IN THE UNITED STATES DISTRICT COURT
FOR THE NORTHERN DISTRICT OF GEORGIA
ATLANTA DIVISION

FAIR FIGHT ACTION, INC, *et al.*,

Plaintiffs,

v.

BRAD RAFFENSPERGER, *et al.*,

Defendants.

Civ. Act. No. 18-cv-5391 (SCJ)

EXPERT REPORT OF STEPHEN C. GRAVES

Stephen C. Graves
Abraham J. Siegel Professor of Management Science
Professor of Mechanical Engineering

Massachusetts Institute of Technology
77 Massachusetts Avenue, Building E62 –579
Cambridge, Massachusetts 02139–4307

Phone 617–253–6602
Email sgraves@mit.edu
http://web.mit.edu/sgraves/www/

My expert Report is attached.

My hourly rate for these services is $300 per hour.

In 2017 I was engaged as an expert witness by New York City for

EVE SILBERBERG; JENNIFER REBECCA WHITE; AND MICHAEL
EMPORER,
Plaintiffs,
- against -
BOARD OF ELECTIONS OF THE STATE OF NEW YORK, et al.,
Defendants
16 CV 8336 (PKC) .

And prepared a report, and was 'cross-examined' in court. (testified live)

Also in 2017, I was engaged as an expert witness by state of Michigan for

MI State A. Philip Randolph Institute, et al. v Ruth Johnson, USDC-ED No. 16-cv-11844.

I prepared a report and then testified by deposition.

Sincerely,

Stephen C. Graves

Stephen C. Graves

Waiting Times in Fulton County, November 2018 Election

Stephen C. Graves

December 2019

In this memorandum I report on the analysis that I did with election-day data from Fulton County. This data was collected as part of a nationwide study conducted by the Bipartisan Policy Center (BPC) and researchers from Massachusetts Institute of Technology (MIT), with an intent to estimate wait times at the polls during the 2018 midterms. Based on my analysis that I report here, it is my opinion that the general findings in the BPC/MIT report[1], for the case of Fulton County in Georgia are accurately stated. As shown in the BPC report, Fulton County, Georgia had the longest wait times of the 3,119 polling places surveyed nationwide. In the following I will first describe the data and how it was collected, then the analysis and finally the results.

Data

Each polling site in Fulton County was asked to record the number of voters waiting in line at hourly intervals, starting with the time at which the site opened and ending at the hour at which the site closed. In Fulton County, all sites opened at 7 AM and then closed at 7 PM.

In Appendix I of this note, I include an example of the data collection sheet. The BPC/MIT report, pp 11-13, provides a general overview of the data collection process.

For Fulton County, this data sheet was completed and collected from 83 polling sites. We obtained these data sheets from the county in response to an open records request. For each data sheet I made a judgment as to whether or not it was usable for my analysis.

Some sheets were deemed unusable because the poll worker recorded the wrong data; for instance, in each hour the number of votes cast was reported rather than the number of voters in line.

Other sheets were deemed unusable due to missing data. Here I had to make a judgment. If there were only a few missing observation, spread over the day, then I kept the data sheet if I thought that I could make a reasonable interpolation for the missing data from the recorded observations. However, if there were a substantial number of missing observations, or missing observations during critical times of the day (e.g., when the polls open), then I discarded the data sheet.

Based on this review of the data, I was able to use the data submitted from 68 polling sites, which account for 135 precincts. Over 59,000 voters voted at these polling sites on election day, 2018.

Analysis

For the data collected at each site, we can estimate the average wait time for a voter at that site. We accomplish this by an application of Little's Law[2] from queuing theory. An overview of the analysis is

---

[1] "The 2018 Voting Experience: Polling Place Lines", November 2019, available at https://bipartisanpolicy.org/report/the-2018-voting-experience/, by Mathew Weil, Charles Stewart III, Tim Harper, Christopher Thomas.

[2] Little, John DC, and Stephen C. Graves. "Little's law." *Building intuition*. Springer, Boston, MA, 2008. 81-100.

described in the BPC/MIT report, pp 14-16. More details and background on the analysis are in the report "Managing Polling Place Resources"[3].

The analysis requires the number of voters who cast ballots at each location. I used two sources of data to determine this count. One was the data sheets; however, many of the data sheets did not report this number. The second source was obtained from the web site https://results.enr.clarityelections.com/GA/Fulton/91700/Web02.221448/#/turnout, which provided counts of the number of votes cast for each candidate in each race. I used the total number of votes cast for governor as a count on the number of voters who cast ballots at each site; this count misses undervotes, and thus will under count the number of voters. Hence, for my analysis, I use the larger number from the two sources.

The estimates of wait time cover only the time period during which the polling site was open. In Fulton County this was from 7 AM to 7 PM. As such, these estimates do not include the time that voters might have waited before the site opened at 7 AM.

Results

In Appendix 2, I report the estimate of average wait time for each of the 68 polling sites for which we had usable data. The polling sites are denoted by the precincts that share the site. I also report my estimate of the number of voters on election day, and the fraction of registered voters that are Black for the site[4].

The average wait time across the sites is 19.1 minutes with a standard deviation of 13.9 minutes. If we weight the sites by the number of voters, then the average wait time becomes 18.6 minutes.

One polling site (precinct 6R) has an estimated wait time of 78.4 minutes. This is about four standard deviations above the mean, and as such, qualifies as an outlier. I decided to remove it from the sample so that it would not skew the analysis. After removing this site, the average wait time across the sites becomes 18.2 minutes with a standard deviation of 11.9 minutes. If we weight the sites by the number of voters, then the average wait time drops to 17.9 minutes.

In the figure below I plot the average wait time by the % Black registered voters at each polling site, and show a trend (regression) line. The regression shows the relationship between average wait time and the % of Black voters. As an interpretation, it says that the average wait time for a polling site with 0% Black voters (x = 0) is 16.2 minutes (y = 16.2), whereas the average wait time for a polling site with 100% Black voters (x = 1) is 20.5 minutes (y = 4.3 + 16.2 = 20.5). And that between these two extremes, the wait time grows by 0.43 minutes for each increase of 10% in the percent of Black voters.

For an additional analysis, I split the sites into two sets depending on whether or not the percent of Black registered voters was more of less than 50%. As is evident from the figure the sites separate quite cleanly into two sets, Black majority sites (with 26000 election day voters) and non-Black majority sites (with 32000 election day voters). For each set I then found the average wait time, weighted by the

[3] Stewart III, Charles. "Managing polling place resources." *Caltech/MIT Voting Technology Project Report* (2015).

[4] The data for number of registered voters and their race comes from "precinct locator file", available from Fulton county site: https://www.fultoncountyga.gov/services/voting-and-elections/precinct-locator

number of votes cast at each site. The average wait time for Black majority sites was 18.8 minutes, versus 17.2 minutes for non-Black majority sites, a difference of 1.6 minutes.

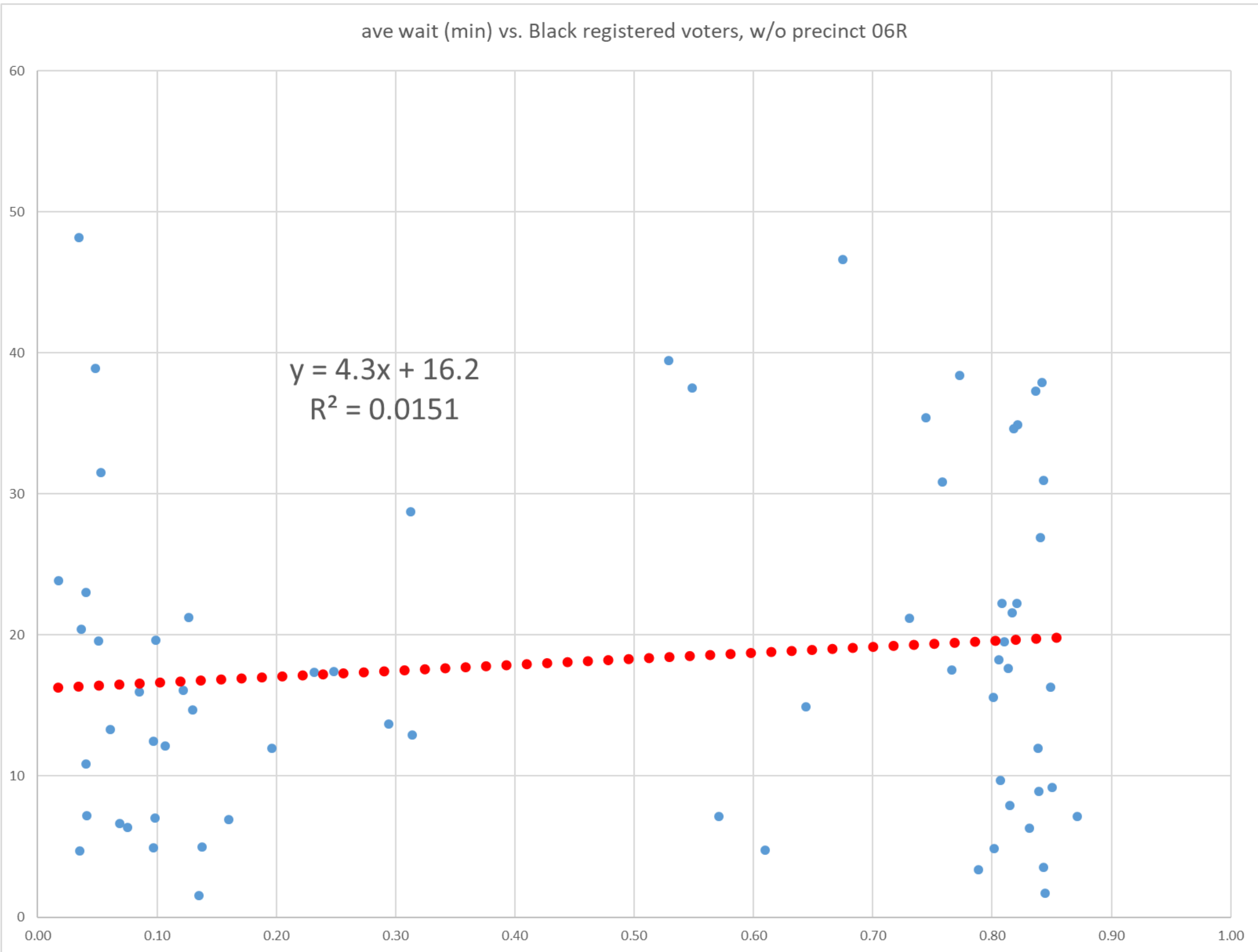


Figure: On the X-axis is the fraction of registered voters that are Black; on the Y-axis is the average wait time, in minutes. Each blue dot corresponds to a polling site. The red line is the trend or regression line fitted to these points.

Appendix I

Line Length Data Collection Sheet

(Fulton County, GA)

6 November 2018

Precinct: 03B, 03H, 09L

Number of Active Registered Voters: 3209

Please use this sheet to record the number of people in line to check in at the indicated times.

- If no one is in line, please enter a zero (0).
- If you are unable to record the line length at a particular time, please enter the number as close as you can to the appointed time. Enter an X if you failed to note the line length at a particular time.

TIME	NUMBER IN LINE	NUMBER OF ACTIVE EXPRESS POLLS	TOTAL VOTERS CHECKED IN
7:00 am*	22	2	0
8:00 am	1	2	69
9:00 am	2	2	122
10:00 am	4	2	171
11:00 am	3	2	217
12:00 pm	4	2	248
1:00 pm	3	1	277
2:00 pm	2	2	318
3:00 pm	Ø	2	356
4:00 pm	4	2	402
5:00 pm	0	2	451
6:00 pm	10	2	
7:00 pm	0	2	540

At what time did the last voter check in to vote? 7:00pm.

