Logistics of Voting in Pandemic: Balancing waiting time with infection risk

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Abstract

The COVID-19 pandemic has caused great disruption of the service sector, which has adapted to implement measures that reduce physical distancing among employees and users; examples include home-office work and setting occupancy restrictions at indoor locations. Within public services, elections pose a unique challenge in which a large percent of the population is summoned in a single day to vote, generating large crowds at the polling stations. The logistical design of the voting process requires balancing between two objectives: on one hand, special measures have to be implemented to maintain physical separation among people to reduce the risk of infection; these sanitary measures also reduce process capacity, thereby increasing voter waiting times. This article studies the logistics and health mitigation measures enacted on the national referendum held in Chile in October 2020, in the midst of the pandemic, focusing on providing recommendations to the Chilean Electoral Service (Servel). Our analysis required a multidisciplinary approach that integrates randomized experiments, process analysis and discrete event simulation to study the effect of capacity constraints on voting centers. Some of these findings were considered in the guidelines that Servel provided to manage capacity and voter arrival patterns at the voting centers.

1 Introduction

The COVID-19 pandemic has impacted daily life in multiple ways. In particular, the service industry has been impacted as a whole due to lockdowns and crowd size limits imposed by health regulations in efforts to mitigate the spread of the pandemic. The service industry has adopted measures to enable operations in a pandemic setting while enforcing health safety guidelines; some of these measures have already been in place for months at supermarkets, shopping malls, and restaurants (for examples, see NY Health Department (2020) and Toronto Public Health (2020)). Election processes, however, present a particular challenge, since by their nature a large percent of the population is summoned at voting centers to exercise their right to vote. Long lines and wait times are a staple of election processes with large participation worldwide. Health safety guidelines that enforce social/physical distancing, reduced contact, and capacity constraints are likely to increase voting times, increasing congestion and depressing turnout. Authorities therefore face additional complexities in balancing the trade-off between risks and waiting times in election processes: it is important to promote a high turnout to validate the democratic process and, at the same time, provide information, infrastructure, and in-place rules to prevent health risks. Failing to do the latter might have a negative impact on the perceived health risks, and in turn, might discourage turnout. Health safety guidelines that are too restrictive could lead to unacceptable waiting times that are known to discourage turnout (e.g. Grant III (1980)).

Such was the challenge faced by the Electoral Service (Servel) of Chile charged with conducting on October 25, 2020 a national referendum on whether the country would begin the process of drafting a new constitution. Servel had to balance on one hand, the enforcement of health measures established by the Ministry of Health to minimize the likelihood of contagion, and on the other, an expeditious process to minimize waiting times promoting participation.

In Chile, all voters, age 18 or older, are automatically registered on a permanent voter registry, that determines the *polling station* where each person casts their vote according to their electoral address. The different polling stations are grouped into voting centers on election day. Therefore, a voter must go to the appropriate voting center to cast her ballot in her assigned polling station; that is, there is no "pooling" of polling stations. Voting centers in Chile are typically located in schools, stadiums and other similar facilities.

The health measures relate mainly to hygiene (sufficient alcohol gel and pens available to each voter before voting, and sanitation of tables, pen, and voting booths) and to keeping a physical distance of at least one meter at all times. In addition there was an increase in the number of voting centers of about 25%, to reduce the number of polling stations assigned to each voting center, facilitating compliance with the new physical distancing recommendations. The implementation of the new sanitary measures imposes two major challenges in the logistics of the voting process. First, the hygiene-related measures lengthen the time required by voters to cast their ballot, which in turn reduces the voter handling capacity of the process, thereby increasing both voter waiting times and overcrowding of people in queues waiting to vote. Second, since the size of closed spaces at voter centers is often limited, queue overcrowding at polling stations is likely to result in violations of physical distancing rules. This study presents an analysis of the impact of these health measures on queue overcrowding at voting centers and polling stations and evaluates a number of proposed strategies for controlling them. While in previous elections overcrowding led to some discomfort for voters, in this instance it might lead to serious danger of contagion.

The main contributions of this study are: (i) determine how voters' weigh the health safety of the voting process vs. the waiting time on their willingness to participate in the election; (ii) to evaluate the impact of the hygiene measures on voting processing times and throughput; (iii) to analyze the effectiveness of establishing maximum capacity levels for voting centers as a means of controlling the number of people overcrowding in polling stations queues, quantifying the trade-off between decreasing overcrowding in polling stations and its consequences on increasing the waiting outside the voting centers; (iv) to identify key drivers of performance of the voting system, in order to prescribe which precautions and incentives should be implemented on election day (e.g., preferential voting hours for elder people, voting centers congestion reporting, free public transport at off-peak hours).

We have carried out this study in collaboration with the Chilean Electoral Service (Servel), which is in charge, among other things, of the operation and logistics of the voting process. This work helped inform decisions of the Chilean Electoral Service (Servel) on how to conduct the referendum regarding maximum capacity at voting centers and measures to flatten the voter arrival rate.

To address this multidimensional problem, we used a combination of statistical analysis, discrete event simulation, and experimental methods from behavioral research. In doing this, we have i) estimated voting times by analyzing TV videos of previous elections, and conducted a small physical simulation, jointly with Servel, reproducing how the voting process will be carried out with these new sanitary measures, ii) simulated the voting process, by developing a discrete event simulation to model the variability on the voters arrival process to polling stations, and the process of ballot casting, and iii) conducted a randomized online experiment to examine revealed preferences of voters regarding overcrowding inside the polling stations and waiting times outside these polling stations.

Given the results of the referendum held on October 25, there will be six elections, including two related to the constitution drafting process, scheduled for the next two years. Therefore, learning from this election process is crucial to design efficient and effectively the upcoming elections, even and hopefully, if the COVID-19 pandemic is over.

In section 2 we describe the relevant literature. In Section 3 we describe the voting process, with the subsequent complexities when hygiene measures are considered. We also describe the methods used to estimate voting times and the results obtained. In Section 4 we describe a novel randomized online experiment to examine people's voting intention dependent upon waiting times outside voting centers and on avoiding crowded polling stations. Section 5 describes the discrete event simulation model, based on the uncertain times of arrival of voters to the voting centers and ballot casting time. With the help of this model, we analyze the results of the simulation, in particular about determining the maximum capacity for voting centers and as a consequence the trade-offs between overcrowding at polling stations and queueing outside the voting centers, the effect of flattening the curve of voter arrivals, and the advantages that could be obtained if the process could manage the polling stations individually. Section 6 provides descriptive statistics from election day and a post-election survey that we conducted to further understand voter's behavior. Finally, Section 7 presents the conclusions and main take-aways from our work.

2 Literature Review

Our work builds on the operations research and service operations management literature studying voter waiting times in elections (Grant III (1980)). Waiting times have been identified as an important factor determining the effective participation of eligible voters in elections (Stewart III Ansolabehere (2015)). Waiting times add inconvenience to the voting process, but also reduces voter confidence that their ballots will be counted. Allen Bernshteyn (2006) studies the allocation of polling stations and voting machines, using historical data from Franklin County, Ohio to propose new allocation methods and evaluate its potential. Their study also suggests that longer waiting times increased the number of the deterred votes in the 2005 election. Pettigrew (2017) shows that waiting times are longer for minority groups relative to white population, suggesting that part of this racial gap is due to the differences in the polling capacity allocated across racial groups. Using smartphone usage data, Chen et al. (2019) provides further evidence that black neighborhoods experience waiting times 26% longer in comparison with predominantly white neighborhoods. Kaaua (2020) studies disparities in waiting time in Florida, and finds difference across political party registrations: a 5% increase in democrat registrants is associated to an increase in waiting time from 40 to 100 minutes. Yang et al. (2009) develop a algorithms that combine optimization and simulation to allocate voting machines to election precincts in order to achieve an equitable waiting times across locations.

As discussed by Highton (2006), identifying the causal effect of voting capacity on voter turnout is challenging because capacity is typically allocated based on projections of turnout, allocating fewer voting machines where turnout is expected to be low. Using a difference-in-difference design, they find that reducing capacity relative to the number of registrants reduced turnout by 3.5% (similar results were obtained by Allen Bernshteyn (2006)). In our setting, the number of voters per voting station is regulated (constant across stations and over time), so we opted to conduct a randomized experiment to estimate voters' sensitivity to waiting.

Edelstein Edelstein (2010) uses simulation to model queues in voting stations and provides some simple guidelines on how to allocate capacity. We follow a similar approach, but focus on providing simple guidelines to control the maximum number of voters in a voting center to prevent overcrowding of people at the voting stations.

The location of polling places has also been identified as an important factor determining voter turnout (Haspel Knotts (2005)). Using geographic discontinuities in the boundaries of voting precincts, Cantoni (2020) estimates that increasing distance to the polling location by 0.245 miles reduces participation in the order of 2-5%. Along this line, Brady McNulty (2011) use the consolidation of voting precincts as a natural experiment to identify the effect of the location of polling places on voter turnout. In the context of voting in a pandemic, deciding the location of voting centers introduces new elements to the decision. For one, it is desirable to reduce the distance from voters to polling stations in order to avoid usage of public transport, which can increase infection spreading. On the other hand, larger establishments with ample space in open-air are more appropriate to install polling stations, in order to reduce infection risk (which is higher indoors); these locations are usually scarce in densely populated cities and may require increasing travel distances. At the time we initiated our study, the location of voting centers had already been decided, so we put our focus on developing models to inform the management of these established locations.

During the COVID-19 pandemic, infection outbreaks have become a major concern in the design and implementation of elections (Landman Splendore (2020)). Cotti et al. (2020) study the presidential primary election held in Wisconsin in April 2020, linking voting patterns with weekly COVID-19 infections in a cross-section of counties to estimate the effect of in-person voting on infection rates. They find that a 10% increase in turnout is associated with an 18.4% in positive test rates. Using data from the same election, Leung et al. (2020) concludes that the election *did not* increase the infection rates, as measured by the instantaneous reproductive number (R_t) and COVID-19 hospitalizations. Cassan Sangnier (2020) analyze the epidemic curve around the French municipal elections in March 15, analyzing the association between turnout and changes in hospitalization rates. They find that the election accounted for 4000 excess hospitalizations by the end of March, but most of these came from locations that were at an advanced stage of the epidemic in terms of infectious load, whereas in areas with low infection levels the election had no effect. For the same town hall election in France, Giommoni Loumeau (2020) found, using a regression discontinuity design, that COVID-19-related restrictions affect voter turnout differently for incumbent (vs. non-incumbent) politicians, and Adam-Troian et al. (2020) found that areas more affected by the pandemic were more likely to support conservative candidates. Therefore, the current pandemic may not only affect health risk perceptions but also voting behavior.

The RAND Corporation conducted a survey with more than 2,000 people in May-June 2020 (Kavanagh et al. (2020)) showing that coronavirus-infection risk perception and trust in the authorities are positively correlated to intention to vote in the U.S. presidential election. However, as this is a correlation analysis, it is not possible to know whether greater intention to vote entails a lower risk perception or whether the latter is what may increase voting intention. Another pre–election survey conducted in Serbia, the Dominican Republic and Nigeria (Buril (2020)) found that respondents were concerned about the influence of the pandemic on their elections. The two most important concerns about people's safety was, in all three countries, that voters would not respect the physical distance in lines and crowded polling stations. We conducted similar studies to measure how health risks and waiting times could potentially affect voting intention in Chile using a randomized experiment to examine causal effects (see Section 4).

