places where the stations are located.[15]

The official matching process currently in force (hereafter described simply as "the current system") is set out in detail in the most recent National Elections Code and related regulations, but the following sums up the main points required for purposes of the present analysis.

- *Geographic subdivisions*. As noted above, Argentina is partitioned for electoral purposes into units known as *circuitos electorales* or electoral subdivisions. The Code currently requires that every adult citizen must vote within the division they officially reside in.
- *Polling stations*. All voters resident in a given electoral division are assigned to *mesas* or polling stations distributed among multiple schools (*polling places*) within the subdivision. The maximum capacity of each station is 350 voters over the course of the election day.
- *Assignment of voters to stations*. An appropriate number of polling stations must be set up within each school. All persons on the official voters list are sorted alphabetically by surname and then assigned to the stations in that order.

Note that the number of polling stations in each school is known in advance. If no geographical data is taken into account other than the

[11] Nevertheless, Argentina's assignment of voters to polling stations is not random within electoral districts. Within each electoral district, which as noted covers an entire province, voters are divided into smaller geographical subdivisions coinciding with local administrative jurisdictions. This is not very different from the voter assignment system used in other countries. The random component of voter assignment results from the assignment of voters to polling stations within these subdivisions, which in the Argentine case is done alphabetically. Our modeling strategy helps identify the deviation of the existing assignment from a benchmark. In our case, we chose to use an efficiency benchmark, which we characterize in terms of wait and travel times.

[12] *Comunas* are geographical and administrative districts of the City of Buenos Aires, identified ordinally (1st to 15th) and ranging in population from 150,000 to 230,000 inhabitants. Each one is subdivided into several electoral divisions.

[13] District 11's population density (14,075 people/km^2) is slightly below the city's average, and similar to that of the urban conglomerate surrounding the City of Buenos Aires (Conurbano Bonaerense), where one-third of the Argentine population resides (Buzai and Marcos, 2012; Gobierno de la Ciudad de Buenos Aires, 2013). Historical turnout rates in District 11 have been identical to those in the greater Buenos Aires region, with which the district shares most of its social, economic and political attributes (Buzai and Marcos, 2012; Gobierno de la Ciudad de Buenos Aires, 2011, 2014).

[14] According to Argetine's Law 26.774, Article 41, each electoral circuit is divided in polling stations, each of which can have up to 350 voters assigned to it and grouped alphabetically. If after the assignment, there is a remainder of fewer than 60 voters, they can be added to existing polling stations per decision of the judge. If the remainder is of more than 60 voters, they will be assigned to a new polling station. This means that there may be a few polling stations with more than 350 voters. Nevertheless, since some voters do not vote, it is rare that more than 350 voters cast a vote in a polling station. Those fine details are of small consequence in our study, so we will not consider them further.

[15] The Directorate is authorized to administer elections under Decree No. 682/2010.

partition into electoral divisions, the assignment just described will be equivalent to any other random assignment of voters to stations.

3.2. Basic problem

The first step in identifying improvements to the current system using the available geographical data is to formulate the basic voter matching problem as described below. Given a specific electoral division, we know:

- The list of voters and their addresses.
- The list of schools available for use as polling places, their addresses and the number of polling stations set up in each one.

We further assume that the assignments of all persons on the voter registry to a polling station in the previous election (i.e., the last place they voted) are also known. A model for voter matching is efficient if it assigns each voter to a school in such a way as to minimize the total distance walked by all voters in the electoral division; for this aspect of the problem, the station assignments within a school are irrelevant. To ensure that voters will not be negatively affected by the implementation of this improved assignment, we incorporate an additional constraint that guarantees that the solution is (weakly) Pareto dominant compared to the current assignment. The constraint requires that no voter may be assigned to a school further from their home location than the one currently assigned. This is in line with the previous literature, which acknowledges that in many applications it is not sufficient to reduce the travel and waiting times for some voters at the expense of additional travel and waiting times for others (Yang et al., 2013, 2014).

3.3. Model extensions

To enrich the analysis and explore other possible improvements to the current matching system, we consider the following variants and extensions:

1. The problem is broadened to include a concept of total voting time, equal to walking time plus waiting (queuing to vote) time.
2. The polling stations are interchangeable, that is, they may be redistributed to other schools provided the total number of stations is maintained.
3. The maximum number of voters per station is an optimization variable rather than just an input. All stations within a school are assumed to have the same capacity.

In the latter two cases, the "capacity" of a school is an output variable assigned by the mathematical problem. In the third case, we highlight that waiting time depends on the number of voters per station.

4. Optimization models

We now set up the model for the basic problem described in Section 3.2 above and then generalize this simple formulation to those described in Section 3.3. As will be explained further in Section 5.3, all of the models rely on voters' residence data grouped by the closest intersection rather than their exact physical location. This is done both for privacy considerations as well as to reduce complexity when solving the problem.