*If the polls opened later than 7:05 am, please indicate when you opened here: N/A.

Please return the completed form in the Envelope labeled "Line Collection Forms."

Thank you!

Appendix II

Polling Site	#voters	ave wait (min)	% black
01C, 01S	822	17.52	0.77
01D, 01E	1263	28.72	0.31
01P	361	22.27	0.82
01T	478	37.53	0.55
03B,03H,09I	536	4.89	0.80
03L	180	15.58	0.80
03P1A,03P2	1000	13.67	0.29
04C,04D	465	22.26	0.81
04I	203	4.73	0.61
06B,06J	1459	48.20	0.03
06R	669	78.43	0.17
07A	1747	5.00	0.14
08A	719	14.69	0.13
08F1	542	23.86	0.02
08G	684	11.97	0.20
08M	533	23.02	0.04
08D,08N1,08N2	688	6.36	0.08
09D	479	11.96	0.84
09M	611	12.91	0.31
10B,10I	880	1.70	0.84
10G,10H1,10H2,10K,11H	1303	6.31	0.83
10J	283	18.23	0.81
10P	421	37.91	0.84
10R	232	7.11	0.87
11B	1026	9.21	0.85
11C	427	16.30	0.85
11G,12I,12L	656	3.52	0.84
11K	448	17.61	0.81
11P	511	26.89	0.84
12E1,12H1,12H2,12J	1793	21.58	0.82
12F	252	30.83	0.76
AP07A,AP07B	1272	19.66	0.10
AP09A,AP09B	1130	7.03	0.10
CP01B,CP011,CP012,CP02,CP04A,CP04B	829	7.17	0.57
CP081,CP083,CP084,CP08A,SC10	525	30.97	0.84
EP02A,EP02B,EP02C,EP02D,EP02E	1432	14.90	0.64
EP03A,EP03B	1536	38.40	0.77

FA01A	839	21.20	0.73
FA01B	1242	46.60	0.67
FA01C	189	35.40	0.74
JC01	1327	15.96	0.09
JC03A,JC03B	577	21.27	0.13
JC06	695	16.10	0.12
JC07	956	12.11	0.11
JC09	716	1.51	0.14
JC11	812	12.49	0.10
JC12,JC14	1164	13.32	0.06
JC13A	564	7.18	0.04
JC18	710	6.67	0.07
ML021,ML022,ML023,ML024	1070	4.67	0.04
ML03,ML071,ML072,ML07A	1632	10.88	0.04
RW01	1492	19.60	0.05
RW05	616	17.34	0.23
RW09,RW19	2235	38.93	0.05
RW20	462	4.94	0.10
RW22A	949	17.39	0.25
SC01B,SC01A,SC01C,SC20,FC01	945	34.89	0.82
SC04	348	39.48	0.53
SC08B,SC08C,SC08D,SC08E,SC08F,SC08G,SC08H	1148	7.94	0.82
SC15	1162	19.54	0.81
SC16A,SC16B	790	8.92	0.84
SC19B,SC19A	329	34.65	0.82
SC30A,SC30B	222	37.30	0.84
SS01	1338	31.50	0.05
SS05,SS06	1065	20.39	0.04
SS11A,SS11B,SS11C,SS11D,SS13A,SS13B	2374	6.91	0.16
UC01A,UC01B,UC01D,UC01E	1016	9.71	0.81
UC02A,UC02B	1717	3.38	0.79

Bipartisan Policy Center

The 2018 Voting Experience

POLLING PLACE LINES

November 2019

AUTHORS

Matthew Weil
Director of the Elections Project, BPC

Charles Stewart III
Co-Director, CalTech/MIT Voting Technology Project

Tim Harper
Senior Policy Analyst, BPC Elections Project

Christopher Thomas
Fellow, BPC Elections Project

STAFF

John C. Fortier
Director of Governmental Studies, BPC

Michael Thorning
Associate Director of Governance, BPC

Brenna McAfee
Project Associate, BPC Elections Project

Rachel Orey
Research Analyst, BPC Elections Project

ACKNOWLEDGMENTS

The authors and staff of this report would like to extend our appreciation to Bipartisan Policy Center interns Joshua Ferrer, Daniel Menegaz, Addie McNamara, Katie Grover, and Susanna Blount; Mayya Komisarchik and Dana Higgins with the CalTech/MIT Voting Technology Project. Each provided contributions and input which helped shape this project and report.

BPC gratefully acknowledges the Democracy Fund whose support helped make the project possible.

DISCLAIMER

The findings and recommendations expressed herein do not necessarily represent the views or opinions of the Bipartisan Policy Center's founders or its board of directors.

Table of Contents

Introduction

The 118.5 million Americans who cast ballots in 2018 represented the largest number ever to vote in a midterm election.[1] Although the number of people voting by mail has been steadily increasing over the past two decades, 2018 also set a record for the number of votes cast in-person in a midterm election, 91.2 million. This was a 39% increase in the number of in-person ballots cast compared with the last midterm election in 2014.

The good news is that despite the surge in turnout in 2018, unacceptably long lines to vote were infrequent. Among in-person voters, only 6% reported waiting more than 30 minutes before they could cast a ballot.[2] The bad news is that the percentage of voters reportedly waiting more than 30 minutes to vote doubled since 2014, when it was only 3%. By drilling down into the data, it's clear that in some states, the surge in long wait times was especially dramatic. Furthermore, disparities persist in states where voters do experience long lines, with long wait times more likely to occur in precincts with high minority populations, high population density, and low incomes.

The U.S. voting experience is a constantly changing playing field. Voters cast ballots by mail, in person at early voting sites, and through apps available to members of the military. But most voters nationwide still go to polling places on Election Day. Whether they experience no line, a short line, or an indefensible line is the outcome of many policy decisions. These include resource availability and deployment, precinct size and location, ballot length, poll workers, and timing.

For those precincts with unacceptably long lines in 2018, local election administrators need to diagnose what went wrong to ensure that problems do not re-emerge in 2020, when it is likely that turnout will be greater than in 2016, the last presidential election. Even so, for the voters in jurisdictions with lines less than 30 minutes long, the findings in this report will help policymakers and administrators to improve the voting experience in 2020 and beyond.

SUMMARY OF FINDINGS

This report documents the results of a nationwide study that the Bipartisan Policy Center and the Massachusetts Institute of Technology conducted in 3,119 individual polling places across the country to measure wait times at the polls during the 2018 midterms. It provides the type of fine-grained analysis of voters' reality as they waited to cast ballots that survey data cannot replicate.

As BPC and MIT found in a previous study of wait times during the 2016 election, long wait times in 2018 were primarily an early morning phenomenon. For the average voter in this study, there were only 7.8 people in line when they arrived at the polls at any point during Election Day. However, if they arrived right when polls opened, they faced a line of 21.2 people. At the same time, 35.8% of line measurements taken at precincts in the study showed no one waiting in line to vote, despite 2018 being the highest-turnout midterm election in a century.

The Presidential Commission on Election Administration (PCEA) recommended[3] that no voter should wait more than 30 minutes to vote. The average wait time in this study was 8.9 minutes; 4.8% of precincts saw wait times that exceeded 30 minutes, while 1.5% exceeded an hour.

The 3,119 precincts in the study represented 2.7% of the estimated 116,000 Election Day polling places nationwide.[4] Over 2.4 million voters visited these polling places on Election Day, representing 3.3% of all Election Day voters. The precincts in the study came from 211 local jurisdictions that were located in 11 states plus Washington, D.C. Among these 211 jurisdictions, 21 experienced average wait times of greater than 30 minutes in at least one polling place.

30 MINUTES TO VOTE

Too often the patchwork of election policies across the country creates barriers to voter-centric reform. BPC focuses on researching, developing, and making policy recommendations on the voting process that improve the voting experience.

The 30-minute benchmark for acceptable in-person wait times to vote was articulated in the final report of the bipartisan PCEA and has become generally accepted as the maximum acceptable wait time for voters under normal circumstances.[5] If voters arrive at the polls at a fairly stable pace, election officials can plan for this traffic, using online tools such as those made available by the Caltech/MIT Voting Technology Project (VTP) to assign resources—poll books, poll workers, and voting booths/machines—to keep lines to a manageable level.[6]

BPC and MIT's research, both in 2016 and in 2018, reveals one important exception to the proviso of voters arriving "at a fairly stable pace." A significant number of voters line up at the polls long before they open, creating an instant backlog at many polling places the moment the polls open. However, as this research also shows, *in most cases* these lines resolve within the first couple of hours of the voting day.

Therefore, in almost every case, the dynamics of polling place lines are predictable and within acceptable bounds. When unacceptably long lines do occur, that is typically because the precinct did not have sufficient staff and equipment resources to clear out the opening backlog at a steady pace. Other reputed causes of unreasonably long lines—such as a bus arriving with scores of voters in the middle of the day or hundreds of voters arriving all at once after business hours—certainly occur, but are the exception, not the rule.

CAUSES OF LONG LINES

One-off circumstances, such as unanticipated service failures or an unexpected influx in arrivals within a short window, can cause long lines. The data indicate, however, that policy decisions in certain states cause or exacerbate many of the longest lines and have led to long lines for years. Academic studies have identified structural causes of long lines such as resource availability and deployment, precinct size and location, ballot length, poll workers, and timing.[7,8]

CONSEQUENCES OF LONG LINES

Why be concerned about long wait times to vote? After all, one could argue that long lines are a sign of great voter interest and democratic fervor. Certainly, pictures of long lines of voters in elections in developing democracies are evidence that citizens of those countries are responding enthusiastically to the transition from tyranny. Be that as it may, the United States is not a developing democracy. It has conducted mass elections for centuries. In the jurisdictions most prone to long lines, large urbanized cities and counties, local governments already have access to scientific management techniques to guard against inconveniencing voters unnecessarily.

Scholarly research has demonstrated the real costs of making voters wait in line to vote. For instance, responses to the 2016 Voting and Registration Supplement of the Current Population Survey suggest that over 560,000 eligible voters failed to cast a ballot because of problems related to polling place management, including long lines.

Long lines also exact monetary costs. Research conducted for the PCEA estimated that the wage equivalent of the time spent waiting to vote in 2012 was over half a billion dollars, which was also about one-fifth of the total budget of local election offices in 2012.[9]

Long lines also influence future elections. In a dissertation written at Harvard University in 2017, Stephen Pettigrew used sophisticated statistical techniques to estimate how many people failed to vote in 2014 because of long lines in 2012. The answer, nearly 200,000, speaks to the persistent effects of long lines in the minds of voters.[10]

The likelihood that voters will stand in a long line is not equally distributed across the voting population. Relying on answers to the 2018 Cooperative Congressional Election Study (CCES), for instance, these are characteristics of voters who wait longer than others:

- African American (11.5 minutes) and Hispanic (11.7 minutes) voters waited longer, on average, than white voters (8.8 minutes).
- Early in-person voters (12.2 minutes) waited longer than Election Day voters (7.8 minutes).
- Residents of the most densely populated neighborhoods waited 25% longer than residents of the least densely populated neighborhoods.[11]
- Voters in Georgia (18 minutes) waited 23 times longer than voters in Vermont (46 seconds).

These factors regularly appear in academic studies of wait times.[12,13] Below is a look at how these factors influence line lengths and wait times in the BPC/ MIT study.