3 Description of the Chilean Voting Process

For the October 25, 2020 national referendum, 14,796,197 eligible voters had to cast their ballots in person at one of 44,697 polling stations that were distributed among 2,715 voting centers nationwide. Voting centers are located in schools, municipal stadiums or parks, so that each polling station has enough space to offer privacy during voting and for the lines formed by voters waiting to enter the polling station.

In the Chilean election process, people who are registered to vote are assigned to a specific polling station corresponding to the person's declared residence. Each polling station has up to 350 voters assigned to it. Five people from each polling station are randomly selected as poll workers to operate that polling station on election day. There is no early voting in Chilean elections, so every vote is cast on election day from 8 am to 6 pm. Every voter must cast their vote at their corresponding polling station. After the polling station closing, poll workers tally results by hand. Results are collected at each voting center and communicated to the Electoral Service, which makes the official announcement. Normally, results are communicated to the public usually within 3 hours after polls close.

A polling station is composed of a check in table, two voting booths, and the ballot boxes where votes are collected. Each voter arriving at the polling station goes through a three step voting process:

1. **Check-in**: The voter shows her identification card which is verified with registration book at the station. The voter receives one or more ballots (depending on the election) and a pencil, and signs on the registration book.

2. **Mark ballots**: The voter enters the booth to privately mark her ballots, close and seal them.

3. **Submit ballots**: The voter leaves the booth, puts the ballots inside the respective ballot boxes and recovers her ID.

By voting regulation, there can be at most three voters in these three stages of the process (notice that two voters could be marking ballots in the two booths available), thereby blocking the process leaving other voters lining up in a queue waiting for their turn to vote at the entrance of the polling station.

3.1 Impact of health safety measures on election process

In an effort to prevent an increase in COVID-19 infections due to the referendum, Servel defined a series of measures to ensure physical distancing and observance of sanitation protocols. Specifically, polling stations on election day would stay open for two additional hours, from 8 am until 8 pm, people had to wear face coverings, keep one-meter away from other voters and poll workers, place their ID cards on the table instead of handing them to the poll worker, remove the face covering for three seconds so that poll workers could confirm the voter's identity, and bring their own pen (if not, poll workers would provide one). In addition, poll workers had to clean the voting booth after every voter exited. The effect of such safety measures on the time it takes voters to cast their votes is unclear, making it difficult to predict the resulting congestion at polling stations on the referendum day.

To measure how long the voting process would take with the pandemic-related measures in place, we conducted a mock voting process, with the help of Servel. We compared voting times observed in this mock voting process with voting times observed in past elections from television footage of previous elections (where no sanitation measures were used). The summary statistics of these observations appear in Table 1. The past election footage provided observations of various voters in the different steps of the voting process, only 17 voters were observed in all three steps. The data shows that without sanitation measures the total estimated voting times is about 105 seconds, this is increased to 168 seconds for the referendum with sanitation measures. We used recordings of the 2017 runoff presidential election in Chile for this comparison, which consisted of a single ballot with two options. Since the referendum includes two ballots which have to be marked, folded and sealed, part of the time increase in the Mark ballot step of the voting process should be explained by this.

The mock voting process was conducted ahead of the referendum with the help of Servel that set up and staffed a voting station that functioned with all the health security protocols introduced for the referendum. Each voter received two ballots which were identical to those used in the actual referendum. We recorded the voting process of 21 volunteers and registered the time each voter took in each of the three voting stages: check-in, marking the ballot and submitting the ballot.[1]

	Regular				*With sanitation*			
Step	# obs.	mean	sd	se	# obs.	mean	sd	se
(1) Check-in	44	38.7	15.7	2.4	21	48.0	12.4	2.7
(2) Mark ballot	56	43.8	13.6	1.8	21	86.9	25.2	5.5
(2) Submit ballot	66	22.3	11.1	1.4	21	32.9	14.8	3.2
All steps$^{(*)}$	17	104.9	24.6	6.0	21	167.8	30.8	6.7

Table 1: Observed mean voting times for different setups of the election process. *Regular* corresponds to the 2017 runoff presidential *election* and *with sanitation* to the process under sanitary measures. All times reported in seconds. The reported statistics include the number of observations on each sample (# obs), mean, standard deviation (sd) and the standard error of the mean (se). *(*)* "All steps" includes the sub-sample of voters for which all the steps (1)-(3) were measured.

The data reported in Table 1 can be used to measure the processing capacity for each case. When two booths are used for the step in marking the ballot, the bottleneck in both cases is given by the Check-in step (Recall that the three voting steps can be conducted

[1] To minimize risk, young voters volunteered to conduct this process which may not be representative of the overall voter population. For one, younger voters may be faster to vote. On the other hand, younger voters have less experience and may take longer to vote. Hence, it is unclear what would be the size and sign of this potential bias (if any).

in parallel). In the regular setup, the processing capacity is 90 voters per hour, which is reduced to 72 voters per hour when sanitation measures are implemented.

3.2 Maintaining physical distance among voters

On a regular election day it is common to observe queues at some of the polling stations and these are likely to increase due to the lower processing capacity implied by the sanitation measures. Social distancing rules imposed by the Health Ministry require a minimum distance of one meter among voters, which is typically implemented by marking the required distance on each polling stations' queue area to delimit where voters should stand. This distance requirement determines the maximum queue length at each polling station – defined as the *station queue capacity* – which depends on the layout and room space where polling stations are setup. Figure 1 illustrates the scheme of a voting center and its polling stations (PS 1 through M) with queue capacity of two voters at each station, represented by circles.

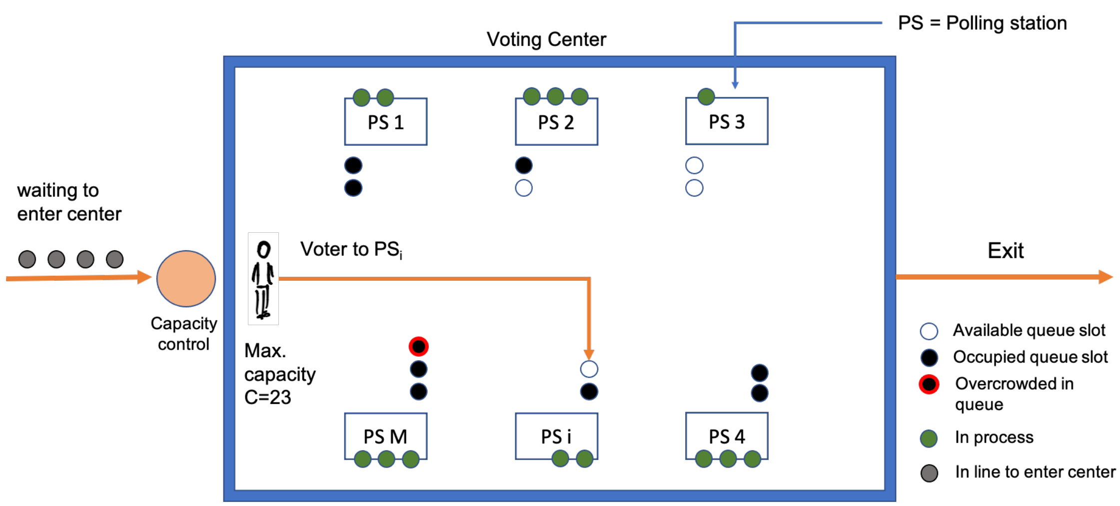

Figure 1: Voting center configuration with a maximum queue length of 2 voters per polling station, maximum 3 voters in process per station and a maximum center capacity of $C = 23$ voters.

Given the stochastic nature of the voting process and the voter arrival process, the number of people waiting at a polling station may become too large and thereby violate the physical distancing protocol. When the number of voters waiting to vote at a station exceeds the station queue capacity, we say that the station is *overcrowded*. In Figure 1 the filled circles indicate voters in queue; polling station M is overcrowded, with the third voter (marked in red) exceeds the station queue capacity.

One option to avoid overcrowding is to block the entrance to each polling station when its maximum capacity is reached. However, this would require real-time monitoring of queues at each polling station, which was infeasible at the time of the referendum. Instead, Servel directed officials in charge to manage the total voting center capacity by keeping count of the total number of voters inside the precinct in *all* the polling stations.

The following trade-off emerges when setting capacity at the voting center. On one hand, reducing capacity would help to lower the number of voters waiting to vote at each station, reducing the probability of overcrowding. However, this would also result in longer lines outside of the voting center waiting to enter the precinct to reach their polling station. In essence, increasing voting center capacity means more voters can directly access their specific polling station, reducing waiting, but queues at polling stations would be longer, increasing infection risk due to overcrowding. While Servel provided guidelines to manage voting center capacity, the specific implementation was left to the officials in charge of each voting center, and therefore not uniform. Small voting centers would use poll workers to communicate to the entrance that queues at different voting stations had spaces, while in larger centers this type of communication would be more difficult.

Defining policies to manage voting center capacity requires balancing waiting times to enter the voting center vs. risk of overcrowding at the polling station. Recommendations on how to balance this trade-off are central to the objectives of our work; in particular, it requires understanding how the perception of risk and long waits influence voter turnout. In the next section, we describe a randomized experiment that seeks to measure how voters decision are affected by waiting times and the compliance to physical distancing measures in the voting process. The findings of this experiment are used later in section 5 to analyze alternative policies to manage capacity at the voting centers.

4 Effect of waiting time and infection risk on voting intention

We conducted a randomized online experiment to examine whether voting intention is affected by people's perception of the risk of being infected at crowded polling stations, and by waiting time. The causal effect of the tradeoff between waiting time and overcrowding on voting intention can be identified by randomly assigning people to different situations. The experiment was conducted during the two weeks before the referendum.

4.1 Methodology

The experiment was conducted using an online adult national representative panel with a sample stratified by gender, country region, socioeconomic status and age, using the information and panel provided by a well-known market research company. Participants (N = 2,060; Mean age: 47.1 years old; 51.2 percent female) were asked to read a vignette describing that on the day of the referendum, they would see images and messages in the media and on social networks with information about their voting center. The rest of the description randomly varied using a 2 (social distancing vs. overcrowding) × 2 (waiting times of 30 minutes vs. 1 hour vs 1 hour and a half vs. 2 hours) between-subject design. In order to vary the waiting time perception, participants read that the messages and images showed a line to enter the voting center. Each participant was told a specific waiting time (in brackets): "You see that there is a line to enter the voting center with a wait of [30 minutes; 1 hour; 1 hour and a half; 2 hours] since Servel determined that only a certain number of people can enter at the same time." To vary participants' risk perception, each participant read whether people next to the polling stations were keeping the recommended social distancing: "Once inside the voting center, the images show some spaces where the polling stations are located. You see that within these spaces there are [many people, making it very difficult; very few people, making it easy] to keep with the recommended social distance."[2] Therefore, all participants read almost exactly the same information, but with different waiting times and/or whether there was overcrowding or social distancing. After reading the vignette, all participants answered the question "how likely is it that you will vote in the upcoming referendum?" (from 1: "I will not vote" to 7: "I will vote"), which is our measure of voting intention. Similar measures of voting behavior have been used in the literature (Gerber Rogers (2009); McGregor (2018)). Participants also answered a question about their trust in the information provided by the authorities, other pandemic-related questions and demographic characteristics. All materials and questions are in the online supplement.