4.1. Basic model

4.1.1. Sets and parameters

Let I be the set of intersections at which voters are grouped and from which the voters are assumed to walk to their assigned polling places. Let S be the set of schools designated as polling places. The following parameters are also defined:

Parameter	Description
$vot_i \in \mathbb{Z}_+,\ i \in I$	Number of voters grouped at intersection i.
$dist_{is} \in \mathbb{R}_+,\ i \in I,\ s \in S$	Distance between intersection i and school s (in km.).
$cap_s \in \mathbb{Z}_+,\ s \in S$	Maximum capacity of school s.
$current_{is} \in \mathbb{Z}_+,\ i \in I,\ s \in S$	Number of voters grouped at intersection i *currently* assigned to school s.

4.1.2. Decision variables

A single set of non-negative integer variables for counting the voters grouped at each intersection who are assigned to the different schools is defined as follows: $x_{is} \in \mathbb{Z}_+,\ i \in I,\ s \in S$. Number of voters grouped at intersection i assigned to school s.

4.1.3. Objective function

The objective function minimizes the total distance walked by all voters:

$$\min \sum_{i \in I} \sum_{s \in S} 2 \cdot dist_{is} \cdot x_{is} .$$

Note that since for obvious reasons voting is assumed to involve walking both to and from the assigned school, the distance a voter actually travels is twice the distance from their residence to their assigned polling station. This double factor does not affect the optimization of the basic model but plays an important role once the model is extended to account for total voting time.

4.1.4. Constraints

1. All voters are assigned to a school:

$$\sum_{s \in S} x_{is} = vot_i \qquad \forall\ i \in I .$$

2. No school's voter capacity is exceeded:

$$\sum_{i \in I} x_{is} \le cap_s \qquad \forall\ s \in S .$$

3. No voter is assigned to a school further from their residence than the current assignment:

$$\sum_{j \in S: dist_{ij} > dist_{is}} (current_{ij} - x_{ij}) \ge 0 \qquad \forall\ i \in I,\ s \in S .$$

4.2. General model with interchangeable polling stations and optimizable polling station capacity

We generalize the basic model by extending it in various dimensions. First, the objective function is expanded to incorporate total voting time and thus includes both travel time to and from the school and waiting time while queuing to vote. Second, we relax constraints limiting the redistribution of polling stations between schools and the maximum number of voters per station.

The notation for the general model is similar to that of the basic formulation. For ease of reference we repeat the definitions of the common sets and parameters below as well as setting out the new ones needed for expressing the model extensions.

4.2.1. Sets and parameters

Set	Description
I	Set of intersections at which voters are grouped.
S	Set of schools designated as polling places.
K	Set of possible polling station capacities (number of voters).
M	Set of possible number of polling stations per school.
Parameter	**Description**
$vot_i \in \mathbb{Z}_+,\ i \in I$	Number of voters grouped at intersection i.
$dist_{is} \in \mathbb{R}_+,\ i \in I,\ s \in S$	Distance between intersection i and school s (in km.).
$current_{is} \in \mathbb{Z}_+,\ i \in I,\ s \in S$	Number of voters grouped at intersection *icurrently* assigned to school s.
$stations_s \in \mathbb{Z}_+,\ s \in S$	Current number of polling stations at school s.
$wait_k \in \mathbb{R}_+,\ k \in K$	Mean waiting time at polling station with a capacity of k voters (in minutes).

4.2.2. Decision variables

In addition to the single set of decision variables in the basic model, the general model incorporates a set for modeling decisions regarding the number of polling stations and their voter capacity and a second set for the resulting total capacity for each school. These variables are as follows:

Variables	Description
$x_{is} \in \mathbb{Z}_+,\ i \in I,\ s \in S$	Number of voters grouped at intersection i assigned to school s.
$cap_s \in \mathbb{Z}_+,\ s \in S$	Number of voters assigned to school s.
$statcap_{skl} \in \{0,1\},\ s \in S,\ k \in K,\ l \in M$	Binary variable indicating whether or not there are l polling stations at school s with k or $k-1$ voters.

Recall that the polling stations at each school must by law have the same number of assigned voters. However, if the total number of voters is not a perfect multiple of the number of stations, the best that can be done is to assign numbers of voters such that any two stations differ by no more than 1 voter. Thus, if the stations have a capacity of k voters, each one will be assigned k or $k-1$ voters. This is captured by the $statcap_{skl}$ variables.

4.2.3. Objective function

The objective function of the general model minimizes the total voting time, defined above as the sum of the walking time to and from the school and the waiting time queuing to vote at the polling station. Thus,

$$\min \sum_{i \in I} \sum_{s \in S} 30 \cdot dist_{is} \cdot x_{is} + \sum_{s \in S} \sum_{k \in K} \sum_{l \in M} k \cdot l \cdot wait_k \cdot statcap_{skl} .$$

The first term is now walking time instead of distance as such, calculated by assuming a walking speed of 4 km/h (i.e., 15 min per km). This translates into multiplying the distance to and from the school by a factor of 30. The second term is the queue waiting time.