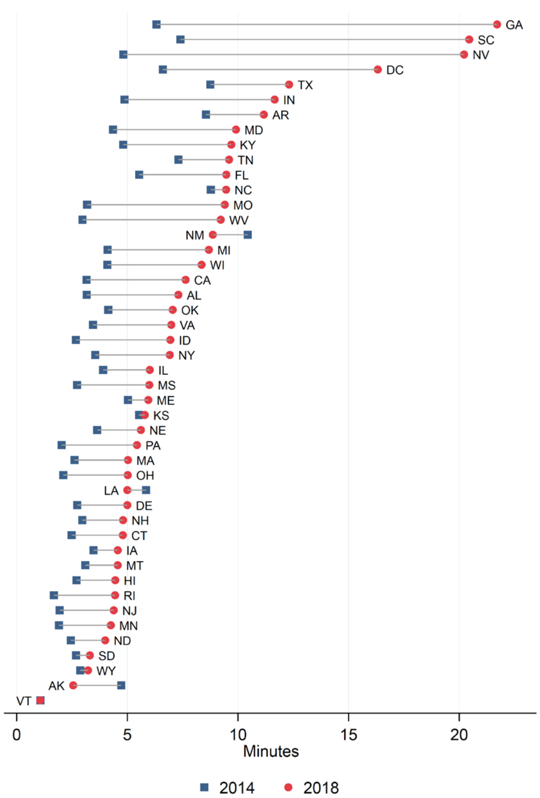
Still, based on two years of wait-time data from thousands of precincts across the country, it is clear that the typical voter experience doesn't involve waiting in a long line. Many of the one-off instances of lines in the study are a knock-on consequence—something went wrong in the polling place and was not resolved quickly. An example is equipment failure or a power outage. If an electronic poll book fails, the line can grow to extraordinary lengths in a matter of minutes if a replacement isn't available or if the failure is not resolvable locally with paper backup pollbooks. If replacements are unavailable or must be delivered from a warehouse across a large county, the line is likely to grow to the point that nothing can be done to ameliorate the problem until the polls close for the day.

Voting Lines in 2018: An Overview

Although the amount of time voters wait to cast a ballot is a major factor that determines the voter's overall opinion about the polling place experience, it is rare for jurisdictions to gather direct information about how long voters wait—this project is a major exception. And even the BPC/MIT Polling Place Line Study does not include participation from all states. Therefore, to gain insight into the typical experience of waiting to vote in 2018, researchers must rely on another source of data.

Luckily, for a decade the CCES has been asking voters how long they waited to vote, and the group did so again in 2018. Although answers to this survey question do not drill down to the precinct level like the BPC/MIT study does, it does sketch a broad portrait of waiting to vote in 2018 compared with wait times in past elections.

Figure 1: Average wait time to vote on Election Day, 2014 and 2018



Note: States omitted because fewer than 20% cast votes on Election Day: Arizona, Colorado, Oregon, Utah, and Washington

Source: CCES[17]

First, the BPC/MIT study examines average wait times. Looking only at respondents who voted in person on Election Day, the average reported wait time in 2018 was 8.7 minutes.[14] Keeping in mind the PCEA's 30-minute benchmark, 5.7% of Election Day voters reported waiting more than half an hour to vote.[15] These wait times were significantly greater than in 2014, the last midterm federal election, when 2.4% of Election Day voters waited more than half an hour and the average wait time was 4.5 minutes.[16] Figure 1 illustrates state averages in 2018 (red circles) compared with 2014 (blue squares).

Two things are notable about Figure 1. First, three states (Georgia, South Carolina, and Nevada) and the District of Columbia stand out compared with the other states in terms of how long voters waited to vote on Election Day. Georgia had a wait time of 21.7 minutes, or 2.5 times the national average.

Second, not only do the wait times of these three states and D.C. stand out compared with other states in 2018, but the *change* from 2014 to 2018 also stands out. In 2014, 90% of the states—including Georgia, South Carolina, Nevada, and the District of Columbia—had an average wait time that ranged between 2.7 and 7.4 minutes. Thus, not only did these four states stand out in comparison with the other states in 2018, they stood out compared with the *change* in wait times from 2014 to 2018.

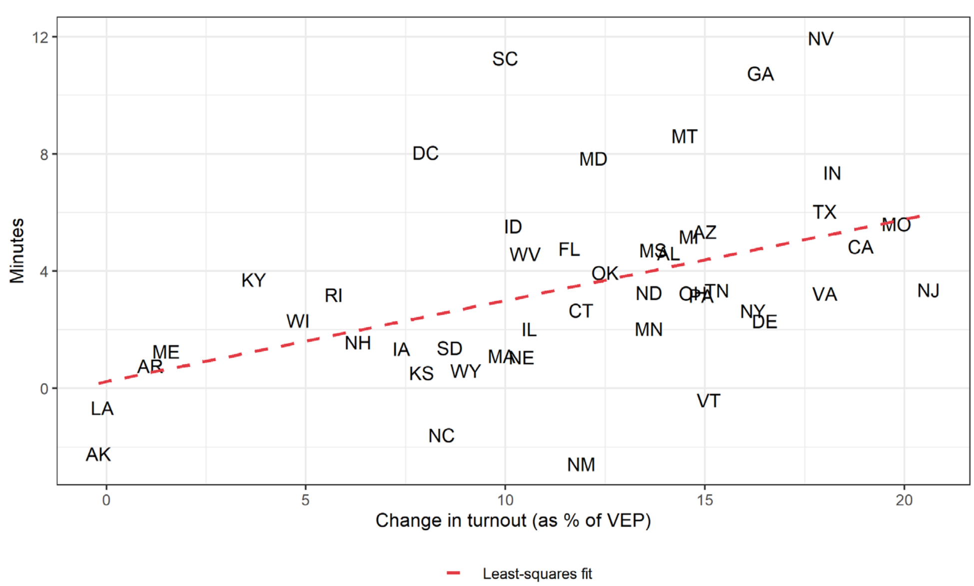
Why were wait times in 2018 double those of 2014? The most obvious answer is that turnout was greater in 2018—38% greater, when measured as a percentage of the voting-eligible population (VEP).[18] In fact, 2018 was the first time since 1912 that midterm turnout as a percentage of VEP was above 50%, which is closer to presidential election turnout levels.[19]

Because Little's Law, which is described below, explains that a main factor determining how long voters wait is the number of people who turn out to vote, it shouldn't be surprising that wait times were longer in 2018—especially if local officials did nothing else to affect wait times, such as change the number of check-in stations or speed up the check-in process.

Although the national turnout rate in 2018 was 38% greater in 2018 than in 2014, there was considerable variation across the states around this nationwide average. For instance, Utah saw an increase of 72%, while Alaska was essentially unchanged.

The reason why some states saw bigger turnout increases in 2018 than others is an important topic but not especially relevant for gaining an understanding of why wait times were longer in 2018 than in 2014. Whether turnout increased

Figure 2: Change in average wait time to vote on Election Day (2014 to 2018) plotted against change in voter turnout



Sources: CCES 2014 and 2018;[20] United States Election Project[21] because of a more energized electorate, changes to voter registration laws, or interest in particular races, the more turnout increases, the more polling places feel pressure to accommodate the increase in voters.

If increased turnout is the reason why wait times in 2018 were greater than in 2014, then there should be a high correlation between the turnout change between 2014 and 2018 and the wait-time change. Figure 2 illustrates that there is a correlation, although it is not "high."[22] In the figure, the horizontal axis shows the change in turnout from 2014 to 2018, while the vertical axis shows the increase in wait times. The red line shows the best-fit line through the data points.[23]

On average, states that saw larger increases in turnout also experienced larger increases in Election Day wait times. Still, not all states with big turnout surges saw equally large increases in wait times. New Jersey and Virginia are examples of states that saw significant turnout increases but experienced relatively moderate increases in wait times.

The scatterplot in Figure 2 shows that dramatic turnout increases do not explain the large increases in wait times in Georgia, South Carolina, Nevada, and the District of Columbia. Several states with equally large turnout increases saw relatively minor increases in their wait times. It must be the case that the states that experienced big wait-time increases in 2018 pushed the resources at hand, mainly check-in locations and voting machines, to their capacity limits or beyond. These issues will be explored further below.

The BPC/MIT Polling Place Line Study

BPC and MIT joined together to create the BPC/MIT Polling Place Line Study. It is a program with a simple goal: to provide local election jurisdictions with actionable data about the lines that formed at their polling places, mostly on Election Day, but in some cases, during early voting. Academic projects conducted in the 2014 and 2016 elections informed the BPC/MIT program, but the study featured one important constraint: The method of collecting data had to be simple and easily implemented by poll workers. To that end, researchers developed a simple coding sheet and a set of instructions that helped poll workers record the number of people standing in line during every hour of the voting day.

All told, 211 local jurisdictions provided usable data for the program in 2018, ranging from Metz Township, MI, with 230 registered voters, to San Diego County, CA, with nearly 3 million registered voters.

The BPC/MIT Polling Place Line Study is extremely simple to implement; the designers were mindful of not adding too much extra time and effort to a poll worker's already busy job description. Researchers estimate the amount of time that a poll worker spent collecting line information was less than one minute at the top of each hour. Every hour, starting when the polling place opened, the poll worker simply had to count how many people were standing in the check-in line and record that single number on a handwritten sheet along with the number of poll books available at the time. Figure 3 shows a typical data-collection form.

At the end of Election Day, the participating counties and municipalities collected all the sheets from their polling places and sent them to BPC or MIT. MIT then keyed in the data and produced an individualized report for each county. After Election Day, MIT gathered data about the number of voters who turned out in person at each of the polling places in the study. (This information was easy to gather from the reports issued by the local jurisdictions in the course of canvassing the election results.)

Figure 3: Typical data-collection form

Line Length Data Collection Sheet
Bedford County, Virginia
November 6, 2018

Precinct: #104 Stewartsville Rescue Squad

Instructions. Please use this sheet to record the number of people standing in line to check in to vote *plus* the number checking in at the indicated times, along with the number of poll books available to accept voters to check in.

If there is no one standing in line at the indicated time *and* no one checking in, please enter a zero ("0").

If you are unable to record the line length at a particular time, enter an "X" in the corresponding space.

Time	Number in line†	Number of poll books
When polls open @ 6:00 a.m.*	9	2
7:00 a.m.	0	2
8:00 a.m.	2	2
9:00 a.m.	3	2
10:00 a.m.	0	2
11:00 a.m.	8	2
12:00 noon	4	2
1:00 p.m.	3	2
2:00 p.m.	0	2
3:00 p.m.	1	2
4:00 p.m.	2	2
5:00 p.m.	4	2
6:00 p.m.	3	2
7:00 p.m.	0	2

†Include the number checking in at that time.

At what time did the last voter check in to vote? 6:40pm

*If the polls opened at some time other than 6:00 a.m., indicate that time here: —

Source: BPC/MIT[24]

Each local jurisdiction received a report that contained at least two parts. The first was a spreadsheet of the data that poll workers had collected on the paper coding forms. The second part of the report calculated the average number of people in line, or line length, during the day; also, by using turnout information, the report calculated the average wait time to vote at each precinct in the jurisdiction. (See below for a discussion on how this calculation was performed.)

Figure 4 shows an example of this kind of report. Election Day turnout was based on official reports published by the local jurisdictions that researchers used to calculate the arrivals-per-minute simply by dividing Election Day turnout by the number of minutes the polls were open during the day. Then, we calculated average line length directly from the observational data provided by the participating jurisdictions. The average wait-time calculations for each precinct used Little's Law, described in greater detail below.