We used the following linear probability model to examine the results of this randomized online experiment:

$$y_i = \beta_0 + \beta_1 T_i + \beta_2 D_i + \beta_3 T_i D_i + \gamma X_i + \varepsilon_i, \tag{1}$$

where y_i is intention to vote of person i, T_i is a continuous measure of waiting time in 30 minutes intervals (based on the assignment of participant i to condition with waiting time 0.5,

[2]Both waiting times and overcrowding levels used realistic scenarios as shown in the media on the referendum day. We also conducted a survey among the same participants after the referendum. Participants reported that actual waiting time varied between none and more than 2 hours, and that some polling stations were almost empty while others were crowded.

1, 1.5 or 2 hours at the voting center) and D_i is a dummy variable indicating whether person i was assigned to a situation with overcrowding ($D_i = 0$) or physical distancing at the polling station ($D_i = 1$). X_i are control variables, which include: gender, socioeconomic status, zone of the country, and group age. These variables were used in the sample collection procedure. ε_i is the error term. Because participants are randomly assigned to different situations, the error term ε_i is orthogonal to the treatment effects D_i and T_i, thereby providing an unbiased estimate of the average treatment effects (Rubin (1974)). As suggested by Ai Norton (2003), we opted to specify (1) as a linear probability model (estimated via ordinary least squares) to facilitate the interpretation of the interaction term, but our results are similar when using a logit model (see the online supplement).

4.2 Results

Table 2 presents results by each experimental condition. We used the probability that the person will vote as a dummy dependent variable, indicating whether the person reported being sure that she or he would vote (vs. not). In the online supplement, we also show results using the likelihood of voting as an ordinal measure – results were consistent. Results show that if there is social distancing, the intention to vote diminishes by 8.7 percent if people have to wait 2 hours ($p = 0.03$, vs. half hour), but when there is overcrowding, waiting time has no sizable effect on the expected turnout ($p = 0.54$). This means that waiting time matters only when social distancing can be respected. For short waiting periods, up to 13.8 percent fewer people would vote if social distancing is not respected ($p < 0.01$).[3]

Consistent with the previous result, Table 3 shows the results using (1) main and interaction effects, waiting time as a continuous measure (in hours) and includes control variables. Results yield a positive effect of complying with social distancing, no sizable main effect of long waiting times unless there is no overcrowding in the voting center. This latter effect is shown through a negative interaction effect, revealing that the risk of maintaining social distancing moderates the effect of waiting time on voting intention. The results suggest that in the condition where the media shows polling stations where physical distancing is respected, each additional 1-hour wait at the voting center reduces the intention to vote by 7 percent ($p = 0.046$ from column 3); in contrast, when physical distancing requirements are not met, the intention to vote is reduced by 19 percent regardless of the waiting time

[3]These turnout rates are higher than actual turnout rates, and they are similar to the ones reported in the most major polls conducted before the referendum (Ipsos - Espacio Público (2020b); Cadem (2020); Bare International (2020)). Even though people may have overestimated their likelihood of voting, which is expected for people who participate in market research panels,we found in a post-referendum survey that most of them actually reported to have voted. For this experiment, the differences across experimental conditions are more important than the absolute numbers.

	0.5 hours	1 hour	1.5 hours	2 hours	N	Δ(2hrs-0.5hrs)	$\chi^2(1)$ p-value
Social distancing	74.3%	77.3%	70.8%	65.6%	1,030	-8.7%	4.6 *0.03*
Overcrowding	60.5%	65.9%	59.4%	63.2%	1,030	2.6%	0.4 *0.54*
N	518	519	509	514			
Δ(over-dist)	-13.8%	-11.4%	-11.4%	-2.4%			
$\chi^2(1)$	11.2	8.3	7.2	0.3			
p-value	*< 0.01*	*< 0.01*	*< 0.01*	*0.56*			

Table 2: Expected turnout as a function of waiting time and social distancing compliance (randomized experimental conditions). Each cell indicates the percentage of people who said that they "will vote" in the upcoming referendum.

($p < 0.01$). This result is robust to different specifications including: (i) when excluding control variables, (ii) using a logit model to estimate (1), and (iii) setting the dependent variable with the entire scale of the declared likelihood of voting, using ordered logit for the estimation (see the online supplement).

	(1)	(2)	(3)
Social distancing (=1, 0 if not)	0.098***	0.189***	0.992***
	(0.020)	(0.050)	(0.221)
	<0.001	*<0.001*	*<0.001*
Waiting time (in hours)	-0.029	0.007	0.096
	(0.018)	(0.026)	(0.114)
	0.111	*0.782*	*0.400*
Social distancing × Waiting time		-0.073*	-0.390*
		(0.037)	(0.162)
		0.046	*0.016*
Controls	Yes	Yes	Yes
Adj. R-squared	0.022	0.023	0.023
N	2060	2060	2060

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 3: Columns (1) and (2) use a dummy dependent variable equal to 1 if the participant reported that she or he would certainly vote, and 0 if not. Column (3) uses the likelihood of voting scale from 1 ("I will not vote") to 7 ("I will vote"). Control variables include gender, socioeconomic status, zone of the country, and group age as used in the sample collection procedure. All columns show robust standard errors between parenthesis and p-values in italic.

Heterogeneous treatment effects. Even though results show that, on average, turnout rates are negatively affected by overcrowding at the polling stations, it may be possible that different population groups react differently to either overcrowding or waiting times. Table 4 shows the results of model (1) with sub-samples grouped by age or socioeconomic status (SES) segments. The results suggest that all group ages reduce the expected turnout rate if there is no social distancing compliance. The online supplement shows, in addition, that older adults seem more sensitive to overcrowding than younger people. It appears that voters younger than 35 years old are the only ones who are negatively affected by waiting time at the voting center, reducing their voting probability by 8 percent for each additional 1-hour wait at the voting center. In terms of the socioeconomic status segment, people with high SES are sensitive to overcrowding but indifferent to waiting, whereas the opposite pattern is observed for the low SES (the online supplement reports all results using the interaction term).

The additional questions in the experiment provide some evidence of the mechanism that may drive these differences across SES. People from low SES reported lower levels of trust in the authorities on issues related to the pandemic ($M = 2.45$, where a larger number means greater levels of trust on a scale of 1 to 5) than people with high SES ($M = 2.74$, $t(2058) = 5.42$, $p < 0.01$). This is in line with recent studies analyzing differences across SES in their response to government mitigation policies during the global pandemic (Bonaccorsi et al. (2020), Allcott et al. (2020), Akbarpour et al. (2020), Weill et al. (2020)) and in Chile (Bennett (2020), Carranza et al. (2020)). This heterogeneity across socioeconomic and age groups represents a challenge in managing capacity at voting centers in terms of maintaining an equal representation: stricter controls to ensure physical distancing at the voting stations also increase waiting time during the voting process, thereby favoring participation of high SES at the expense of low SES and younger voters.

5 Designing Capacity Controls for Voting Centers

As we have shown in the previous analysis, voter turnout is affected by waiting times and the sanitary conditions at the polling stations. In this section, we examine different scenarios to determine the optimum capacity of each voting center in order to reduce waiting time and risk of contagion, which in turn would increase turnout. On this regard, each voting center has a predetermined number of polling stations, and its physical configuration (size, roofed or open-air, space layout, etc.) determines the maximum number of voters at each polling station (in the process of casting their ballot and waiting in line to vote) without violating the physical distancing rules. A direct way of enforcing the rules would be to supervise the number of voters at each polling station, blocking further access whenever

	(1) 18-35 y.o	(2) 36-64 y.o	(3) Over 65 y.o	(4) High SES	(5) Low SES
Social distancing (=1, 0 if not)	0.092**	0.069^{+}	0.135***	0.152***	0.043
	(0.034)	(0.035)	(0.037)	(0.028)	(0.030)
	0.008	*0.052*	*<0.001*	*<0.001*	*0.144*
Waiting time (in hours)	-0.078*	-0.007	-0.002	-0.005	-0.053*
	(0.031)	(0.032)	(0.032)	(0.025)	(0.027)
	0.013	*0.820*	*0.946*	*0.834*	*0.045*
Controls	Yes	Yes	Yes	Yes	Yes
Adj. R-squared	0.028	0.015	0.032	0.032	0.015
N	727	722	611	1043	1017

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4: Main effects of waiting time and social distancing compliance on voting intention, from linear probability models, for different population groups. All columns show robust standard errors between parenthesis and p-values in italic.

the number reaches the station's capacity. This, however, would require the installation of monitoring technology capable of reporting the actual number of voters at any given station in real time, which was not available at this election. Thus, the option that was implemented in this referendum was to control the aggregate capacity at the voting center, temporarily blocking the entry of new arriving voters into the center, whenever the center reached its capacity. This is similar to the process used by some supermarkets and other retail businesses to monitor overcrowding in indoor facilities. Implementation of such a strategy is viable with any relatively simple method for maintaining a precise count of the number of entries and exits at the center's access points.

There are two main disadvantages when managing the aggregate center's capacity, compared to managing each polling station separately: (i) since voters' arrivals at polling stations are random, when a station has an occupancy level below its capacity, it produces some slack that might lead to other stations exceed their capacity, while still complying with the center's maximum capacity; and (ii) when the center capacity is set low, it is more likely that some stations will be empty while voters assigned to these stations are waiting outside because the center is at full capacity. This produces starving at the polling stations, which reduces throughput and thereby increases waiting time to enter the center. These inefficiencies would be avoided if overcrowding control could be exercised, in real time, at the polling station level.

We conducted two complementary analysis to measure the trade-off between throughput loss and voter overcrowding when capacity controls are set at the voting center. The first approach uses a stylized model to illustrate this trade-off, while the second approach provides a more detailed and rigorous analysis based on discrete-event simulation. The latter can be used to set voting center's capacity to meet a pre-specified service level standard.

5.1 Trade-off between waiting time and voter overcrowding

We begin by formulating a stylized model of a voting center composed by a set of M identical polling stations, each with the same queue capacity L_q and at most L_p voters simultaneously in process of casting the ballot, and thus, each station can hold a maximum of $L = L_q + L_p$ voters maintaining the required physical distance. In addition, we assume that the arrival rate is identical across stations.

We are interested in analyzing the throughput of the system when the center's capacity, denoted by C, has been reached and the access to the voting center is blocked. Specifically, we consider the following rule to set the voting center capacity:

$$C(\alpha) = \alpha \times L \times M, \tag{2}$$

where the value α, which is fixed, determines the capacity control policy. A value of $\alpha = 1$ sets the center's capacity as the sum of the station's capacities, whereas values of $\alpha < 1$ are more conservative and aim to reduce the probability of exceeding a station's capacity. Since the arrival rate is the same for all stations, each of these $C(\alpha)$ voters inside the center is equally likely to belong to any polling station. Hence, when the center has reached its capacity, the number of voters at any station can be represented by a random variable X that follows a Binomial distribution with parameters $(p = 1/M, C(\alpha))$.