4.2.4. Constraints

1. All voters are assigned to a school:

$$\sum_{s \in S} x_{is} = vot_i \qquad \forall\ i \in I\ .$$

2. The school capacity is exactly the number of voters assigned to it:

$$\sum_{i \in I} x_{is} = cap_s \qquad \forall\ s \in S\ .$$

3. No voter is assigned to a school further from their residence than the current assignment (the non-increasing distance restriction):

$$\sum_{j \in S: dist_{ij} > dist_{is}} (current_{ij} - x_{ij}) \geq 0 \qquad \forall\ i \in I,\ s \in S\ .$$

4. The capacity of a school depends on the number of polling stations and their capacity:

$$1 + \sum_{k \in K} \sum_{l \in M} l \cdot (k-1) \cdot statcap_{skl} \leq cap_s \leq \sum_{k \in K} \sum_{l \in M} l \cdot k \cdot statcap_{skl} \qquad \forall\ s \in S\ .$$

5. A certain number of polling stations and their respective voter capacities must be defined for each school:

$$\sum_{k \in K} \sum_{l \in M} statcap_{skl} = 1 \qquad \forall\ s \in S\ .$$

6. The number of polling stations after all relocations must be the same as the number in the current assignment (i.e., before redistribution):

$$\sum_{s \in S} \sum_{k \in K} \sum_{l \in M} l \cdot statcap_{skl} = \sum_{s \in S} stations_s .$$

5. Estimation of model parameters

In this section we describe the methodology for estimating waiting times using a queuing theory model (see, e.g., Kleinrock, 1975), and how the geographical data from the voters list was processed to determine voters' distances from schools designated as polling places.

5.1. Modeling of voter queues

To implement the general model incorporating voter waiting time we must capture certain details of the voting process that lead to the formation of voter queues outside polling stations. In particular, we must determine the relationship between average queue waiting time and polling station capacity, which is a function of the voter arrival and voting rates. The interarrival time is the time that elapses between two consecutive voter arrivals at a polling station queue while service time is the time a voter takes to cast a ballot once it is their turn to leave the queue and enter the voting booth.

To estimate these parameters we collected data during the two rounds of the Argentine midterm elections of 2013: the mandatory primaries (referred to as 'PASO' in Spanish) held on August 11, and the general election that took place on October 27. These elections are well documented in Singer (2014). On both election days we recorded the voting process dynamics at randomly chosen polling stations of a school in the district. The information we registered included the exact times at which voters arrived, entered a voting booth, and then exited the booth, at which point the next voter in the queue can enter.[16]

Not surprisingly, voter arrival rates varied throughout the day. To

[16] We also recorded the gender and (approximate) age of each voter; neither of these traits seem to correlate systematically with arrival and wait times.

control for that phenomenon we grouped the data on arrival and service times into different time slots and analyzed each time slot separately. Analyses of these data suggest that arrivals approximately follow a Poisson process with a different rate for each group. The service times, on the other hand, approximated a log-normal distribution that did not vary throughout the day. For time slots where we did not have enough data to estimate the average arrival rate we extrapolated the data from those time slots that were estimated accurately.

5.2. Estimation of waiting times and queue simulation

Having inferred the characteristics of the voter arrival and service times, we conducted a series of simulations to estimate the voter queue waiting times. Simulation techniques have proved to be useful in previous electoral studies, such as Yang et al. (2009, 2014); Herron and Smith (2016). We built and implemented a simple queue simulator in the Ruby programming language. The voter arrival rates for various periods during the election day were inputted to the simulator, which then generated voter arrivals following a non-homogeneous Poisson process with a constant rate for each period and simulated the service times using a log-normal distribution fitted to the data.

These results were validated by comparing the average simulated waiting times to the real data, that is, the results observed in the field. We then used the simulator to estimate the average voter waiting times as a function of the number of voters assigned to each polling station. Thus, we performed simulations in which the arrival rates were varied in proportion to the station capacities.[17] The formula used to compute the arrival rate λ_k for a given time slot and station with k assigned voters was $\lambda_k = k\lambda_{350}/350$. For each unit of station capacity between 60 and 500 voters we ran 100 simulation iterations and computed the average waiting time for each run. These average waiting times are represented by the circles in Fig. 2. As can be seen, they are highly correlated to an exponential function so we estimated the parameters of the function that best fit the circled points. The resulting function was