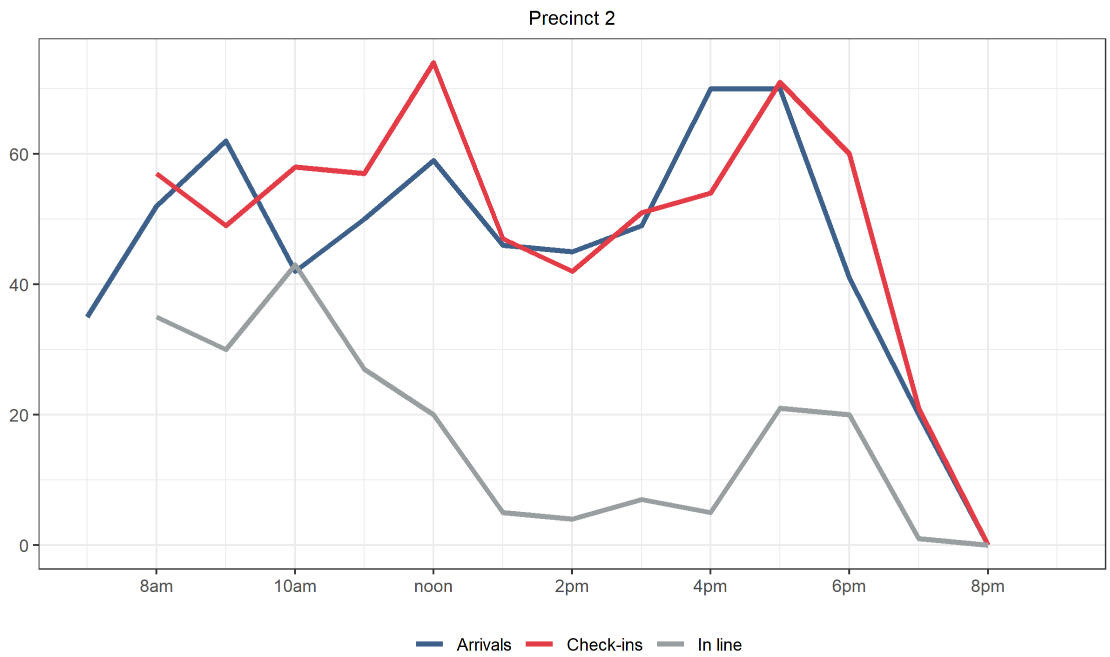
Figure 4: Example precinct wait-time report (excerpt)

Precinct	Election Day turnout	Avg. line length	Arrivals per minute	Avg. wait time	Time last voter checked in	# of data entries
1001 Goldsboro Fire Hall	592	2.6	0.8	3.4	7:50 PM	14
2001 Greensboro VFC Community Hall	1377	0.7	1.8	0.4	7:55 PM	12
3001 Denton Fire Hall	1395	1.6	1.8	0.9	7:55 PM	14
4001 Preston Fire Hall	1249	5.7	1.6	3.6	8:00 PM	14
5001 Federalsburg Fire Hall	1071	2.2	1.4	1.6	7:50 PM	14
7001 Ridgely Fire Hall	1081	1.1	1.4	0.8	7:55 PM	14
8001 Colonel Richardson High School	618	0.8	0.8	1.0	7:58 PM	13

Source: BPC/MIT[25]

Counties that were able to provide hourly data about voter check-ins from their e-poll-book systems received an additional report. This report calculated how many voters had arrived at the polling place each hour. The details of the report each jurisdiction received is illustrated by the graph in Figure 5, which displays the data provided by the county for one particular precinct, includes the line length at the start of each hour (the solid gray line), the number of check-ins each hour (the red line), and when the voters arrived (the blue line).

Figure 5: Typical graph showing hourly precinct arrivals, check-ins, and number of voters waiting in line



Source: BPC/MIT[26]

The Science Behind the BPC/MIT Polling Place Line Study

The foundation of the BPC/MIT Polling Place Line Study is queuing theory, a field of management science and operations research that characterizes how long it takes to provide services to customers—be they grocery store patrons, medical office patrons, or cars exiting a parking lot—in terms of three major factors: (1) the arrival patterns of customers, (2) how long it takes to serve customers, and (3) how many stations, such as check-out stands, customers can be served at. Although there are limitations in drawing analogies between voters and customers, in the case of managing polling places, the analogy is very apt.

A full description of the science behind the program can be found in *Managing Polling Place Resources*, published by the VTP in 2015.[27]

A core concept in queuing theory is Little's Law, which states that in a stable system,[28] the long-term number of people waiting in line is equal to the long-term arrival rate multiplied by the average time a customer spends in the system. Using a little algebra, if one knows the arrival rate at a polling place and the average number of people in the check-in line to vote, one can then calculate the average wait time at a polling place with the following equation:

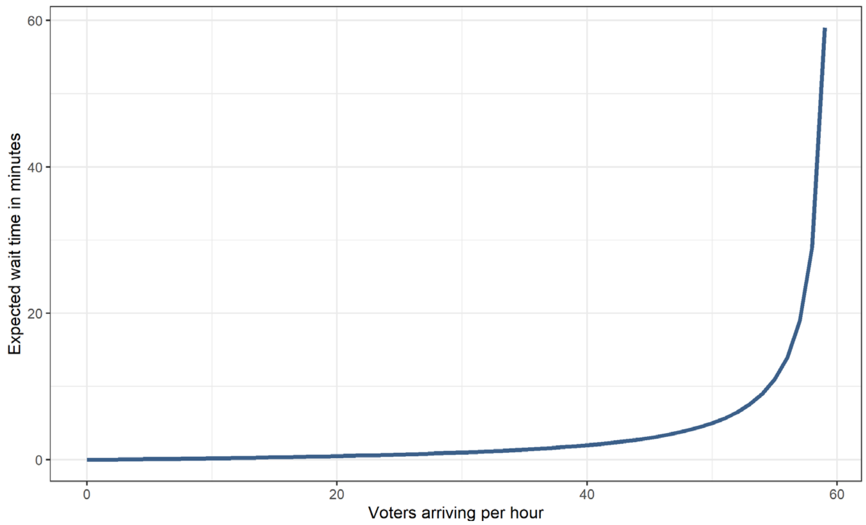
$$\textit{Average wait time} = \frac{\textit{Average line length}}{\textit{Arrival rate}}$$

The jurisdictions involved in the BPC/MIT Polling Place Line Study provided the number of people who voted on Election Day at each of the precincts in the study. Using the information from the data-collection forms already discussed, the average line length was calculated using the Little's Law formula.

There are other methods to calculate average wait times. In particular, if one knows the number of check-in stations in a polling place, how long it takes to check in a voter, and the arrival rate of voters, it is possible to estimate the average wait time to check-in. The VTP polling place toolkit website contains a spreadsheet that election officials can use to make this calculation and see whether they have enough resources in polling places to keep wait times to reasonable lengths.[29]

Using calculations from this spreadsheet, one can demonstrate how wait times fluctuate from election to election as the turnout level fluctuates. Consider a typical polling place with one check-in station that that is open for a 12-hour voting day and that can check in a voter in one minute, on average. Figure 6 graphs how average wait times change as the hourly arrival rate varied from zero to 60 voters per hour.

Figure 6: Example of how wait times to vote vary as the number of voters arriving per hour varies



The primary insight in this example is that there is virtually no wait to vote across all values of arrival rates, but when the arrival rate reaches a critical point, the expected wait time increases exponentially. With 40 voters per hour, the average wait time is only two minutes; at 50 voters, it is five minutes; at 55 voters, the wait time is 11 minutes; and at 59 voters per hour, the wait time is almost an hour.

The sharp inflection of the graph at around 55 voters is sometimes called the “elbow of death,” as the arrival rate approaches the polling place’s “utilization limit” of 60 voter check-ins per hour.[30]

The example shown in Figure 6 is relevant to understand why some states—or precincts—can see big increases in turnout and yet not see wait times increase, while others can see similar turnout increases and see wait times explode. If a precinct’s arrival rate was previously far from its utilization limit, it can more easily absorb an increase in turnout than a precinct that was previously close to its limit.

In this example, a precinct (Precinct A) that had previously had an arrival rate of 30 voters per hour, far from the utilization limit, and then experienced an increase in the arrival rate to 42 voters per hour would see its average wait time increase from one minute to 2.3 minutes. Another precinct (Precinct B) that had previously had an arrival rate of 45 voters per hour, much closer to the utilization limit, would see its wait time increase from three to 19 minutes if it experienced the identical arrival-rate increase of 12 voters per hour. Furthermore, 21% of voters would wait more than 30 minutes in Precinct B; 5% would wait more than an hour. (Practically no one would wait more than 30 minutes to vote in Precinct A, even at an arrival rate of 42 voters per hour.)

The states and local jurisdictions that saw the biggest increases in wait times in 2018, such as Georgia, South Carolina, Nevada, and D.C., probably were near their own local utilization limits in 2014, and thus near the elbow of death. With a dramatic increase in turnout, but without an adequate increase in resources, such as voting machines and poll books, wait times exploded. The other states that saw similar turnout increases in 2018 but experienced minor wait-time increases, such as Virginia and New Jersey, probably had few precincts near the elbow in 2014, resulting in greater polling place resilience when the surge hit in 2018.[31]

It is significant that most of the states with the biggest increases in wait times rely heavily on electronic voting machines, both direct-recording electronic machines and ballot-marking devices, and thus cannot easily or inexpensively expand polling place capacity whenever turnout surges. Therefore, it seems especially important for states with electronic machines to assess their resource needs well in advance of elections that might see big turnout surges.

The Results of the BPC/MIT Polling Place Line Study in 2018

Clearly, there are a variety of ways to manage long Election Day lines. To take a narrower focus, it's valuable to examine the results of the BPC/MIT Polling Place Line Study, to look at who participated, and to learn generally from the data gathered.

BPC put out a nationwide call, asking for local jurisdictions to participate in the program in 2018. BPC made every effort to encourage jurisdictions of all types from across the country to participate. Still, this was a voluntary program, so the jurisdictions were not chosen randomly.

Nonetheless, the demographic characteristics of the precincts included in this study closely correspond to nationwide demographics. This correspondence can be tested using data from the political data firm Catalist, a company that provides voter file information to campaigns.

As Table 1 shows, the demographic (and other) characteristics of the participating jurisdictions are very similar to the characteristics of local jurisdictions nationwide. The sample of jurisdictions has slightly greater African American populations, more college graduates, and more renters than nationwide. This probably reflects the fact that a few very large urbanized jurisdictions were part of the program, whereas the smallest and most rural jurisdictions primarily came from three states—Connecticut, Michigan, and Virginia—that had statewide participation programs. Later in this report, it will be shown that precincts with large minority populations tend to have longer wait times than precincts that are nearly all white. Thus, this report's estimates of average wait times may slightly overestimate the true national average. Because the oversampling of predominantly African American precincts is slight, it is likely that the overestimate of national wait times is also slight.

Table 1

Demographics vs. Catalist Data

	Sample	Nationwide
White	75.4%	77.4%
Black	11.8%	10.2%
Hispanic	6.9%	7.6%
Other race	6.0%	4.8%
Over 65	24.8%	25.3%
College graduates	38.9%	32.1%
Living in poverty	10.5%	11.8%
Renters	10.6%	7.6%

WHO PARTICIPATED IN THE PROGRAM?

The BPC/MIT Polling Place Line Study in 2018 included 219 local jurisdictions, of which 211 produced Election Day line data that was usable for this report.

Appendix A lists the 211 jurisdictions that provided usable polling place line data in 2018.

These jurisdictions covered a broad swath of the United States. By the numbers:

- 11 states, plus the District of Columbia
- 18.0 million registered voters[32]
- 10.5 million votes cast, or 9% of nationwide turnout
- 3,119 precincts

All told, the jurisdictions provided more than 41,000 hourly records of line-length data. Coupled with the 2016 effort, this represents the largest, most broad-based observational study ever conducted of wait times in polling places.

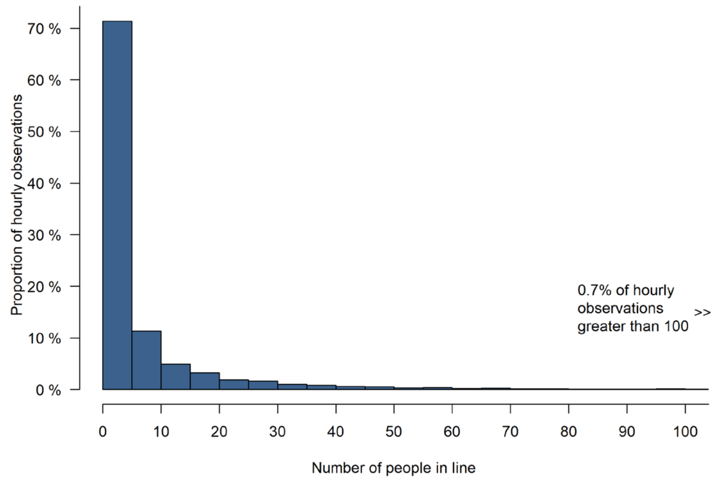
FINDINGS

There are six main empirical findings that are important to emphasize.