We recall that, by design, a polling station allows a maximum of L_p voters in process at the same time, distributed among the three steps described in Section 3. When $X = 0$, the polling station could process some of the voters that are waiting to enter the center. We say that a station is *starving* when a new arriving customer to the station would immediately start the check-in process. When $X \geq L_p$, any additional voter arriving to the station must wait to be served and, therefore, the station is not starving (because at least one of the X voters is waiting in queue). When $0 < X < L_p$, the station would be starving if none of the X voters is on the check-in step. As an approximation, we consider that a station is starving with probability one when $X \leq L_p - 1$. and therefore loses throughput. We define *throughput loss* as the probability that a voting station is starving. For the remaining analysis, we set $L_p = 3$, based on the design used in previous elections (in Section 5.2 we simulate alternative designs with $L_p = 1$).

When $X > L$ the station is exceeding its capacity and therefore is overcrowded, making

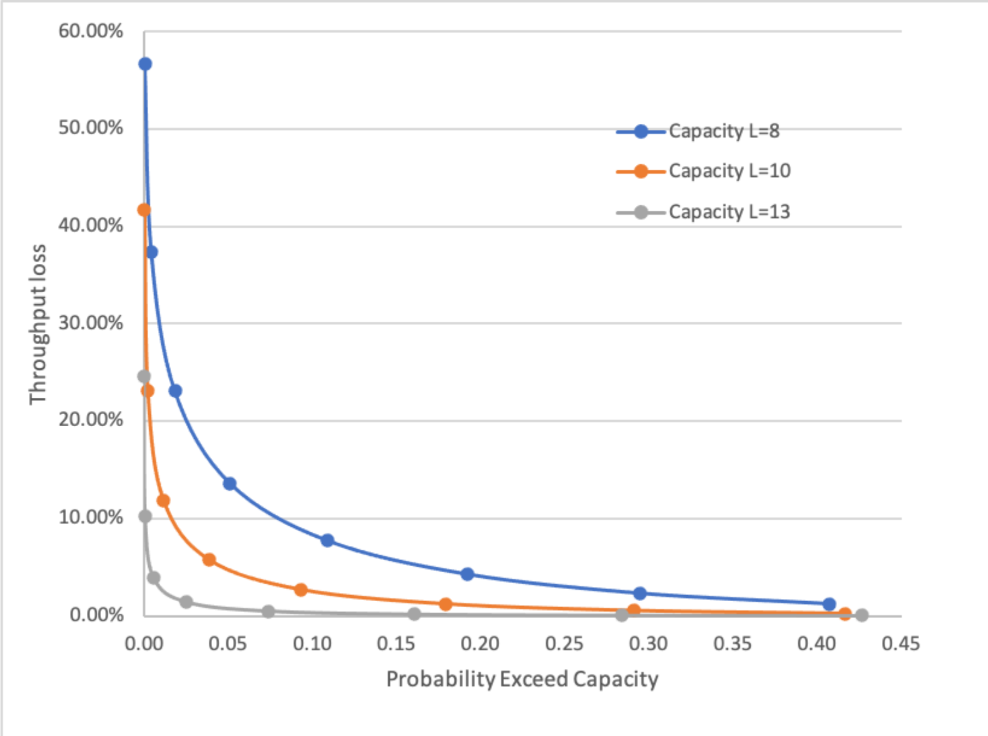

Figure 2: Trade-off between probability of exceeding station capacity (L) versus throughput losses generated by starving at the polling station. The number of stations is $M = 20$; each dot corresponds to a different value of α increasing from from 0.3 to 1.0 from left to right.

it difficult to maintain physical distancing.[4] Figure 2 shows the probability of exceeding station's capacity versus the throughput loss due to starving, for different levels of station capacity L and adjusting the parameter α that controls the centers capacity, $C(\alpha)$. Each curve corresponds to a different value of L, and each point in the curve corresponds to a different value of $\alpha \in \{0.3, 0.4, \ldots, 1.0\}$, ordered from left to right (higher values of α imply higher probability of exceeding the polling station capacity, L). The figure is generated fixing $M = 20$, which is the median number of polling stations among the voting centers in Chile, but the effect is robust when changing the number of polling stations. Given the capacity rule established by equation (2), the expected number of voters on each station is $E(X) = \alpha L$, which is independent of M. The variance $Var(X) = \alpha L(1 - (1/M))$ is insensitive to M for values above 10 (which correspond to the smaller voting centers). Using the Normal approximation for the Binomial distribution, we note that the distribution of X does not change significantly with M.

Figure 2 shows that reducing the overcrowding probability (exceeding polling station

[4]Note that the station's queue may also be exceeding its queue capacity L_q when $L_q + 1 \leq X \leq L$, and thus, $X > L$ is a sufficient but not necessary condition for overcrowding.

capacity) has a significant cost. During high peak loads in which the voting center reaches capacity, reducing overcrowding probability from 0.2 to 0.05 in a polling station with capacity $L = 8$ increases the throughput loss threefold (from 4% to 13.5%).

Interestingly, about a month before the referendum (see Servel (2020)), Servel recommended to set the maximum voting center capacity equal to the number of voting stations multiplied by 10 (the $10M$ rule). This policy does not account for heterogeneity among polling stations across voting centers: some centers are located in schools with small rooms with low L, where overcrowding would be significant, whereas other centers are located in stadiums with ample capacity at the polling stations. In a school with station capacity $L = 10$, the $10M$ rule is equivalent to set $\alpha = 1$, at which the probability of exceeding the station capacity is more than 0.4. Overall, setting center capacity equal to the sum of the station's capacities (i.e. $\alpha = 1$) leads to significant overcrowding, with more than 40% of the time exceeding the maximum capacity for all the capacity values of L shown in the Figure, making the policy insufficient to control physical distancing at the station when the center is running at capacity. Note that at the larger polling stations with capacity $L = 13$, the probability of overcrowding can be kept below 5% without sacrificing much throughput (the loss is less than 1.5%). This phenomenon highlights the importance of considering the characteristics of the polling stations when setting the voting center capacity.

Our simplified analytical model reveals that there is an important trade–off to be considered when setting appropriate capacity levels at the voting centers. Increasing this capacity can lead to significant overcrowding at the polling station when the center's capacity is reached. On the other hand, setting low capacity at the voting center can lead to throughput losses induced by starving, which increases waiting time in periods where demand exceeds capacity. To study this trade-off in further detail, we implemented a discrete event stochastic simulation, incorporating realistic arrival patterns and variability in service times, which is described in the next subsection.

5.2 Analysis using discrete-event simulation

In this subsection we develop a discrete-event simulation model that captures the major sources of uncertainty in the arrival process of voters and casting the ballots, which is used to predict waiting times to enter voting centers and overcrowding in the polling stations.

The input consists of the voting center characteristics, arrival process structure, and the ballot casting times. For the voting center, we define M as the number of polling stations, and $C(\alpha)$ as the voting center maximum capacity. For the polling station, define L as the total maximum capacity at the station, equal to the queue capacity, L_q plus the maximum number of voters in process, L_p. Recall that, due to the random times at the several steps of the ballot casting process, it is possible to have the station queue exceeding L_q even though the total capacity at the polling station L has not been reached (later in this section we provide details on how the processing times at each step are simulated). Additional implementation details are described in the online supplement (Appendix 8).

We used the following metrics to evaluate the performance of the system: (1) fraction of voters waiting more than W minutes outside the voting center, with $W \in \{0, 15, 30, 45, 60, 90, 120\}$, and (2) duration of overcrowding period, when the station's queue occupancy exceeds L_q voters, and thus, there is a violation of the maximum station's queue capacity, with $L_q \in \{4, 7, 10, 13\}$.

5.2.1 Parameters and simulation scenarios

In this subsection we describe the parameters used for the simulations and the scenarios considered regarding voters turn out and arrival processes over the voting period.

- Ballot casting times: we use the following procedure to generate processing times at each of the three steps of the voting process. Let $Z = Z_1 + Z_2 + Z_3$ denote the total processing time, including the three steps. We model Z as a shifted log-normal (May et al. (2000)), in which $Z - \delta$ follows a log-normal distribution. Given the sample of 21 observations $\{Z^{(i)}\}_{i=1\ldots 21}$ from the mock election process (see Table 1), the shift parameter δ is set by the minimum value (120 seconds in our sample). Using the shifted values $Z^{(i)} - \delta$, we calculated the parameters (μ, σ^2) of the log-normal using the method of moments.[5] Based on this, total voting time is generated as $120 + logNormal(\mu = 3.7, \sigma^2 = 0.35)$ which is then allocated to each voting step proportionally using the mean times at each step reported in Table 1: 30%, 50% and 20%.

- Voting center size: we consider centers with $M \in \{10, 20, 30\}$ polling stations. For the 2017 runoff election, 15% (50%, 92%) of the voting centers had up to 10 (20, 30) polling stations. In all 79% of voting centers had between 10 and 30 polling stations.

- Polling station capacity: we consider polling stations of sizes $L \in \{4, 7, 10, 13\}$.

- Voters in process: the operation of the polling station considers a maximum of 3 voters in process, considering the three steps simultaneously (check-in, mark ballot, and

[5] The method of moments estimator is given by $\mu = \log\left(\frac{\mathrm{E}[X]^2}{\sqrt{\mathrm{Var}[X]+\mathrm{E}[X]^2}}\right)$ and $\sigma^2 = \log\left(\frac{\mathrm{Var}[X]}{\mathrm{E}[X]^2} + 1\right)$, with $X = Z - \delta$ and using $E(X) = 167.8 - \delta$ and $Var(X) = 30.8^2$ reported in Table 1.

submit ballot).

The following simulation scenarios were considered:

- Control policy: we evaluated different levels of capacity control for the center, $C(\alpha) = \alpha \cdot L \cdot M$, with $\alpha \in \{0.3, 1.2\}$. We analyzed the performance of these simplified control policies because they are relatively easy to communicate to the voting center managers and implement in practice.

- Voters arrival process: we consider two scenarios for the arrivals of voters to the voting stations. The first scenario was based on Servel's estimation that nearly 50% of voters would arrive in a two-hour range close to lunchtime, from 12-2pm.[6] The remaining 50% of voters were evenly distributed in the off-peak hours of the voting day. Due to the pandemic, voters are likely to adapt their voting time, as suggested by the experiment presented in Section 4. In our experiment, we also asked participants at what time they would be more likely to cast their ballots, considering that people older than 60 have priority to vote between 2 pm and 5 pm (see the online supplement). Based on this information, we also considered a second scenario using these responses. These scenarios are reported in Table 5. Although the voting centers where opened until 8pm, very few voters reported to vote after 6pm, therefore, we set 6pm as the closing time (data from the election confirms that few voters attended after 6pm, see Section 6 for details.

- Turnout: each polling station was assigned 350 registered voters, simulating different levels of turnout. The 2017 election had a turnout of 50%, which we used as a base scenario. Some polls prior to the referendum estimated turnouts above 70% (Bare International (Bare International (2020)) and Ipsos (Ipsos - Espacio Público (2020a)) predicted voter turnout of 83% and 78%, respectively). Hence, for the simulations, we considered turnout values of 50%, 60%, and 70%.