$$wait_k = \exp(-2.5897 + 0.0133k) + 1.17 .$$

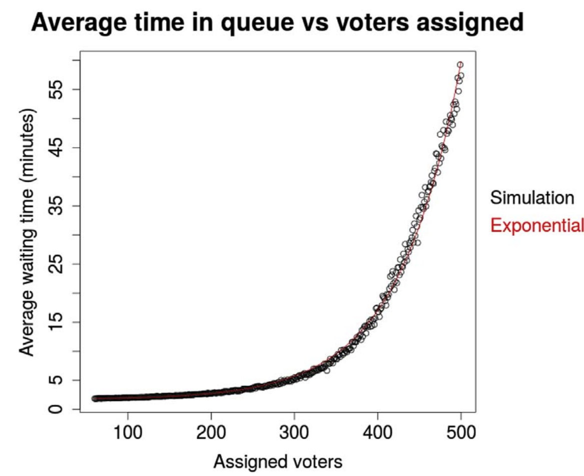

Fig. 2. Each circle represents the average voter waiting time generated by 100 simulations executed for each possible number of assigned voters. The curve is the exponential function that best fits the circled points.

The curve in Fig. 2 represents this function, which illustrates how the waiting time at a polling station increases as the number of voters assigned to the station increases. It can be seen that while the average waiting time increases moderately in the first intervals and up to about 16 min when the number of voters reaches 400, it then grows dramatically to about an hour when the number of voters reaches 500. This reflects the key characteristic of the increasing exponential function in that the higher is the number of voters, the faster is the rate of increase of the waiting time.

5.3. Coding of voter residence data

As noted earlier, the geographical data used to define voters' residences for purposes of calculating their walking distances was derived from the voters list for the 11th administrative district of Buenos Aires. The list contained three data fields for each voter: address, assigned school and polling station number. Unfortunately, this information was neither entirely well ordered nor even wholly accurate. The main defect was the inconsistencies in street name spellings, but the use of a single field for the street name and the house, building and/or apartment number also complicated the automatic processing of the data.[18] To rectify this situation we implemented some rudimentary speech recognition and grammar corrector heuristics that did spare us much manual work, but considerable manual revision was still required to fix cases the heuristics could not handle. If the model were applied at a much larger scale, these problems would present a more serious obstacle.

Once the data were finally clean and well ordered, we used Google's geocoding API (Google, 2016) to map each voter's address to its latitude and longitude. These coordinates were then loaded into a geographic information system (GIS) along with layers that included the streets and intersections of Buenos Aires. The tool used for this process was Quantum GIS (QGIS Development Team, 1999).

Since our solution does not require extreme precision and privacy was a concern, we grouped voters at the intersection nearest to their exact addresses. The data used in our simulations is the number of voters "located" at each intersection, which for our purposes is a sufficiently accurate estimate of the voter residence. We then calculated the matrix of distances from every intersection to every school. In addition to maintaining voter anonymity, these modeling choices significantly reduced the size of the optimization problem we had to solve.

Finally, any intersection that had no grouped voters was discarded as irrelevant. An example of the numbers of voters grouped at each intersection in a single electoral division is shown in Fig. 3.

6. Computational results

The voter matching models were implemented using Pyomo, an open-source optimization modeling language. The GNU Linear Programming Kit (GLPK), also freeware, was used as the solver. The optimization problems were fed with the real-world voter data described above. The results are discussed below.

The expected total voting time under the current official assignments and the assignments generated by the basic model with and without the optional restriction of not increasing distances for any voter (Constraint 3) are shown in Fig. 4. The two basic models produced significant improvements for every electoral division. The total time savings per voter ranged from 5 min (Division 115) to more than 15 min (Division 117), the average for the entire 11th *Comuna* being 10 min and 40 s. Since the average time under the current official

[17] The wait time experienced by a voter is a random variable. The variability of waiting time could potentially matter as much as its average, and create a mean-variance tradeoff. We chose average waiting times as the relevant input in our analysis because it is undoubtedly important. Nevertheless, the choice is without loss of generality in this case: queuing theorists studying M/M/1 queues have established that the random variable that represents *sojourn time* (total time in the queue, including service) is exponentially distributed with parameter $\mu - \lambda$ (i.e., rate of service minus rate of arrivals). For exponential random variables, both the mean and the standard deviation are $1/(\mu - \lambda)$, so there is no tradeoff in this case. For more complicated queues with different distributions, the tradeoffs between mean and variance in wait times should be considered in the analysis.

[18] For example, the street properly spelled as Calle Joaquín V. González was found on the list under numerous different variations such as Joaquin V Gonzalez, Av Joaquin V Gonzalez, J V Gonzalez, J B Gonzalez, J Gonzalez, V Gonzalez, Gonzalez, and Joaquin V Gonzales.