1. **The average number of people in line at any given time was 7.8. However, this average masks an important detail: Most lines were very short, but a few were very long.**

The graph in Figure 7 shows the distribution of the number of people standing in line each hour for the precincts included in the study. The average line length was 7.8 people. However, a small number of precincts that experienced incredibly long lines strongly influences this average. Compare the average with the median number of people in line, which is just two. In other words, half of the hourly line counts were longer than two people and half were shorter. Finally, the modal (that is, the most common) number of people in line at any hourly observation was zero. Overall, just over one-third (35%) of all the recordings in the data had nobody in line at all.

Figure 7: Distribution of all 41,264 observed hourly line lengths across 3,119 voting locations in the 2018 election

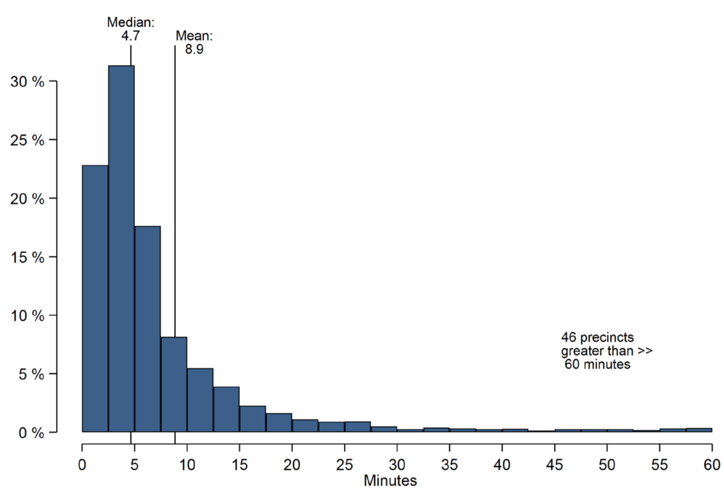


Source: BPC/MIT[33]

A major challenge of running an election is not about understanding how long lines will be *on average*. Instead, election officials must account for how long the line will be *at its worst*. Another way of exploring the line-length data is to ask how long the *longest* line was for each precinct in the sample. For 70% of precincts, there were 10 or more people in line at least once during the day. Put another way, 30% of precincts *never* had more than 10 people in line throughout the entire time they were open.[34] Only 13% experienced a line of 50 or more during the day. Finally, just one in 30 precincts (3.3%) had more than 100 people standing in line to vote at least once during the day.

2. **The average wait time for precincts in the study was 8.9 minutes. The small number of precincts with very long average wait times also influenced this result. In addition, only a small proportion of precincts had average wait times of greater than 30 minutes.**

Figure 8: Average wait times in 3,119 polling places



Source: BPC/MIT[35]

In all, there was enough data to calculate the average hourly wait time in 97.6% of the precincts in the study (3,043 out of 3,119). Figure 8 shows the estimated average wait time for voters in these polling places. In most areas, lines were typically very short. The mean wait time across these precincts was 8.9 minutes; the median was just 4.7 minutes. Just over three-quarters (78.7%) of precincts had an average wait time of less than 10 minutes. These findings are largely consistent with survey-based estimates of average wait times from the 2018 election, which found that 76% of voters waited less than 10 minutes to vote.

However, some areas had much longer wait times. At the high end, one out of 20 (4.8%) precincts had average wait times that were longer than 30 minutes.

3. **Average wait times are longer in precincts with a high percentage of minority voters, more renters, and lower incomes.**

One of the most important policy questions in recent years has been about the relationship between polling place wait times and demographic factors, particularly race. Until very recently, the statistical correlation between the race of a voter and the waiting time to vote has been based on public-opinion studies. These studies have regularly found that African American and Hispanic voters wait longer to vote than whites.

The findings in the BPC/MIT report are consistent with public-opinion-based studies.

Public-opinion surveys are valuable for exploring the perceptions voters have formed about their voting experience and for characterizing those experiences nationwide. One limitation of public-opinion surveys is that they rely on voters' memories, which can become clouded over time and influenced by what they hear others report. An advantage of direct-observation studies, such as this one, is that they directly measure wait times and don't depend on the recall of voters.

This study, therefore, provides a good opportunity to verify public-opinion studies that have previously correlated demographic factors with wait times. BPC and MIT have been able to match most of the precincts from the study with demographic data obtained from Catalist. Using this matched data, we can see whether demographic characteristics of polling places are correlated with wait times without public-opinion surveys.

First, precincts with a higher proportion of minority voters tend to have longer wait times than precincts that are predominantly white. Figure 9 illustrates this finding; it graphs the average wait time as a function of the percentage of registered voters in a precinct who are non-white.

Figure 9: Average wait times as a function of percent that is non-white

Source: BPC/MIT[36]

Consistent with past studies, the more voters in a precinct who are non-white, the longer the wait times. In precincts with 10% or less non-white voters, the average wait time was 5.1 minutes, the median was 3.6. In precincts with 90% or more non-white voters, the average and median climb to 32.4 and 13.3 minutes, respectively.

Two patterns are particularly important to notice in Figure 9. First, the mean and median are fairly close to each other in precincts with low non-white populations, and then they diverge significantly in precincts with high non-white populations.

Because outliers strongly influence averages, this divergence between the mean and median wait times indicates that in predominantly minority precincts, there are a few precincts with exceptionally long wait times that are pulling up the average. This is not to dismiss problems experienced in precincts with greater than 80% minority populations. But it is to suggest that the few precincts that have extraordinarily long lines are disproportionately in minority communities.

The second pattern is related to the first. The average and median wait times march upward in a fairly linear fashion in the range of 0% to 70% minority population, then the average begins to grow exponentially. This underscores that the mismatch between resources and voting demand is especially great in precincts with a large fraction of minority voters.

Another demographic of interest is the percentage of the population who are renters. A large rental population implies an area with a great deal of population turnover. With high population turnover, two factors might increase wait times: (1) new voters, whose inexperience with the process may slow down check-in and voting times; and (2) highly mobile voters who may find themselves in the wrong precinct on Election Day and thus casting provisional ballots, another process that can slow down lines.

Precincts in areas with more renters, in fact, experience longer wait times, as illustrated by Figure 10. The relationship is not as dramatic as that seen with race, but the pattern occurs, nonetheless. In precincts where fewer than 10% of residents are renters, the mean wait time was 7.9 minutes and the median was 4.4 minutes. In the few precincts where the rental rate exceeded 60%, the average grew to 16.6 minutes, with the median at 8.1 minutes. Finally, as discussed above,

Figure 10: Average wait times as a function of percent who are renters

Source: BPC/MIT[37]

the fact that the mean and median are fairly close in low-rental areas suggests that there are many fewer precincts with exceptionally high wait times. This is in contrast to the high-rental areas, where the mean and median are quite far apart.

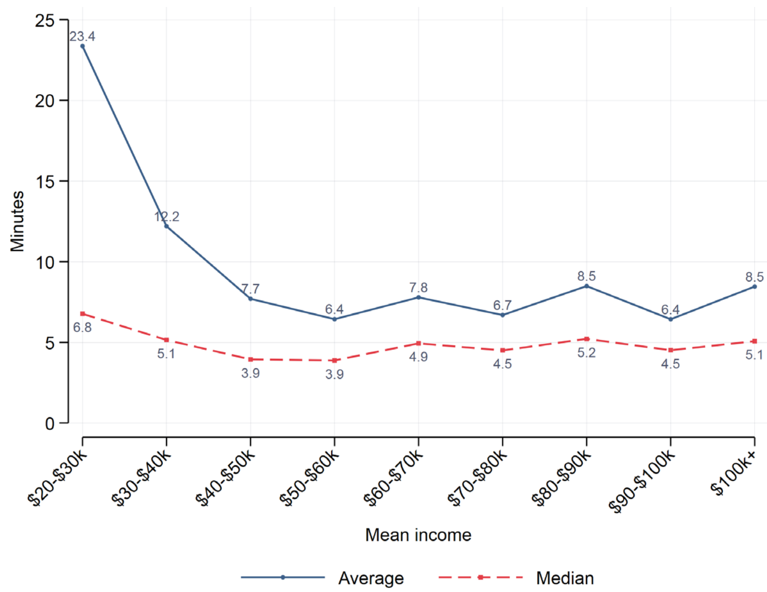
A final demographic factor of wait times is income. Income is correlated with a number of factors that might cause long lines. One is political clout; election officials representing jurisdictions with higher average incomes may be more successful in agitating for extra resources if wait times creep up.[38]

As Figure 11 shows, the correlation between a precinct's income and wait times is largely determined by especially long wait times in the lowest-income areas. Considered together, the average wait time in precincts with an average income of less than $40,000 is 15.4 minutes, compared with 7.7 minutes in other precincts. Beyond average incomes of $40,000, average wait times are relatively flat, fluctuating randomly.

Interestingly enough, the median wait time, 4.7 minutes, is essentially constant for all levels of average income. This means that low-income precincts are much more likely to experience exceptionally long lines than middle- and upper-income precincts. For instance, 3.4% of the precincts with average incomes of less than $40,000 had average wait times of greater than 30 minutes. This contrasts with 0.7% of precincts with higher average incomes. In other words, precincts in areas with average incomes of less than $40,000 were four times more likely to experience wait times of greater than 30 minutes than precincts in areas with incomes above that.

Of course, the three demographic factors discussed here are all correlate with each other. Precincts with high minority populations tend to have lower average

Figure 11: Average wait times as a function of average income



Source: BPC/MIT[39]

incomes and more renters. Which factor has the most statistical power in explaining average wait times?

The answer is race. A simple statistical model provides the answer; Appendix B reports its results. In summary, it is the case that race and the percentage of renters individually show statistically significant influences on average wait times. However, once researchers explore all three demographics simultaneously, the only factor that retains explanatory power is race.[40] The analysis suggests that the difference in wait times between a precinct that is 100% non-white and one that is 100% white is 20 minutes.

This effect is quite large, but consistent with other studies. Unfortunately, we did not design this study to explore the causes of wait times beyond easily measured factors such as demographics and arrival rates. The small amount of research that has probed this question suggests that longer lines in minority-dominated precincts are primarily due to local differences in political influence, which result in minority precincts being less well-supported on Election Day.[41,42,43,44]

4. The longest lines tended to occur in the morning, right after the polls opened.

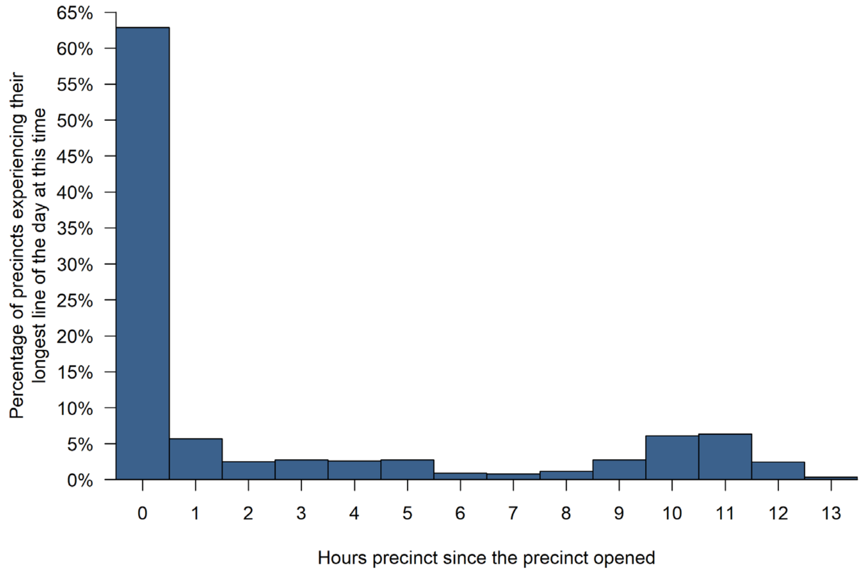
When Americans vote on Election Day, they tend to vote in the morning. According to the 2014 Survey of the Performance of American Elections, the last time the survey was conducted during a midterm election, 22% of Election Day voters had cast a vote by 9 a.m. and 48% had voted by noon. The statistics for 2016 were very similar—24% and 56%, respectively.