- Design of polling stations: we consider three plausible configurations for the polling stations. (i) Two voting booths and a maximum of three voters in the voting process simultaneously, subject to at most one voter at the check–in step. This is the standard configuration proposed by Servel. (ii) Same as (i), but with only one voting booth, for cases where the physical space of voting center is small (this in fact was observed

[6] We asked about the data that supported this assumption, but it seems that it was based on anecdotal evidence. However, we also reviewed several videos from the previous election in Chile, and in fact a peak of voters arrived between 12pm and 2pm.

	8- 11am	11am -12pm	12 - 2pm	2 - 4pm	4 - 5pm	5 - 6 pm
Scenario 1	10.0%	15.0%	50.0%	10.0%	10.0%	5.0%
Scenario 2	34.0%	15.3%	16.7%	24.8%	4.6%	4.6%

Table 5: Alternative scenarios for the distribution of arrivals to the voting center during the election day.

in several voting centers during the referendum). (iii) One voting booth and at most one voter in process. Although Servel assigns 5 poll workers per station, some stations may operate with as few as 3 workers. With 3 workers, it becomes difficult to maintain hygiene measures for more than one voter simultaneously, which motivated simulating this design.

5.2.2 Results

We focus our simulation analysis on quantifying the trade-off between overcrowding at the polling stations and waiting times. Figure 3 provides an illustration of this trade-off for a hypothetical voting center with 20 polling stations, 2 booths, a maximum of 3 voters in process and arrival scenario 1, with 50% of the arrivals concentrated between 12 and 2pm (see Table 5). Each curve in the graph corresponds to a different value of the station's queue capacity, L_q, set at 4 and 7 voters. Each point at the curves corresponds to a different value of α for the capacity control policy specified in equation (2) (the text labels at each point show the corresponding value of α).

As expected, lower values of α reduce overcrowding at the polling stations, reducing the minutes in which the station's queue capacity L_q is overrun, but at the same time increases the waiting time outside the voting center. For example, with a station queue capacity of $L_q = 7$, setting $\alpha = 0.3$ — the voting center capacity is $C(0.3) = 0.3 \times 20 \times (7+3) = 60$ voters — reduces the overcrowding periods to less than 5 minutes in total (throughout election day), but around 20% of the voters wait more than 30 minutes. For a lower queue capacity of $L_q = 4$, setting the capacity control at $C(\alpha = 0.3) = 0.3 \times 20 \times (4+3) = 42$ achieves similar periods of overcrowding, but doubles the number of voters waiting more than 30 minutes.

In what follows, we present the simulation results for different demand scenarios (turnout and arrival times) and polling station designs. Figures 4, 5 and 6 correspond to different design of the polling stations. Each figure presents multiple graph corresponding to different demand scenarios. The horizontal axis shows the corresponding value of α used on each simulation run. For each value of alpha, multiple simulations were run using different values of the number of stations ($M \in \{10, 20, 30\}$) and polling station queue capacity ($L_q \in$

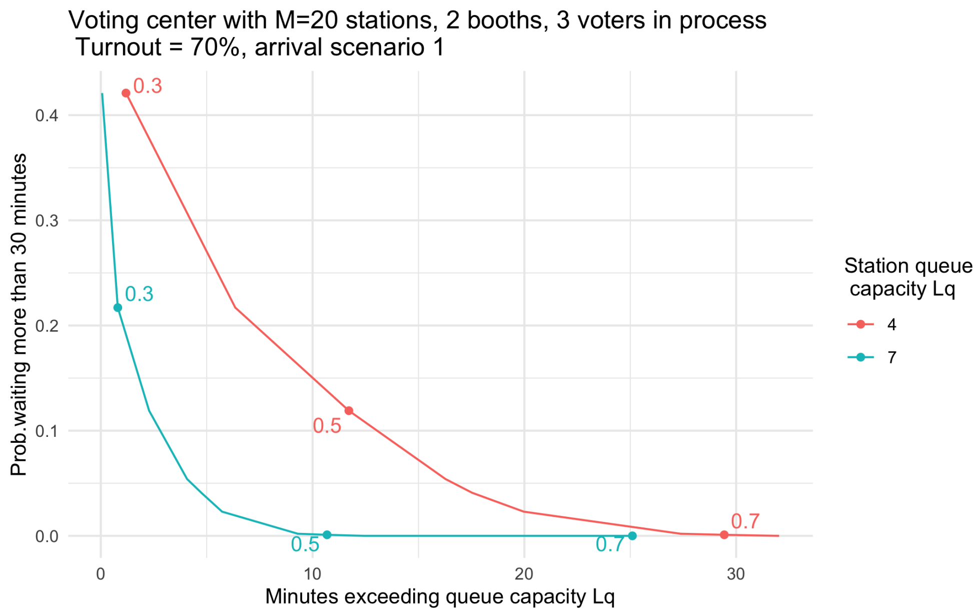

Figure 3: Trade-off between queue length violation time and waiting time outside the voting center, for $M = 20$ and a maximum queue length $L_q = 4$ and $L_q = 7$. Each point on the curve corresponds to a different value of α determining the voting center capacity $C(\alpha) = \alpha \times M \times (L_q + 3)$. Selected points on each curve indicate the corresponding value of α.

$\{4, 7, 10, 13\}$). Two performance measures are shown with different curves in the graphs: (i) the probability of waiting more than 30 minutes is presented in blue and the units are shown in the left vertical axis; (ii) the minutes exceeding the queue length L_q — a measure of overcrowding — is shown in green and corresponds to the right vertical axis. The plotted line corresponds to the median value of the corresponding performance measure across all the simulated scenarios for a given α, and the vertical bars shows the range (maximum and minimum values). In what follows, we present a more detailed explanation on how to interpret each graph, as we discuss the results obtained across the multiple scenarios analyzed.

Case 1 (Figure 4): 2 voting booths, 3 voters in process.

The 3 graphs presented in Figure 4 correspond to 3 alternative turnout levels with arrivals patterns given by Scenario 1 (Table 5), with 50% of voters arriving at peak-time between 12 and 2pm. We observe that when turnout is 50%, both waiting times and overcrowding is minimal, and capacity controls are rarely used. But at higher levels of turnout, we observe that low capacity levels can generate substantial waiting time for voters: setting α at 0.3 or lower leads to more than 25% of voters waiting more than 30 minutes, and as high as 40% of voters when turnout is high (70%). In contrast, when voting center capacity is set equal to the sum of the polling station capacities (i.e. $\alpha = 1$), waiting time drops significantly but

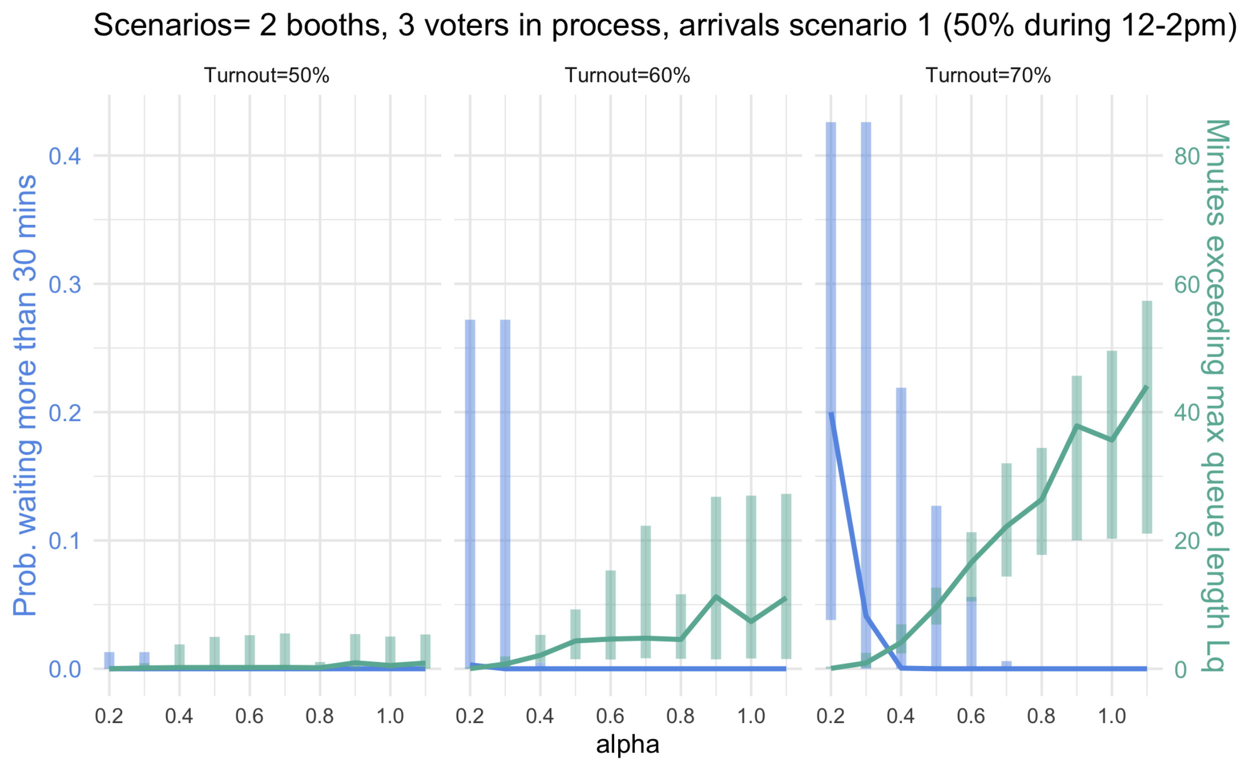

Figure 4: Simulation analysis considering a polling station design with 2 voting booths and maximum of 3 voters in process. Each graph corresponds to a different turnout and the arrival pattern corresponds to scenario 1 from Table 5. Lines indicate the median and the color bars the range (max and min) across the simulations with different values of M (number of stations) and L_q (queue station capacity).

overcrowding appears. With a turnout of 70%, the median across all simulated scenarios yields around 40 minutes of overcrowding during election day, with worst case scenario of 50 minutes.

For a turnout of 60%, a capacity control with $\alpha = 0.4$ is reasonable, since it essentially eliminates waiting time, keeping low levels of overcrowding at the polling stations. When turnout is 70%, controlling overcrowding requires some voters to wait: with a capacity control of $\alpha = 0.6$, overcrowding is limited to 10 minutes, with a worst case of 12% of voters waiting more than 30 minutes.

With the arrival pattern of scenario 2 (not shown in the figure), where arrivals are more homogeneously distributed over time, there is essentially no waiting outside the voting center and no overcrowding at the polling stations. Hence, in this scenario, capacity controls are not needed.

Case 2 (Figure 5): 1 voting booth, 3 voters in process.

With a single booth, the step of marking the ballot becomes the bottleneck of the voting process (see Table 1), lowering process capacity and thereby deteriorating system performance. Figure 5 shows the performance measures for the two arrival patterns (separated into different rows) and turnout levels (separated into columns). Note that the vertical-axis is re-scaled across rows, to facilitate visualization. First, we observe that the arrival pattern of scenario 2 (bottom graphs) — with fewer voters in peak-periods — leads to systematically better performance metrics relative to scenario 1. These improvements notwithstanding, capacity controls are needed to prevent overcrowding when turnout increases to 70%. For $\alpha = 1$, queue station capacity is exceeded during 20 minutes in the worst-case escenario. Setting $\alpha = 0.4$ reduces overcrowding to 10 minutes in the worst case, without adding waiting time. To further reduce overcrowding, it is necessary to increase the fraction of voters waiting more than 30 minutes to up to 25% (with $\alpha \leq 0.3$).