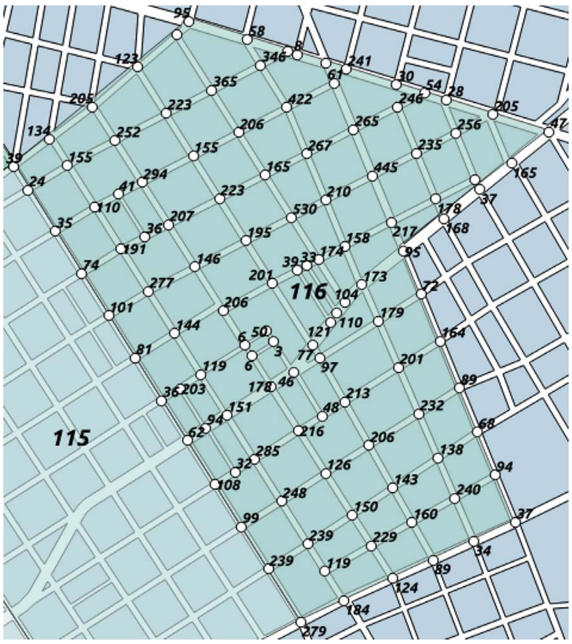

Fig. 3. Number of voters assigned to each intersection in electoral division 116.

assignments is 38 min and 19 s, the savings amount to more than 27%.

Confronting these results with Fig. 1 suggests there may be a correlation between the variation in the improvements among the electoral divisions and the geographical distributions of the schools within them. The smallest improvements are found in divisions where most of the schools are close to each other (such as 113, 114 and especially 115) while the largest savings occurred in divisions where the school distribution is relatively evenly spaced (for example, 116, 117 and 118). This is what we would intuitively expect given that the model attempts to assign voters to schools in such a way that their walking distances are as short as possible. If the designated schools are all close together, it will make little difference which ones voters are assigned to.

The results of the basic model with the non-increasing distance restriction (eliminating model assignments that increase any voter's total voting time beyond that for the current official assignments) are also shown in Fig. 4. As can be seen, with the sole exception of Division 113 the negative impact of the added condition was negligible. We therefore opted to keep the constraint in all model runs.

Turning now to the general model, we implemented three variants denoted Models 2, 3 and 4. Model 2 allowed capacity to be varied from school to school; Model 3 allowed polling stations to be relocated from one school to another; and Model 4, specified in Section 4.2, allowed both modifications. The results of the three variants together with those of the basic model, now denoted Model 1, are shown in Fig. 5.

What stands out in these results is that the performance of Model 2 was almost the same as that of Model 1 while Models 3 and 4 were all but identical. Since the difference within both pairs was that school capacities were allowed to vary, the fact that in neither case did this variation change performance suggests that having flexibility in school capacity affords no advantage, at least as long as the mean number of voters per polling stations remains close to 350. Therefore, minimizing distance in this scenario would seem to be more important than minimizing wait times, which in turn highlights the importance of generating good assignments with respect to the travel time between home locations and polling places as considered under our approach.

Especially noteworthy is the substantial improvement between the first pair (Models 1 and 2) and the second pair (Models 3 and 4), an average reduction of 3 min. The option provided by the latter two formulations to relocate polling stations meant that they could be moved between schools wherever this would improve voting times. How effective was this flexibility can be appreciated by comparing the geographic distributions of the intersection (i.e., voter) assignments generated by Model 4 with those of Model 1. The respective distributions for the two models are shown in Figs. 6 and 7 for electoral divisions 115 (on the left) and 116 (on the right). The intersections are tagged with a number whose final digit matches the final digit of the school (a red star) it was assigned to; for greater readability, tags of intersections assigned to the same school have the same shape and color.

In the Model 1 case (Fig. 6), we see that Division 115 voters assigned to Schools 1 and 3 are concentrated roughly in two parallel vertical bands while those assigned to School 2 are scattered throughout the division. This pattern reflects the bunching of the 3 schools at the "bottom" of the division map.