Across all the precincts reflected in this study, the longest lines tended to be present the moment the polls opened, which was due to the large number of voters who lined up early. Lines during the first couple of hours of voting remained long even in the best of circumstances because the large number of voters who arrived before work hours encountered the backlog of voters caused by the opening queue.

Figure 5 above provides an example of this pattern; it showed the arrival, check-in, and line-length dynamics of a representative precinct. In that example, 35 people were waiting in line to vote when the precinct opened at 8 a.m. Between 8 and 9 a.m., another 52 people arrived. Because the poll workers were able to check in 57 people during that first hour, the line shrank from 35 at 8 a.m. to 30 at 9 a.m. In the first couple of hours of voting, poll workers were unable to clear the backlog of voters created by the line of voters already in place when the polls opened. It was only late in the day, when hourly arrivals eased up a bit, that the line began to steadily drop. (It also helped that for the 11 a.m.-to-noon hour, the number of voters that poll workers were able to check in surged by about 50% for that one hour, allowing more of the line to clear.)

To highlight the more general point, the graph in Figure 12 presents the hour in which each precinct in the study reported its longest line on Election Day. To account for different precinct opening times in different jurisdictions, the x-axis of the graph displays the number of hours since the precinct opened. (For instance, if the polls opened at 7 a.m. and the longest line appeared at that time, the results for the opening hour are reported for Hour 0. If the longest line occurred at 8 a.m., the line is reported as occurring at Hour 1.) The y-axis shows the proportion of precincts that experienced their longest lines at this time.

Figure 12: When did precincts experience the longest line of the day?



Source: BPC/MIT[45]

The overwhelming majority of Election Day precincts, 63%, had their longest lines when the doors opened. An additional 6% had their longest lines during the first hour of voting. In other words, 69% of Election Day precincts had their longest lines within the first hour of voting, with the lines declining after that.

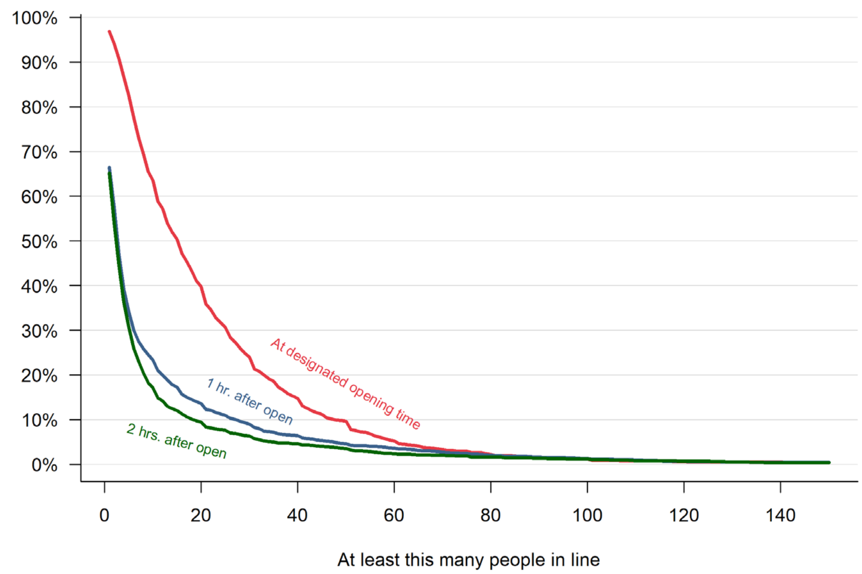
In 2018, there was a notable surge in longest lines around the period between nine and 12 hours after poll openings. (This surge did not occur in 2016.) This time generally corresponds with the late-afternoon/end-of-work-day period. (For example, if polls open at 6 a.m., then the period between nine and 12 hours later would be from 3 p.m. to 6 p.m.) Overall, 17.5% of precincts experienced their longest lines at this time. This is in contrast with 2016, when the corresponding figure was approximately 1%.

This difference could be a result of the sample of precincts being slightly different in 2018 than in 2016. While this is a real possibility, it is more likely that midterm voters (such as in 2018) tend to be different from on-year voters (such as 2016).

5. **Although lines tend to be the longest at the beginning of the day, they dissipate quickly in most precincts.**

Although lines tend to be the longest at the beginning of the day, most precincts managed to reduce the length of their lines quickly. Figure 13 shows the percentage of the Election Day precincts in which the line at Hour 0, Hour 1, or Hour 2 was of a certain length. The percentage of precincts with any given line length decreased with each passing hour. For example, 7.5% of precincts had more than 50 people in line when they opened, but within one hour, that number had dropped to 4.3%, falling to 3.2% within two hours. Similarly, while

Figure 13: Percentage of precincts with at least a certain number of people in line early in the day



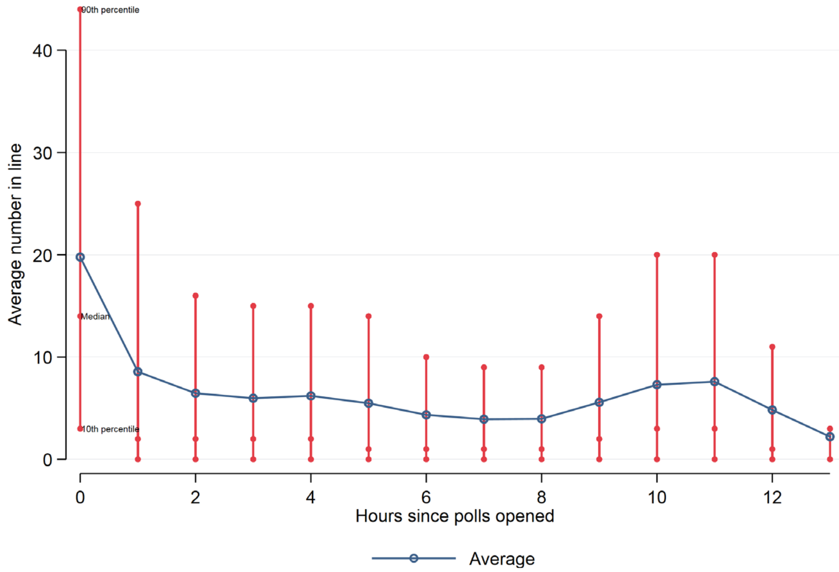
Source: BPC/MIT[46]

only about 34.6% of precincts had fewer than 10 people in line at the beginning, 82.8% had lines of fewer than 10 people within two hours.

Comparing these results with the BPC/MIT report from 2016, there are two important patterns. First, the length of lines when the polls opened was not appreciably shorter in 2018 than in 2016. Second, these opening lines dissipated much more quickly in 2018, which was a major reason overall wait times in 2018 remained less than in 2016.

Given the results reported thus far, it should not be surprising that average lines on Election Day tended to drop as the day progressed. Figure 14, which displays a graph of average line lengths for each hour of the day, illustrates this. In addition, Figure 14 shows the hourly median and the 10th and 90th percentiles. As before, the chart accounts for the fact that polls open at different times by calling the opening hour "Hour 0," the end of the first hour "Hour 1," etc. (For instance, in a state where the polls open at 7 a.m., Hour 0 is 7 a.m., Hour 1 is 8 a.m., etc.)

Figure 14: Average number of people in line each hour after polls open



Source: BPC/MIT[47]

Consistent with the data reported above, the average precinct saw 20 people in line when the doors opened on Election Day 2018. By the end of the first hour, that number had been more than cut in half, to 8.6. Even though there was a small surge toward the end of the day, the average in any hour was never as great as it was in the first hour of voting.

The data plotted in Figure 14 that show the variability of line lengths each hour help to round out the picture. Note that the median and mean at opening time are relatively close (median = 14 and mean = 20), which indicates that line lengths across precincts in the study occurred fairly symmetrically. Even by the end of the first hour, the median (2) is quite far from the mean (8.6). Also note that the 90th percentile value at the end of the first hour (25) is far above the mean. This pattern holds from Hours 1 to 13. Statistically, this shows that a small number of outlier precincts with exceptionally long lines heavily influence the average line length after the first hour. The typical precinct has only a handful of people waiting to check in—the median is no more than three people in line after the opening. Finally, it is notable that the variance of line lengths increases dramatically between Hours 9 and 11. Again, because the mean and median are not affected much, this shows that extraordinarily long lines to vote in the hours after work are rare, even if they are troubling.

6. **If a precinct clears its morning line quickly, it is unlikely to experience long wait times for the rest of the day. If the morning line persists, long wait times are likely to occur for the entire day.**

There is a crush of morning voting on Election Day. The BPC/MIT Polling Place Line Study shows the importance of clearing that morning line. A high volume of voters at the start of the day—both those waiting when the polls open and those coming soon after they open—will lead to lines at most precincts. However, most of those precincts showed the ability to clear those lines within the first couple of hours of voting, never to experience them again for the rest of the day. Conversely, the precincts that could not clear their morning lines after a couple of hours were highly likely to see long lines and long wait times until they closed their doors, often hours after the official polling place closing time.

Do long lines early in the day make a precinct more likely to be burdened by long lines after 5 p.m.? Does having a long line right now mean that a precinct is likely to have one in two or six hours?