System performance deteriorates significantly when arrivals follow scenario 1. Under this situation, capacity controls are needed even when turnout is 50%, and preventing overcrowding has a significant cost in terms of waiting time. Periods of overcrowding may be extended for more than an hour when $\alpha \geq 1$ and turnout is above 60%. Capacity controls with $\alpha \in [0.4, 0.6]$ are effective in containing overcrowding below 60 minutes, but waiting times become substantial when turnout is higher than 50%, with 20%-40% of the voters waiting more than 30 minutes. With a turnout of 50%, a capacity control with $\alpha = 0.4$ is sufficient to prevent overcrowding with minimum costs in terms of waiting time.

Case 3 (Figure 6): 1 voting booth, 1 voter in process, arrival scenarios 1 and 2. Restricting the stations to process one voter at a time drastically reduces the capacity of the system down to approximately 20 voters per hour. Figure 6 reveals that when arrivals are concentrated between 12-2pm (scenario 1), waiting times are substantial at all turnout levels, with more than half of voters waiting more than 30 minutes, regardless of the level of capacity control used. For example, for scenario 1 of voter arrival process, there is a probability higher than 50% of waiting outside, independently of the capacity of the voting center, number of tables or physical space for waiting at each polling station. Preventing overcrowding for more than an hour requires strict capacity controls with $\alpha \leq 0.4$, which implies that more than 70% of the voters will have to wait more than 30 minutes (considering all of the worst case scenarios that were analyzed).

5.2.3 Summary of the simulation results and recommendations.

Based on our simulation analysis, we draw several conclusions for the design and management of the voting process:

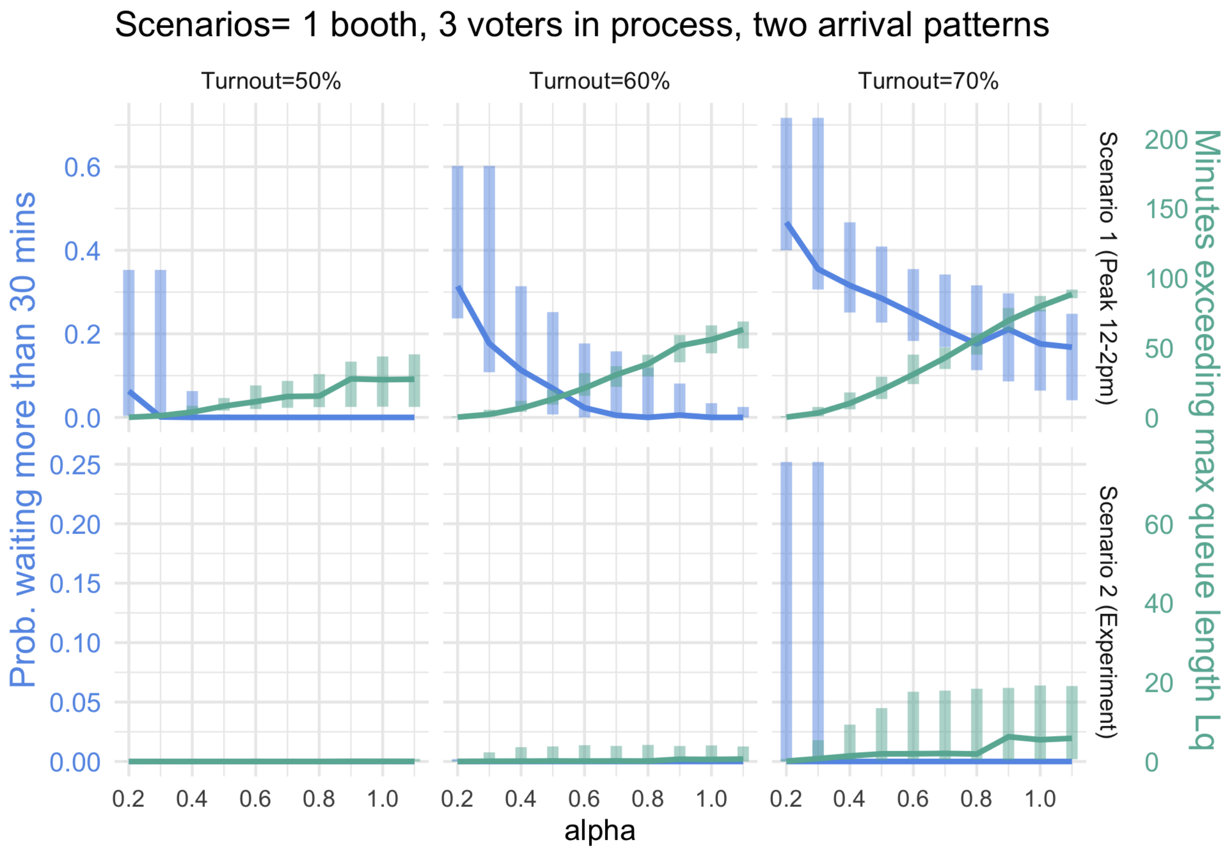

Figure 5: Simulation analysis considering a polling station design with 2 booths and maximum of 3 voters in process. Each column corresponds to a different turnout. Arrivals patterns include scenario 1 (top) and 2 (bottom) described in Table 5, re-scaling the vertical axis to facilitate visualization. Lines indicate the median and the color bars the range (max and min) across the simulations with different values of M (number of stations) and L_q (queue station capacity).

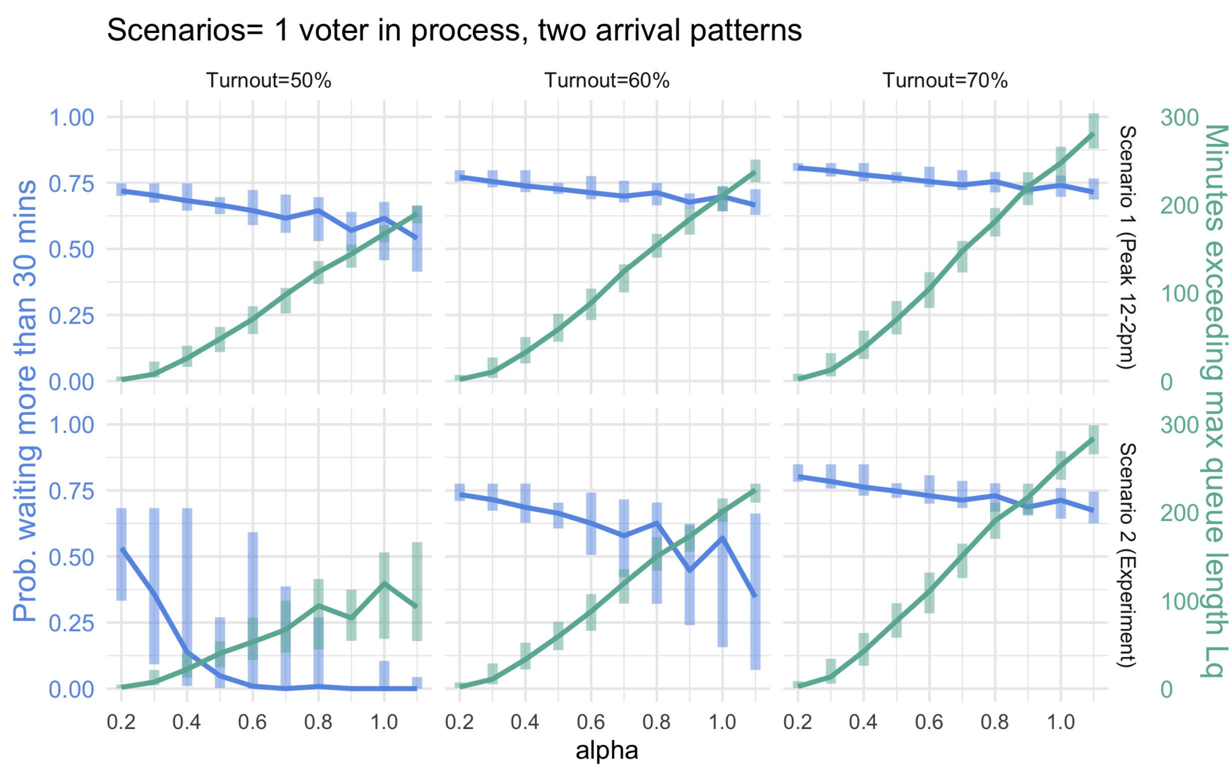

Figure 6: Simulation analysis considering a polling station design which allows at most one voter in process. Arrivals patterns include scenario 1 (top) and 2 (bottom) described in 5. Lines indicate the median and the color bars the range (max and min) across the simulations with different values of M (number of stations) and L_q (queue station capacity).

- Flattening arrival patterns — that is, avoiding a high concentration of arrivals during peak-hours — has a first order effect in reducing overcrowding and waiting times. To highlight this critical issue, we held several press interviews to communicate the importance of arriving early to vote and avoid the period before lunch time as in previous elections (La Tercera (2020)).

- Turnout and arrival patterns vary across voting centers, and therefore, some locations will exhibit higher turnouts with concentrated arrivals during peak hours. In this situation, capacity controls are needed in order to prevent overcrowding. The simple capacity rule given by equation (2), which accounts for the number of polling stations and their capacity, appears to be effective to maintain appropriate levels of occupancy at the stations. When the voting station operates with two booths and up to three voters in process, setting capacities with α in the range $[0.4, 0.6]$ provides a reasonable balance to prevent overcrowding without dramatically increasing voter waiting times.

- In terms of process design, it seems feasible to operate the polling station with a single booth, to the extent that this layout helps to increase queue capacity at the stations. With this design, complying with physical distancing requires the use of capacity controls with $\alpha \leq 0.5$ (with overcrowding periods shorter than 30 minutes), which may induce significant waiting when turnout is high (70%) and arrivals are concentrated in peak hours (scenario 1 in Table 5).

- It is important to ensure that enough poll workers are available so polling stations can operate at full capacity. When a polling station processes one voter at-a-time, capacity is reduced substantially and waiting times explode in every scenario analyzed.

We presented these recommendations to Servel before the election. Based on these recommendations, Servel provided more flexibility to voting centers so they could manage the capacity controls taking into account the characteristics of the polling stations and voter arrival patterns.

6 Discussion based on the aftermath of the Referendum

The analysis described in previous sections was conducted before the referendum, with the purpose of providing guidance to Servel to design an efficient and safe election under these challenging new sanitary conditions. In this section, we describe some additional analysis that were conducted *during* and *after* the election in order to learn possible aspects of the design and implementation that could be improved for the forthcoming elections during the pandemic.

6.1 Descriptive statistics and anecdotal evidence on the election day

The referendum took place on October 25, which resulted in a clear majority (78%) approving the change to a new constitution. The overall perception was that the voting process was safe in terms of sanitary conditions, although some voting centers experienced long lines and waiting times to enter the center.