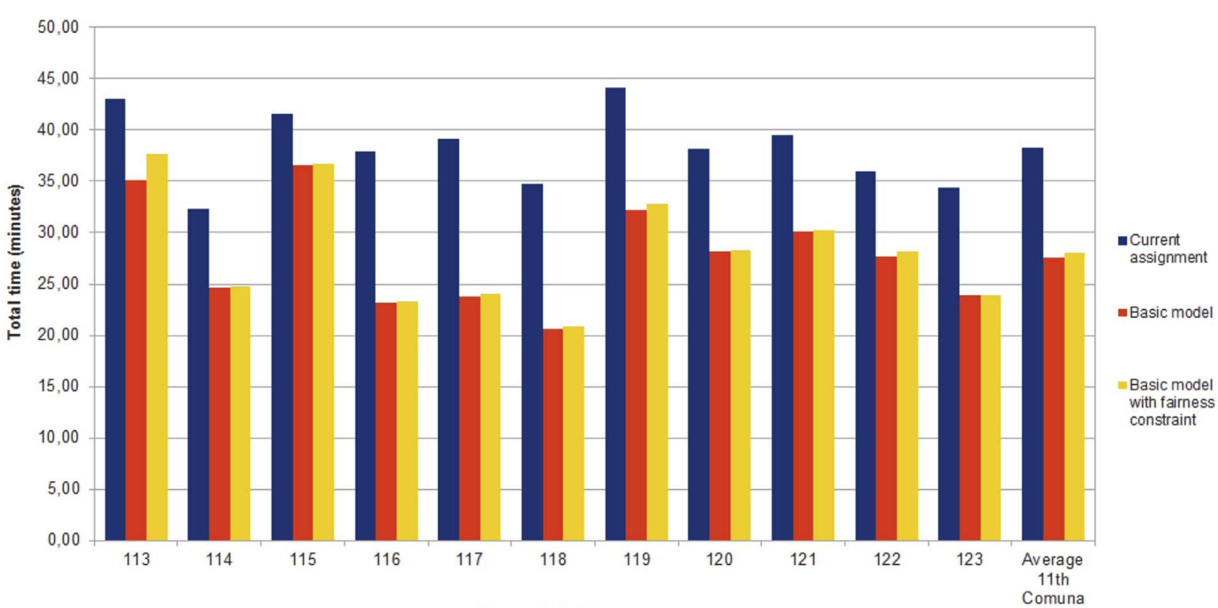

Fig. 4. Total voting time per person under the current official assignments and the basic model assignments (with and without the non-increasing distance restriction).

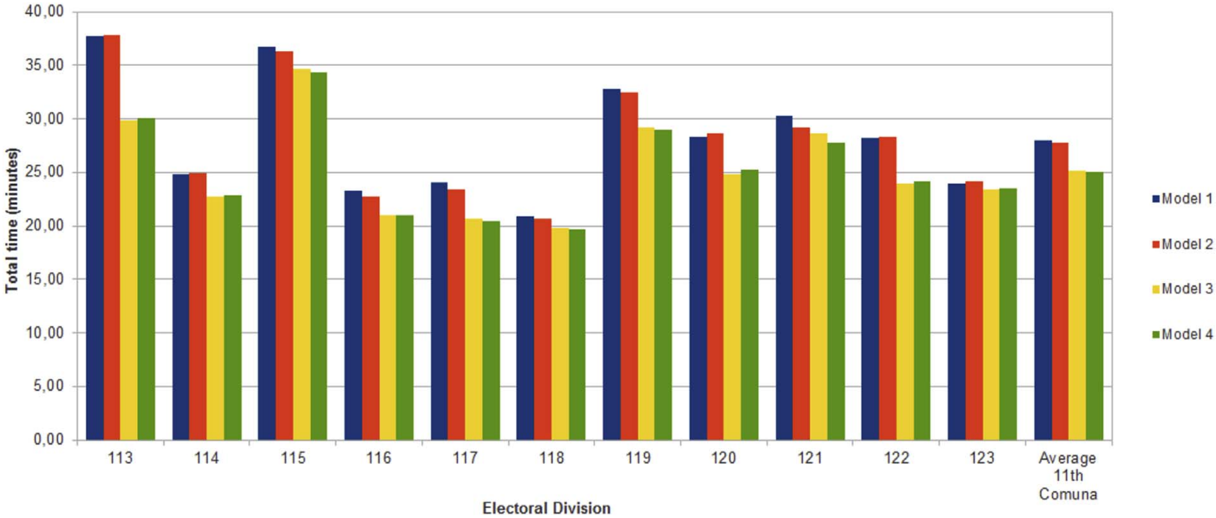

Fig. 5. Total voting time per person under assignments generated by the basic model (Model 1) and the general model variants (Models 2, 3 and 4).