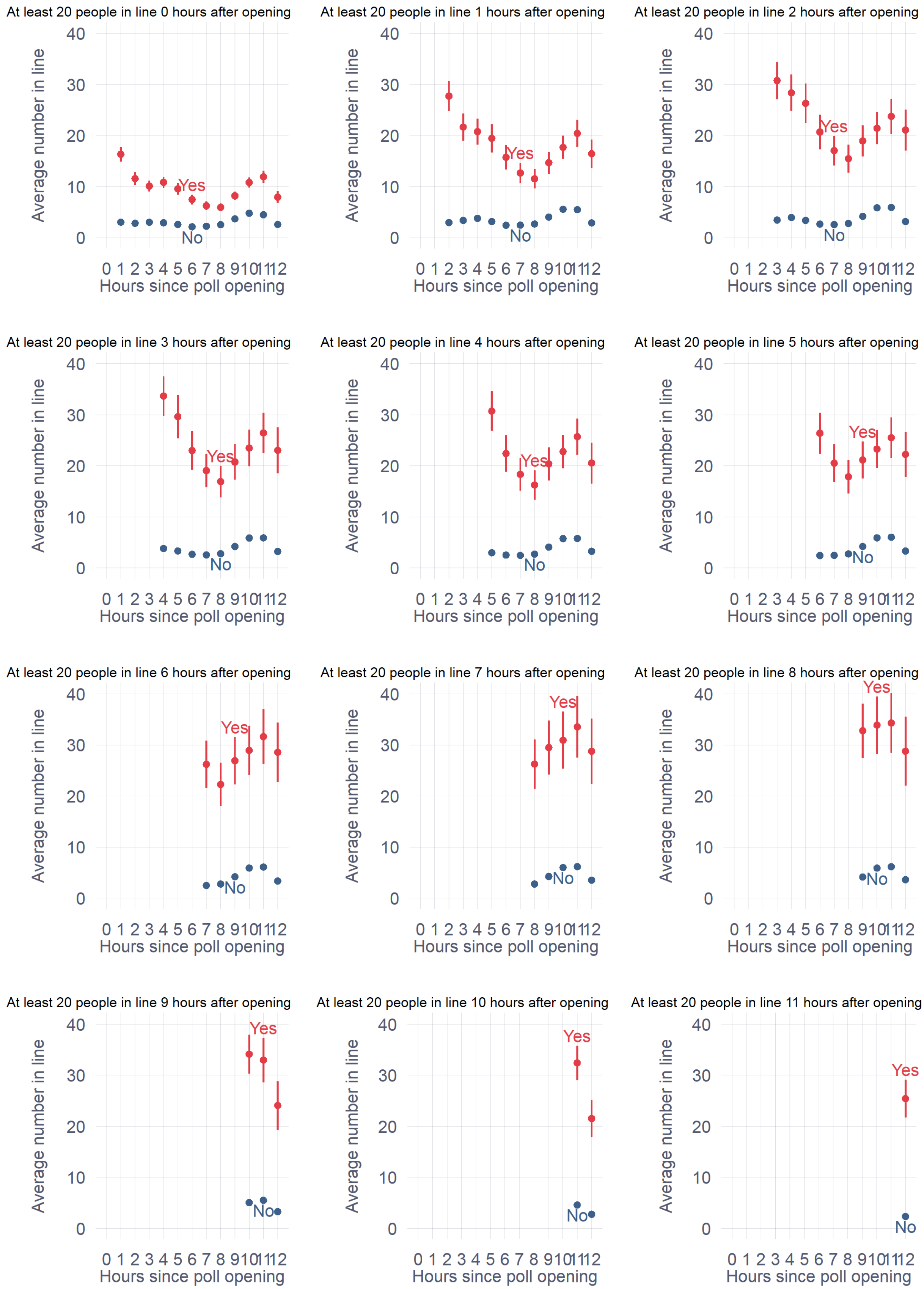
Overall, the data suggest that the answers to these questions are no to the first and yes to the second. While precincts that have long lines right when the polls open are slightly more likely to have long lines later in the day, most precincts with long lines at the opening see those lines recede fairly quickly. However, as the day progresses, if a precinct has a long line later in the morning or in the afternoon, it is unlikely the lines will shorten appreciably until closing time.

The graphs in Figure 15 illustrate these points. This figure has 12 graphs. Each graph shows the average number of people in line later in the day, broken down by whether there were 20 or more people in line at that hour or less than 20 people in line. For instance, the very first graph charts the average number of people in line each hour for the rest of the day, for precincts that had 20 or more people in line when the polls opened ("Yes") and for precincts that had fewer than 20 in line ("No"). In these precincts, if there were at least 20 people in line when the polls were open, there are an average of 16.4 in line at the end of Hour 1, 11.6 in line at the end of Hour 2, etc. In contrast, if there were fewer than 20 people in line when the polls opened, there was an average of 3.1 and 2.8 in line at the end of Hours 1 and 2, respectively.

Scanning across all the graphs, notice that the circles in red climb from one graph to the next. This shows that as the day progresses, having 20 or more people in line at any moment portends longer and longer lines down the road. For instance, in precincts that have more than 20 people in line when the polls open, the average line length at the end of Hour 4 is 10.8 people. However, in precincts that have more than 20 people in line at the end of Hour 1, the average number of people in line at the end of Hour 4 rises to 20.8. If there are still more than 20 people in line at the end of Hour 2, the average number in line at the end of Hour 4 rises again to 28.4.

This shows how precincts very quickly diverge in the morning according to two paths: those that can get the lines under control within an hour or two and those that cannot.

Figure 15: How the number in line now predicts the number in line the rest of the day



Source: BPC/MIT[48]

Conclusion

After two national iterations of the BPC/MIT Polling Place Line Study, it's clear that long lines most fundamentally form when there is a misallocation of resources necessary to handle the service requirement of a polling place. In other words, there aren't enough poll books, voting booths, ballots, or machines to handle the crowd.

What's more:

1. Lines at polling places can be studied—and brought under control—by using approaches and tools that businesses have been employing for decades.
2. To effectively manage polling places and reduce lines, election officials must collect information about the number of people in line on a regular basis at every polling place in their jurisdiction.
3. Best-practice management techniques and policies that encourage a smooth flow of voters in polling places can reduce long lines.
4. Long lines are not the norm for most voters, but at a substantial fraction of polling places, voters wait longer than the 30-minute maximum, and at a smaller but still troubling group of polling places, lines can stretch for over one hour.
5. Whether it's issues that are unique to a polling place or more general problems relating to chronic capacity shortages, both can cause long lines.
6. Lines are longest on the morning of Election Day.
7. Longer lines are correlated with precincts unable to handle early morning lines and precincts that are more urban, denser, and have higher minority populations.

Want to Know More?

The principles behind the BPC/MIT Polling Place Line Study have been a core part of management science for decades. The following is a brief list of resources that may be especially helpful to election administrators.

- Alexander S. Belenky and Richard C. Larson, "To Queue or Not to Queue?" *OR/MS Today*, 2006. Available at: http://www.orms-today.org/orms-6-06/queues.html. (Brief, accessible introduction to queuing theory as applied to elections.)
- Caltech/MIT Voting Technology Project, "VTP Toolkit." Available at: http://web.mit.edu/vtp/. (Collection of online tools that help with allocating resources and minimizing polling place lines.)
- Charles Stewart III, "Managing Polling Place Resources," *Caltech/MIT Voting Technology Project Report*, 2015. Available at: http://web.mit.edu/vtp/Managing%20Polling%20Place%20Resources.pdf. (Comprehensive report on polling place lines and how to manage and study them.)
- Richard C. Larson and Amedeo R. Odoni, *Urban Operations Research* (Upper Saddle River, NJ: Prentice-Hall, 1981). Available at: http://web.mit.edu/urban _ or _ book/www/book/. (Chapter 4 provides a straightforward introduction to queuing theory.)

A small-but-growing academic literature has emerged based on public-opinion research and direct observation that address the issues in this report. Below is a brief list of peer-revised articles that dive more deeply into the issues addressed in this report:

- Michael C. Herron and Daniel A. Smith, "Precinct Resources and Voter Wait Times," *Electoral Studies*, 42: 249-263, 2016. Available at: https://doi.org/10.1016/j.electstud.2016.02.014. (Observational study of Hanover, N.H., in 2014 combined with computer simulations to understand the relationship between polling place resources and wait times.)
- Stephen Pettigrew, "The Racial Gap in Wait Times: Why Minority Precincts Are Underserved by Local Election Officials," *Political Science Quarterly*, 132(2): 527-547, 2017. Available at: https://www.stephenpettigrew.com/articles/pettigrew-2017-psq.pdf (Most comprehensive analysis of the influence of race on wait times, based on a large academic survey research study in 2006, 2008, 2012, and 2014.)

- Robert M. Stein, Christopher Mann, Charles Stewart III, et al., "Waiting to Vote in the 2016 Presidential Election: Evidence from a Multi-County Study," *Political Research Quarterly*, March 28, 2019. Available at: https://journals.sagepub.com/doi/abs/10.1177/1065912919832374#articleCitationDownloadContainer. (Largest-ever academic study of polling place dynamics, based on direct observation of precincts in over 25 local jurisdictions.)
- Douglas M. Spencer and Zachary S. Markovits, "Long Lines at Polling Stations? Observations from an Election Day Field Study," *Election Law Journal*, 9(1): 3-17, 2010. Available at: https://doi.org/10.1089/elj.2009.0046. (Perhaps the first academic study of polling place wait times based on direct observation of lines in the 2008 presidential primary in northern California.)
- Charles Stewart III and Stephen Ansolabehere, "Waiting to Vote," *Election Law Journal*, 14(1): 47-53, 2015. Available at: https://doi.org/10.1089/elj.2014.0292.(Overview of research presented to the PCEA about lines at polling places.)

Appendix A. Participating Jurisdictions

Jurisdiction	Precincts	Hourly Observations
Pinal County, AZ	58	776
Orange County, CA	45	614
San Diego County, CA	806	10,271
Boulder County, CO	15	195
Andover, CT	1	15
Ansonia, CT	6	88
Barkhamsted, CT	1	15
Bethlehem, CT	1	15
Bozrah, CT	1	14
Branford, CT	7	98
Brookfield, CT	2	29
Canaan, CT	1	15
Canton, CT	1	14
Colebrook, CT	1	15
Columbia, CT	1	15
Cornwall, CT	1	15
Coventry, CT	1	15
Eastford, CT	1	15
Ellington, CT	2	30
Essex, CT	1	15
Franklin, CT	1	15
Granby, CT	2	30
Hartland, CT	1	15
Killingworth, CT	1	15
Litchfield, CT	4	54
Lyme, CT	1	15
Monroe, CT	2	28
North Stonington, CT	1	14
Prospect, CT	2	30
Salem, CT	1	15
Southington, CT	3	44
Sterling, CT	1	14
Suffield, CT	1	15
Willington, CT	1	14
Windsor Locks, CT	2	30
Windsor, CT	4	57
Wolcott, CT	3	44
Woodstock, CT	1	15

Jurisdiction	Precincts	Hourly Observations
Washington, DC	66	857
Escambia County, FL	59	746
Hernando County, FL	25	320
Marion County, FL	120	1,560
Pasco County, FL	89	1,154
Taylor County, FL	1	13
Fulton County, GA	63	789
Baltimore City, MD	126	1,702
Caroline County, MD	7	97
Carroll County, MD	36	495
Algoma Township, MI	3	42
Augusta Township, MI	1	14
Banks Township, MI	1	14
Baroda Township, MI	1	14
Battle Creek City, MI	6	83
Bear Lake Township, MI	1	14
Beaver Township, MI	1	14
Bedford Township, MI	4	56
Belding City, MI	3	40
Bellevue Township, MI	1	12
Bertrand Township, MI	1	14
Big Creek City, MI	1	12
Blair Township, MI	1	14
Bloomfield Township - Missaukee County, MI	1	14
Bloomfield Township - Oakland County, MI	30	413
Blumfield Township, MI	1	14
Bridgewater Township, MI	1	14
Bridgman City, MI	1	14
Brighton Township, MI	4	54
Brookfield Township, MI	1	14
Buchanan Township, MI	1	14
Carson City, MI	1	14
Casnovia Township, MI	1	14
Charleston Township, MI	1	14
Charlotte City, MI	4	56
Chesaning Township, MI	2	28
City Of Alpena, MI	4	54
Clam Lake Township, MI	1	14
Clearwater Township, MI	1	14
Cleon Township, MI	1	14
Cohoctah Township, MI	1	14
Coloma City, MI	1	14

Jurisdiction	Precincts	Hourly Observations
Columbus Township, MI	2	27
Commerce Township, MI	10	135
Concord Township, MI	1	14
Cooper Township, MI	5	69
Courtland Township, MI	2	28
Deerfield Township, MI	2	28
Delta Township, MI	14	194
Detroit City, MI	50	665
DeWitt Township, MI	3	41
Dexter Township, MI	3	42
Durand City, MI	2	26
Eastpointe Township, MI	11	150
Echo Township, MI	1	14
Elba Township, MI	3	42
Ellis Township, MI	1	14
Eureka Township, MI	2	28
Fairfield Township, MI	1	14
Farmington City, MI	3	41
Filer Township, MI	1	14
Forest Township, MI	1	14
Franklin Township, MI	1	14
Free Soil Township, MI	1	13
Freedom Township, MI	1	14
Fruitland Township, MI	2	28
Fruitport Township, MI	4	54
Gobles City, MI	1	14
Grand Blanc Township, MI	11	150
Grattan Township, MI	2	28
Grosse Pointe Woods City, MI	2	27
Hagar Township, MI	1	14
Harrison City, MI	1	14
Hartford City, MI	1	14
Hartland Township, MI	5	70
Hatton Township, MI	1	14
Hayes Township, MI	3	42
Hazel Park City, MI	1	14
Highland Township, MI	3	39
Howell City, MI	31	423
Jefferson Township, MI	1	13
Juniata and Wells Townships, MI	1	13
Kalamazoo Township, MI	10	133
Kingsford City, MI	1	13
Lake Charter Township, MI	1	14
Lakefield Township, MI	1	14