We collected data on voter turnout for each voting center (Servel (2020)). Across all voting centers in the country, the median turnout was 50%, which is substantially below the 70% projected by several survey studies. In the Chilean capital, Santiago, the median turnout across centers was 57%, but with some variation: the first and last deciles were 46% and 68%, respectively. Hence, the scenarios considered in our simulations covered reasonably well the different conditions experienced at the voting centers.

During referendum day, we conducted an online survey among voters, where respondents provided information through an in-site survey at their voting center. The survey was distributed through social networks, and although not representative, it is useful to provide insights about voters experience on election day. The survey requested voters to enter the times at which they: (i) arrived to the voting center; (ii) entered the voting center; (iii) joined the station queue; (iv) started voting; and (v) finished voting. Using this information, we calculated the arrival patterns and some statistics regarding waiting times to enter the center and at their polling station, which are reported in Table 6. Arrival patterns are aligned to scenario 2 reported in Table 5 (which was obtained in the pre-election experiment). In general, waiting time to enter the center was relatively low, although some voters experienced waiting times higher than 50 minutes between 10am and 2pm. Waiting times at polling stations were low; anecdotal evidence from voters indicate that, in many cases, there was no queue at the polling station. The overall perception is that voting centers where conservative at managing capacity, keeping polling stations with low occupancy to prioritize compliance with social distancing.

Comments by voters indicated some variations in the layout and process design of the polling station. Some of them operated with two booths and maximum of 3 voters in-process. Others reported polling stations with a single booth. Finally, several voters indicated that at their polling station there were periods of time in which only one voter would be processed at-

Time block	Arrivals	med(W center)	p90(W center)	med(W station)	p90(W station)
8–10am	0.16	4	35	2	17
10am–12pm	0.33	10	50	2	10
12–2pm	0.19	10	60	3	12
2–5pm	0.16	0	10	1	5
5–8pm	0.05	0	4	1	5

Table 6: Summary statistics of the online survey conducted on election day during the voting process. Waiting times (W) at the voting center or polling station are reported in minutes. Statistics include the median (med) and the 90 percentile (p90), which are calculated for each time block in which the respondents voted. Arrivals indicate the fraction of respondents that voted within each time block.

a-time, even when there were voters waiting at the station. This anecdotal evidence provides support that conditions varied across locations, which may in part explain the variation in waiting times across respondents of the survey.

6.2 Post-election survey

Our on-site survey provides information on arrival and waiting times, but as mentioned before, it is based on a non representative sample. Thus, to complement this analysis, we conducted a survey, two days after the referendum, with the same participants from our randomized online experiment from Section 4 . Ninety percent of the participants in the experiment answered this new survey, where whose intention to vote was consistent with their reported behavior: 94% of those who said that they would vote for sure actually went to vote on the referendum day. Importantly, risk of contagion pre-referendum reduced whether people actually went to vote. For example, there was an 87% turnout among those who reported that it would be safe to vote on the referendum day. In contrast, turnout was 62% among those who reported that risk of contagion was high. Therefore, the perception of contagion risk was actually correlated to voting behavior, consistent with previous surveys (Kavanagh et al. (2020)).

During the election, thanks to the measures adopted, most voter respondents (77.2%) reported that inside their voting centers people strictly respected the physical distance of at least one meter, and only 1.3% reported that physical distance was not respected at all (the rest was in between). In addition, only 3.2% of voter respondents had to wait more than one hour in line to enter their voting center, 6.4% more than 30 minutes and less than an hour, and the rest less than 30 minutes (i.e., roughly 10% waited more than 30 minutes). The turnout was larger for high SES areas of the city. However, and contrary to what we expected, we found that people from the low SES experienced longer waits before entering the voting centers (12% waited more than 30 minutes) than those in the high SES (8% waited more than 30 minutes). We note, nonetheless, that people from low SES were also more likely to concentrate the time when they went to vote in a few hours (34% voted only between 10 am and 12 pm) compared to people from high SES who spread out their time to vote over the day. In spite of their higher turnout, this may have decreased the waiting time.

The responses to the survey indicate that long waiting times and crowded centers did affect voters decisions on whether to vote and the time at which they voted. In fact, the main reason given by respondents who did not go to vote or tried to vote but returned to their homes was to avoid the risk of contagion (28.2%). In addition, 7.7% of these respondents did not vote or returned to their homes because of long lines outside the voting center. The two main reasons for choosing a voting time were (i) *"I thought there would be fewer people at that time, making it easier to maintain a physical distance of 1 meter between people"* (31.0%) and (ii) *"I thought that at that time the wait would be short"* (22.4%). Therefore, using timely communication to help people change their voting time (via the media or other source) can certainly help to avoid overcrowding and long waiting times.

In light of these results, priority should be given to the implementation of incentives for managing the timing of voter arrivals at polling stations. Possible actions could include:

- Establish preferential arrival times for different age groups.
- Organize transport to polling stations that is segmented by geographic area and free of charge at certain hours.
- Adopt measures to ensure polling stations open at the posted start time in order to reduce uncertainty for voters willing to vote early.
- Provide real-time information on voter congestion at each polling station, allowing voters to time their arrivals for periods when congestion is low.

7 Conclusions

In this paper we investigate measures to mitigate congestion in a nationwide referendum that was held in Chile during the pandemic. In particular we evaluate the impact of capacity constraints on voting centers in waiting times and overcrowding, and investigate voter's attitudes toward risk and wait times. Elections are a particularly challenging service process that involves a massive participation of voters on one specific day, which leads to congestion, and where having long wait times can depress turnout. This trade-off is only made more poignant with the pandemic, where health safety measures increase estimated voting times, and congestion and long waits can also increase the risk of contagion.

To analyze the trade-off between overcrowding and waiting times, we use a discrete event simulator to represent the voting process. Given that the pandemic has changed fundamental parameters of the voting process, our work also conducted both a study of voting times in an election with health safety measures and a study to estimate the effect of risk of contagion on the arrival times of voters. We compare voting times from a mock voting process with health safety measures to observed voting times in video footage of past elections. We show that voting times increase by 60% (from an estimate of 1:45 minutes for a regular election to 2:48 minutes for the referendum) and that even the past election observed voting times exceeded common knowledge estimates. Our randomized experiment showed that voters are less likely to vote if there is a perception of overcrowding and that in the absence of overcrowding voters are sensitive to waiting times (7% less likely to vote for each additional hour of wait). This implies that it is necessary to enforce capacity constraints at voting centers to reduce overcrowding but, in addition, waiting times must be kept in check.

The discrete event simulation modeled different configurations of voting centers under different turnout and arrival distribution scenarios with homogeneous polling stations. The results contrast the amount of time there was overcrowding at polling stations versus the likelihood that voters waited more than 30 minutes to enter the voting center for different maximum capacity constraints. The maximum capacity at a voting center with M homogeneous polling stations, each with L allowed queue length is defined by αML, with values of α between 0.3 to 1.2. Our simulations show that both voter turnout and the pattern of the arrival rate are critical for the existence of overcrowding at voting centers. These results also show that an α value between 0.4 to 0.6 is able to balance the time that overcrowding occurs at polling stations with the probability of waiting more than 30 minutes by voters, see Figures 4, 5 and 6. We validated our findings with an online informal survey during the referendum and a follow up post-election survey for the same participants of the randomized online experiment. These results show that, while most voters did not experience overcrowding (77.2%) and had reasonable waiting times (3.2% waited more than one hour), there were voters that did experience congestion, numbers that were in line with an election that had a 51% turnout rate. These results are in line with our simulations for that turnout scenario and the fact that 28.2% did not vote to avoid the risk of contagion shows the importance of using a maximum capacity that helps reduce the perception of overcrowding.

This work was developed at the request of and in collaboration with the Chilean Electoral Service (Servel). Our work helped clarify the total voting time with health safety measures and which steps of the voting process could be changed to reduce voting time. Our simulation analysis to find the right equilibrium between overcrowding and waiting time outside the voting center suggested that the capacity originally defined by Servel would lead to severe overcrowding. Our work informed recommendations by Servel to voting centers to define a maximum capacity that depended on each voting center's conditions and generated Servel's communication strategies that stressed bringing your own pen to vote (to reduce voting time), distributed voter arrival throughout the day, and suggested that the elderly vote at off-peak hours.

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8 Implementation of the discrete event simulation

This appendix provides further details of the implementation of the discrete event simulation of the voting centers and their polling stations under alternative designs and demand characteristics.

We describe the arrival of voters as a Poisson process with arrival rate equal to $\lambda_i(t)$ for station i, with $i = 1, \ldots, M$, and $t \in [0, T]$, where T is the simulation time where polling stations are open.

At the initialization step, the simulation clock is set to $t = 0$ with an empty system. We use the following notation: $N(i, j)$ is the number of voters in step $j \in \{1, 2, 3\}$ of station $i = 1 \ldots M$, q_i is the number of voters in queue at station i, $N_C = \sum_i q_i + \sum_{i,j} N(i, j)$ is the total number of voters in the center and Q is the queue length of voters waiting outside to enter the voting center.

Each arriving voter has a pre-assigned polling station. Upon arrival, the counter Q is updated and the entity waits at the first *Hold* process. If the amount of voters inside the center, N_C, is below the maximum capacity threshold, $C(\alpha)$, then the voter proceeds to her designated station updating Q and N_C.

At the polling station arrival, there is another *Hold* process. Here, the simulation keeps track of the queue using the counter q_i and $N(i, j)$ for the voters in progress within station i, and step j $\forall i = 1, \ldots, M$ and $j \in \{1, 2, 3\}$. Once the voter is allowed to proceed, q_i and $N(i, j)$ are updated and the random processing times at each step (Z_1, Z_2, Z_3) are generated.

Once the voter finishes a step in the voting process, the $N(i, j)$ counters are updated and all relevant information for the voter is recorded. When the voter finishes voting, she exits the system and the number of voters in the center, N_C, is updated.

Figures 7 and 8 show schematic flowcharts of the discrete-event simulation at the voting center and polling station, respectively. This discrete–event simulation model was implemented in Python 3.8 using the SimPy package. We run 100 replicas of a voting day, and obtained a coefficient of variation smaller than 0.01 for all metrics under study.

9 List of variables collected for the randomized experiment

- Date.
- Gender.
- Age.