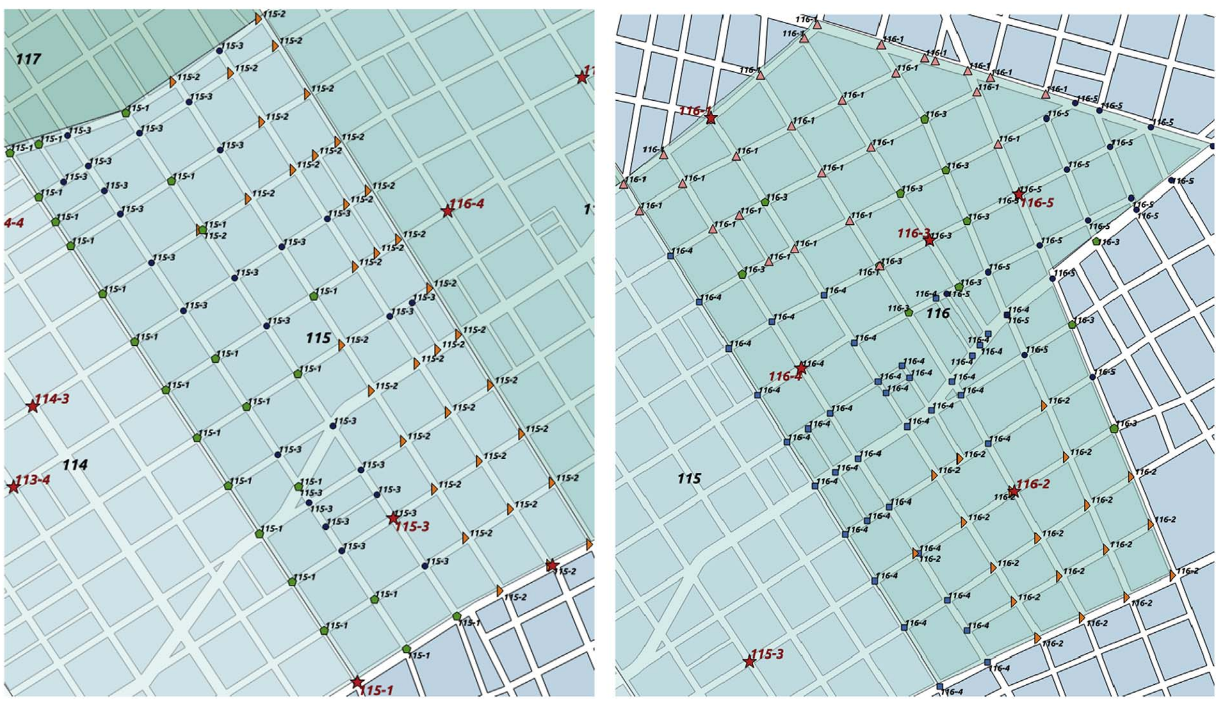

Fig. 6. Model 1 (basic model): distribution of voter assignments by intersection in electoral divisions 115 and 116. Intersections are numbered to match the school their grouped voters are assigned to.

These improvements suggest that the basic model's performance is enhanced by allowing polling stations to be relocated from one school to another. It should be noted, however, that we did not set any limit to the number of stations a school may have. This implies that the results corresponding to Models 3 and 4 are in fact the upper bound of what could be attained.

7. Conclusions

A recent body of literature has produced persuasive evidence that voting costs are not evenly distributed across the electorate, affecting political representation and undermining confidence in democratic governance. For these reasons scholars have turned their attention to issues associated with the administration of elections. Our paper relies on analytical models to quantify the costs of voting associated with travel and wait times faced by voters, and assesses the transparency and efficiency of the voter assignment process. We illustrate our contribution using voter assignment data from an electoral district in the 2013 midterm elections in Argentina. Our models and the computational experiments conducted to test them provide ample evidence that the voter assignment resulting from the current system is inefficient. The implementation of our benchmark model would cut the average voting time under the current official assignment by more than 27%. These models fulfill basic criteria of efficiency, non-increasing distances, and objectivity: they reduce voting time, ensure that no individual voter is made worse off under the optimized assignment, and are based on objective criteria associated with minimizing the sum of travel and wait times.

Our analysis also revealed that relaxing the constraint that imposes an equal number of voters assigned to each polling station, as stipulated under the current election regulations, would be of little benefit since the resulting reductions in voting times were almost the same as those