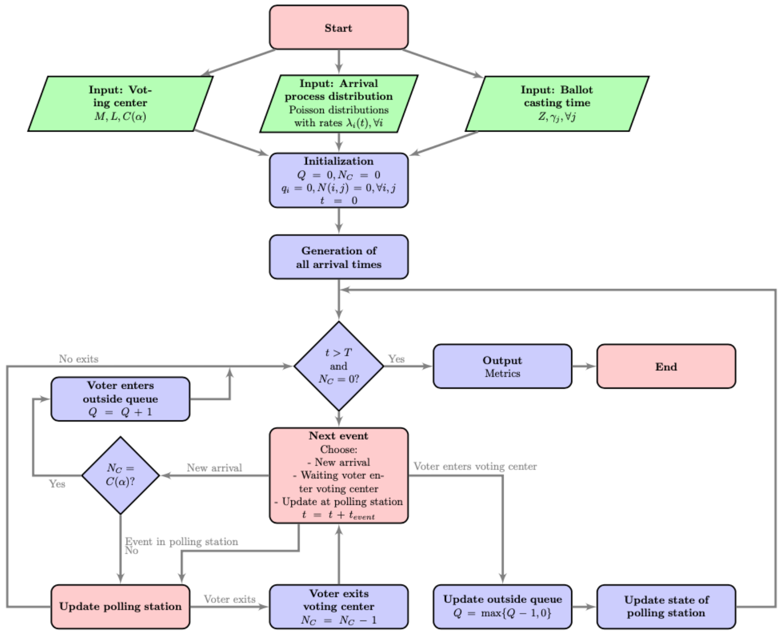

Figure 7: Discrete Event Simulation Flowchart at the Voting Center

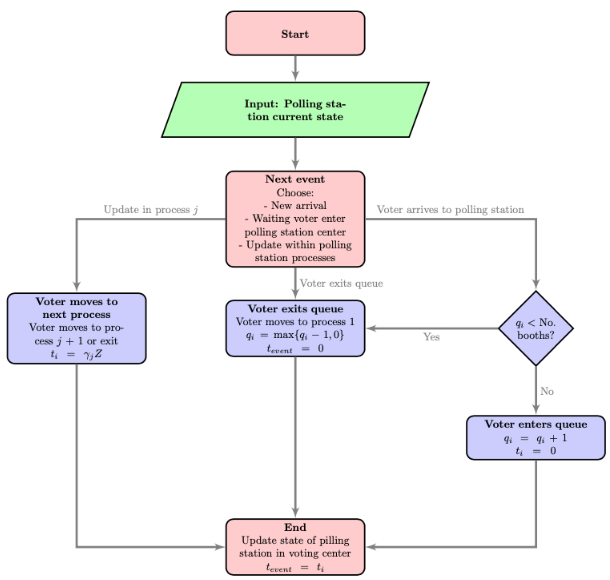

Figure 8: Discrete Event Simulation Flowchart at the Polling Station

- Socioeconomic status (SES).
- Country region.
- Experimental conditions (in brackets and translated from Spanish):

> "Imagine that it is October, 25th, referendum day, and the voting centers are open for voting. You are seeing images and messages on the social networks and media about people who are voting at the same voting center that you were assigned.
>
> You see that there is a line to enter the voting center with a wait of [30 minutes; 1 hour; 1 hour and a half; 2 hours] since Servel determined that only a certain number of people can enter at the same time.
>
> Once inside the voting center, the images show some spaces where the polling stations are located. You see that within these spaces there are [many people, making it very difficult; very few people, making it easy] to keep with the recommended social distance."

- "Considering the previous scenario, how likely is it that you will vote in the upcoming referendum? (from 1: "I will not vote" to 7: "I will vote")."
- "At what time are you more likely to go to vote?." (options in two-hours blocks).
- Questions about the time participants would go to vote if different measures are applied: (a) People older than 60 have priority and cannot be designated as poll workers; (b) Free public transport between 8 am and 12 pm; (c) People older than 60 have priority to vote between 2 pm and 5 pm; (d) People younger than 30 have priority to vote between 6 pm and 8 pm; (e) At the time the person expected to go vote he/she finds out that the waiting time is 1.5 hours and people are respecting the social distance; and (f) At the time the person expected to go to vote he/she finds there is no wait to vote but the social distance is not being respected.
- "How risky are the following activities in the context of Coronavirus" (1: Extremely safe to 4: Extremely unsafe)[7]: (a) Grocery shopping; (b) Attending gatherings of more than 50 people; (c) Eating takeout from restaurants; (d) Playing on playgrounds; (e) Eating or drinking in a place that provides table service and has implemented social

[7] Statements from a survey conducted by the USC Dornsife Center for Economic and Social Research (2020).

distancing guidelines; (f) Taking a walk, hiking or exercising; Overall score: $M = 2.97$ ($SD = 0.46$).

- "From 1 to 7 (1: "Very unlikely" to 7: "Very likely"), how likely do you think it is that you will become infected with COVID-19 in the upcoming referendum?" $M = 3.74$, ($SD = 1.73$).

- "How much do you agree or disagree with the following statements" (1: "Totally disagree" to 5: "Totally agree"): (a) "I trust in the information provided by the authorities about the upcoming referendum" ($M = 2.88$, $SD = 1.11$), (b) "I trust in the information provided by the authorities about the Coronavirus ($M = 2.60$, $SD = 1.21$), (c) "I trust that people will respect self-care measures to avoid becoming infected with Coronavirus" ($M = 2.40$, $SD = 1.12$).

- "Do you know the municipality where you are registered to vote?" Yes: 97.66% (then, they indicated their municipality from a list).

- "Did you vote in the previous presidential election?" 77.86% Yes, 20.29% No, 1.84% Do not remember.

- Occupation (32.14% Full- or part-time paid employment; 15.78% Self-employed; 9.32% Unemployed; 4.56% Looking for work; 5.73 A homemaker; 8.74% Student; 20.92% Retired; 2.82 % Other).

- Monthly personal income before the current pandemic (in Chilean Pesos) (21.58% $0 to $250,000; 32.23% $250,000 to $500,000; 25.68% $500,000 to $1,000,000; 10.40% $1,000,000 to $1,500,000; 4.93% $1,500,000 to $2,000,000; 3.27% $2,000,000 to $3,000,000; 1.12% $3,000,000 to $4,000,000; 0.78% More than $4,000,000).

- "Did the current pandemic affect your monthly income?" (34.03% "No, it has not changed"; 28.11% "Yes, it is much worse"; 33.98% "Yes, it is a little worse"; 0.78% "Yes, it is much better"; 3.11% "Yes, it is a little better").

- Educational background (2.19% High school - incomplete; 19.18% High school diploma; 21.23% College - incomplete; 50.25% Undergraduate college degree (BS, BA); 7.16% Graduate degree (MA, PhD, MBA, etc.)).

- "Do you have any comment about this study? (e.g., a question was hard to answer or hard to follow)" [open-ended].

10 Additional analyses for the randomized experiment

	0.5 hours	1 hour	1.5 hours	2 hours	N	$\Delta\%_{2hrs/0.5hrs}$	$\lvert t\rvert$ *p*-value
Social distancing	6.19	6.23	5.86	5.82	1,030	-6.3%	2.26 *0.02*
Overcrowding	5.35	5.73	5.46	5.57	1,030	4.0%	1.10 *0.27*
N	518	519	509	514			
$\Delta\%_{overcrowding/distancing}$	-13.5%	-8.1%	-6.8%	-4.3%			
$\lvert t\rvert$	4.66	2.99	2.11	1.35			
p-value	*<0.01*	*<0.01*	*0.04*	*0.18*			

Table B1: Reported likelihood of voting (from 1: "I will not vote" to 7: "I will vote") as a function of waiting time and social distancing compliance (randomized experimental conditions).

	(1)	(2)	(3)
Social distancing (=1, 0 if not)	0.183***	0.914***	0.987***
	(0.050)	(0.238)	(0.232)
	<0.001	*<0.001*	*<0.001*
Waiting time (in hours)	0.003	0.032	0.056
	(0.026)	(0.116)	(0.112)
	0.906	*0.784*	*0.615*
Social distancing × Waiting time	-0.068+	-0.364*	-0.392*
	(0.037)	(0.171)	(0.166)
	0.063	*0.034*	*0.018*
Controls	No	Yes	Yes
Adj./Pseudo R-squared	0.012	0.023	0.013
N	2060	2060	2060

+ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B2: Robustness of results (1) excluding control variables, (2) logit model instead of a linear probability model, and (3) an ordered logit model with the likelihood of voting scale as dependent variable. All columns show robust standard errors between parenthesis and p-values in italic.

	(1) 18-35 y.o	(2) 36-64 y.o	(3) over 65 y.o	(4) High SES	(5) Low SES
Social distancing (=1, 0 if not)	0.353*	0.555***	0.629***	0.723***	0.296*
	(0.145)	(0.157)	(0.172)	(0.125)	(0.130)
	0.015	*<0.001*	*<0.001*	*<0.001*	*0.023*
Waiting time (in hours)	-0.225^{+}	-0.108	0.054	-0.006	-0.190
	(0.131)	(0.142)	(0.149)	(0.112)	(0.117)
	0.086	*0.446*	*0.716*	*0.959*	*0.105*
Controls	Yes	Yes	Yes	Yes	Yes
Adj. R-squared	0.007	0.023	0.039	0.032	0.015
N	727	722	611	1043	1017

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B3: Main effects of waiting time and social distancing compliance on voting intention, for different population group, using the likelihood of voting scale (from 1: "I will not vote" to 7: "I will vote") as dependent variable. All columns show robust standard errors between parenthesis and p-values in italic.

	(1) 18-35 y.o	(2) 36-64 y.o	(3) over 65 y.o	(4) High SES	(5) Low SES
Social distancing (=1, 0 if not)	0.988**	0.962*	1.115**	1.099***	0.903**
	(0.358)	(0.384)	(0.409)	(0.304)	(0.321)
	0.006	*0.013*	*0.007*	*<0.001*	*0.005*
Waiting time (in hours)	0.022	0.055	0.251	0.143	0.054
	(0.183)	(0.200)	(0.212)	(0.156)	(0.166)
	0.906	*0.782*	*0.237*	*0.36*	*0.746*
Social distancing × Waiting time	-0.508^{+}	-0.328	-0.389	-0.304	-0.483*
	(0.262)	(0.283)	(0.297)	(0.224)	(0.233)
	0.053	*0.247*	*0.191*	*0.174*	*0.039*
Controls	Yes	Yes	Yes	Yes	Yes
Adj. R-squared	0.010	0.023	0.040	0.033	0.019
N	727	722	611	1043	1017

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B4: Main and interaction effects, for different population group, using the likelihood of voting scale (from 1: "I will not vote" to 7: "I will vote") as dependent variable. All columns show robust standard errors between parenthesis and p-values in italic.

	(1) 18-35 y.o	(2) 36-64 y.o	(3) over 65 y.o	(4) High SES	(5) Low SES
Social distancing (=1, 0 if not)	0.189*	0.189*	0.210*	0.226**	0.150*
	(0.085)	(0.086)	(0.089)	(0.069)	(0.073)
	0.028	*0.029*	*0.018*	*<0.001*	*0.04*
Waiting time (in hours)	-0.040	0.041	0.028	0.024	-0.010
	(0.044)	(0.045)	(0.046)	(0.035)	(0.038)
	0.359	*0.361*	*0.539*	*0.496*	*0.8*
Social distancing × Waiting time	-0.078	-0.097	-0.060	-0.060	-0.085
	(0.063)	(0.064)	(0.064)	(0.050)	(0.053)
	0.215	*0.128*	*0.35*	*0.238*	*0.112*
Controls	Yes	Yes	Yes	Yes	Yes
Adj. R-squared	0.029	0.016	0.032	0.032	0.017
N	727	722	611	1043	1017

$^{+}$ $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table B5: Main and interaction effects, from linear probability models, for different population group, using a dummy dependent variable equal to 1 if the participant reported that she would certainly vote, and 0 if not. All columns show robust standard errors between parenthesis and *p*-values in italic.