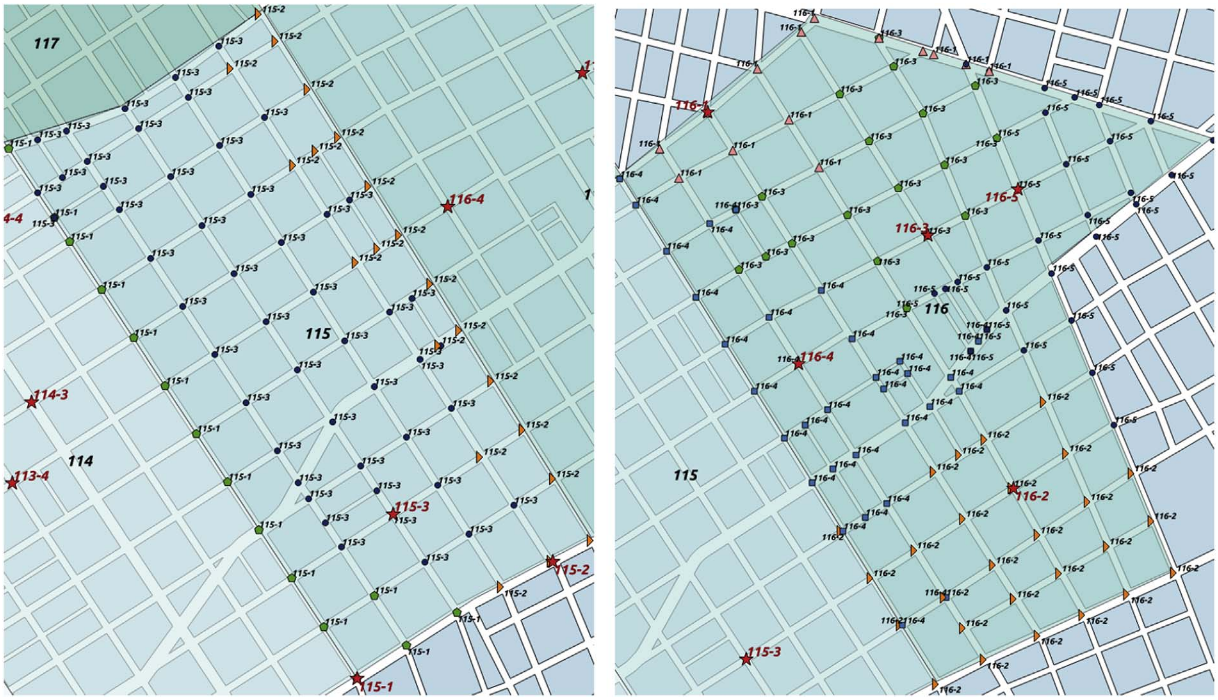

Fig. 7. Model 4 (with station relocation option): distribution of voter assignments by intersection in electoral divisions 115 and 116. Intersections are numbered to match the school their grouped voters are assigned to.

obtained with the unrelaxed version. By contrast, a redistribution of stations among the various polling places within an electoral division may bring significant voting time improvements. Computing how large these reductions might be for a voting division and measuring their impact on turnout and voter satisfaction would necessarily require the collection of additional data. If the benefits prove to be considerable, changes could be implemented promptly since current regulations allow for such changes, unlike modifying the number of voters assigned to each voting station.

It should be noted that the district used for this study is a densely populated area in the City of Buenos Aires. We may safely speculate that the gains would be smaller if the basic voter assignment model were applied to districts in rural areas or lower-density urban areas where the electoral subdivisions are significantly larger. In those cases, increasing the number of polling sites and relocating them across the district could play a more important role.

Comparisons of the different electoral divisions in Buenos Aires suggest that significant improvements could also be obtained if polling places were distributed within the divisions more uniformly. This would require a political decision to redesign the City's electoral subdivisions and would possibly be more difficult to implement. In any case, district redesign is an optimization problem in its own right that we leave for a future investigation.

We would also point out that although the current official method of matching voters to polling stations in alphabetical order is simple and intuitive, these virtues by themselves are of limited value. The implementation of any of the models presented here is eminently feasible and would generate results that are more efficient than the current allocation. The improved assignment we have proposed could be easily implemented under Argentina's current electoral rules, requiring only a minor administrative decision to drop the requirement that the voters in each electoral division be assigned to voting stations in alphabetical order.

The lessons to be drawn from our analysis, using data from a subdivision of an electoral district in Argentina where voting is mandatory, should be placed in their proper perspective. Imposing penalties for abstaining reduces the net costs of participation and creates a sense of obligation that motivates individuals to turn out to vote. But even when voters face no penalties for abstaining, voting is voluntary, or voters solely internalize their self-interest, reducing the costs of casting a vote should increase the expected value of voting, all else being equal. Lowering the costs of participating in elections is likely to encourage individuals to turnout. To the extent that travel and wait times increase the cost of voting, we should expect that a more efficient assignment of voters to polling stations would have a positive effect on turnout irrespective of the electoral rule. And to the extent that higher voting costs are more taxing on groups in the electorate with systematically different preferences, lowering travel and wait times is likely to affect political representation. Optimal assignment of voters to polling stations can reduce the hurdles to political participation, which have been shown to disenfranchise significant groups of voters. Our paper proposes the use of linear programming as a tool for election administration to reduce voting costs associated with the travel and wait times; our analyses suggest that there is ample room for improvement even in settings where voting is mandatory.

In any event, our modeling strategy can be used in many different settings, and could help generate better estimates of the role of geographical and temporal conditions on the electoral experience of voters in Argentina and elsewhere. There is ample evidence in comparative electoral studies that costs of participation vary for different socioeconomic groups of voters, and it has also been shown that these differential costs have important consequences in terms of political representation. Our models show that in theory the estimated efficiency gains in the Argentine case—where voting is mandatory—are high, and would likely be even higher where voting is voluntary. Assessing the impact of varying travel and wait times on electoral outcomes under different electoral rules and systems would, however, require a more rigorous evaluation beyond the scope of this paper.

Finally, we underscore the methodological contribution of our paper. Assigning voters to polling stations is analogous to a matching problem whose formulation and resolution are well studied within the *Operations Research* community. The modeling strategy presented here can be extended to the analysis of other fundamental problems in politics such as the allocation of scarce resources, electoral redistricting, political mobilization, and conflict. We believe this is a promising area of research for political scientists and methodologists.

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