Jurisdiction	Precincts	Hourly Observations
Lansing City, MI	35	437
Lansing Township, MI	5	65
LaSalle Township, MI	2	28
Leland Township, MI	1	14
Leslie Township, MI	1	14
Lima Township, MI	1	14
Litchfield City, MI	1	14
Locket Township, MI	1	14
Long Lake Township, MI	2	27
Lyndon Township, MI	1	14
Madison Township, MI	3	42
Manistee City, MI	2	28
Manistee County, MI	10	138
Marion Township, MI	4	56
Marquette City, MI	6	84
Mason City, MI	3	42
Metz Township, MI	1	14
New Buffalo City, MI	1	14
Novi City, MI	20	277
Oceola Township, MI	5	68
Olive Township, MI	1	13
Orchard Lake City, MI	1	14
Otsego City, MI	1	14
Ottawa County, MI	45	654
Parma Township, MI	1	14
Paw Township, MI	1	14
Pentland Township, MI	1	13
Petersburg City, MI	1	14
Pittsfield Township, MI	8	104
Pleasant Ridge City, MI	1	14
Port Huron City, MI	9	123
Portage City, MI	12	168
Portage Township, MI	3	42
Raisinville Township, MI	2	28
Richland Township, MI	3	41
Riverview City, MI	3	42
Saginaw Township, MI	13	170
Sand Beach Township, MI	1	14
Scio Township, MI	8	109
Scipio Township, MI	1	14
Sodus Township, MI	1	14
Somerset Township, MI	2	28
St. Charles Township, MI	2	25
St. Clair Shores City, MI	12	163

Jurisdiction	Precincts	Hourly Observations
St. Johns City, MI	3	42
St. Joseph City, MI	3	42
Sterling Heights City, MI	45	613
Sylvan Lake City, MI	1	12
Sylvan Township, MI	1	14
Tawas City, MI	1	14
Taylor City, MI	12	161
Traverse City, MI	7	97
Troy City, MI	25	344
Tuscola Township, MI	1	14
Utica City, MI	1	14
Vevay Township, MI	2	28
Vienna Township, MI	5	70
Walker City, MI	9	126
Waterford Township, MI	6	82
Watertown Township, MI	2	28
West Branch City - Missaukee County, MI	1	14
West Branch City - Ogemaw County, MI	1	14
Westland City, MI	16	216
Whitehall Township, MI	1	14
Wilson Township, MI	1	14
Windsor Township, MI	3	41
Ypsilanti Township, MI	8	107
Minneapolis City, MN	119	1,599
Douglas County, NE	211	2,793
Hamilton County, OH	200	2,707
Arlington County, VA	30	398
Bedford County, VA	30	409
Buchanan County, VA	11	154
Chesapeake City, VA	50	672
Chesterfield County, VA	65	873
Culpeper County, VA	15	210
Fairfax City, VA	4	54
Gloucester County, VA	11	157
Goochland County, VA	10	136
Greene County, VA	4	54
Hanover County, VA	28	383
Louisa County, VA	15	210
Orange County, VA	10	135
Petersburg City, VA	7	95
Prince William County, VA	65	876
Rockingham County, VA	29	402
York County, VA	8	106
	3,180	**42,203**

Appendix B. Regression Analysis of Demographic Factors Affecting Average Wait Times

Variable						
Non-white pct.	20.42*** 2.39	—	—	—	22.36*** (4.30)	20.13** (5.58)
Log (renter pct.)	—	1.24* (0.51)	—	—	0.20 (0.47)	0.05 (0.40)
Log (avg. income)	—	—	-1.77 (2.64)	—	0.17 (1.89)	-1.27 (1.49)
In-person voters (1,000s)	—	—	—	—	0.0002 (0.0006)	(0.0005) (0.0013)
Intercept	3.88*** (0.44)	12.0*** (2.2)	27.41 (29.1)	-0.56 (1.43)	2.05 (20.0)	17.8 (16.4)
N	2,830	2,776	2,830	2,830	2,776	2,776
R^2	.10	.04	.002	.0009	.12	.14
Fixed effects?	No	No	No	No	No	State

* $p < .05$
** $p < .01$
*** $p < .001$

Note: Robust standard errors reported in parentheses. Standard errors also clustered at the state level.

Endnotes

1 Total turnout statistics for 2018 are available at the United States Elections Project, "2018 November General

2 Nationwide wait times in this paragraph are based on responses to the 2016 and 2018 Cooperative Congressional Election Study. Available at: https://cces.gov.harvard.edu.

3 Presidential Commission on Election Administration, *The American Voting Experience: Report and Recommendations of the Presidential Commission on Election Administration*, January 2014. Available at: https://www.eac.gov/assets/1/6/Amer-Voting-Exper-final-draft-01-09-14-508.pdf.

4 The number of Election Day polling places comes from: U.S. Election Assistance Commission, Election Administration and Voting Survey, 2018. Available at: https://www.eac.gov/research-and-data/election-administration-voting-survey/.

5 Presidential Commission on Election Administration, *The American Voting Experience: Report and Recommendations of the Presidential Commission on Election Administration*, January 2014. Available at: https://www.eac.gov/assets/1/6/Amer-Voting-Exper-final-draft-01-09-14-508.pdf.

6 MIT-Caltech Voting Technology Project, *VTP Toolkit*. Available at: http://web.mit.edu/vtp/.

7 Stephen Pettigrew, "The Racial Gap in Wait Times: Why Minority Precincts Are Underserved by Local Election Officials," *Political Science Quarterly*, 132(2): 527-547, 2017.

8 Robert M. Stein, Christopher Mann, Charles Stewart III, et al., "Waiting to Vote in the 2016 Presidential Election: Evidence from a Multi-County Study." *Political Research Quarterly*, March 2019. Available at: https://journals.sagepub.com/doi/abs/10.1177/1065912919832374.

9 Charles Stewart III and Stephen Ansolabehere, "Waiting to Vote," *Election Law Journal*, 14(1): 47-53, 2015.

10 Pettigrew, Stephen, "Long Lines and Voter Purges: The Logistics of Running Elections in America," Harvard University, PhD dissertation. 2017.

11 The BPC/MIT Polling Place Line Study defines "least densely populated" as living in a ZIP code that is in the bottom quartile, in terms of population/square mile. It defines "most densely populated" as living in a ZIP code that is in the top quartile. The cut-off points of these two regions are 259/square mile and 3,894/square mile. The average wait time in the least densely populated region is 6.7 minutes; for the most densely populated region, it is 8.4 minutes.

12 Stephen Pettigrew, "The Racial Gap in Wait Times: Why Minority Precincts Are Underserved by Local Election Officials," *Political Science Quarterly*, 132(2): 527-547, 2017.

13 Charles Stewart III and Stephen Ansolabehere, "Waiting to Vote," *Election Law Journal*, 14(1): 47-53, 1985.

14 The 95 percent confidence interval of this estimate is 0.2 minutes.

15 The 95 percent confidence interval of this estimate is 0.3 percentage points.

16 The 95 percent confidence intervals of these estimates are 0.2 percentage points and 0.1 minutes, respectively.

17 Cooperative Congressional Election Study. Available at: https://cces.gov.harvard.edu.

18 United States Elections Project, "2018 November General Election Turnout Rates," December 14, 2018. Available at: http://www.electproject.org/2018g.

19 United States Election Project, "National General Election VEP Turnout Rates, 1789-Present." Available at: http://www.electproject.org/national-1789-present.

20 The correlation between the two variables shown in Figure 2 is r = 0.43.

21 The line of best fit uses the linear regression statistical technique.

22 Cooperative Congressional Election Study, 2014 and 2018. Available at: https://cces.gov.harvard.edu.

23 United States Election Project, "National General Election VEP Turnout Rates, 1789-Present." Available at: http://www.electproject.org/national-1789-present.

24 BPC/MIT Polling Place Line Study.

25 Ibid.

26 Ibid.

27 Charles Stewart III, *Managing Polling Place Resources*, Caltech/MIT Voting Technology Project, 2015.
Available at: http://web.mit.edu/vtp/Managing%20Polling%20Place%20Resources.pdf.

28 A "stable system" is one in which average values of the critical elements of the queue—the arrival rate and the amount of time a customer spends in the system—do not trend upward or downward but remain steady across time.

29 MIT-Caltech Voting Technology Project, *VTP Toolkit*.
Available at: http://web.mit.edu/vtp/.

30 In the case of voting, polls reach a utilization limit when the number of people who arrive in a period of time (like an hour) exceeds the number of people who can be served during that period. In the example here, the utilization limit is 60 people per hour, because the polling place can only check in 60 people per hour. If more than 60 people arrive per hour, the line must keep growing until arrivals stop. Even when slightly fewer than 60 people arrive per hour, the wait time will be long, because of the variability in when people arrive. However, the line will eventually stabilize, unlike the situation where the arrival rate exceeds the utilization limit.

31 At the risk of immodesty, the BPC/MIT Polling Place Line Study has had a special relationship with Virginia since 2015, in terms of helping to apply the principles of queuing theory to managing polling place resources. Part of that relationship involved providing many Virginia counties with feedback concerning the match between turnout and polling place resources in anticipation of the 2016 election. It is likely that this additional attention to planning played a role in helping Virginia cope with the 2018 turnout surge.

32 Voter registration and turnout statistics come from: U.S. Election Assistance Commission, Election Administration and Voting Survey, 2018. Available at: https://www.eac.gov/research-and-data/election-administration-voting-survey/.

33 BPC/MIT Polling Place Line Study.

34 Because poll workers generally recorded line lengths at the top of each hour, it is likely that some precincts in this study that recorded never having a line of more than 10 people in fact had a longer line at some other time in the hour. However, because line lengths are "sticky" over short periods of time, it is likely that the number of precincts in the study that had *unrecorded* lines of greater than 10 people is relatively small.

35 BPC/MIT Polling Place Line Study.

36 Ibid.

37 Ibid.

38 In the one peer-reviewed journal article that deeply explored the racial divide in wait times, Pettigrew shows that "election officials appear to systematically provide more poll workers and voting machines to white precincts than minority ones." Stephen Pettigrew, "The Racial Gap in Wait Times: Why Minority Precincts Are Underserved by Local Election Officials," *Political Science Quarterly*, 132(2): 528, 2017. To be clear, however, BPC and MIT did not gather data about precinct-level resource allocation among the precincts in this study and therefore cannot directly address the resource-allocation hypothesis in these jurisdictions.

39 BPC/MIT Polling Place Line Study.

40 A multiple regression framework simultaneously explores demographic factors.

41 Stephen Pettigrew, "The Racial Gap in Wait Times: Why Minority Precincts Are Underserved by Local Election Officials," *Political Science Quarterly*, 132(2): 527-547, 2017.

42 Charles Stewart III and Stephen Ansolabehere, "Waiting to Vote," *Election Law Journal*, 14(1): 47-53, 1985.

43 Robert M. Stein, Christopher Mann, Charles Stewart III, et al., "Waiting to Vote in the 2016 Presidential Election: Evidence from a Multi-County Study." *Political Research Quarterly*, March 2019.
Available at: https://journals.sagepub.com/doi/abs/10.1177/1065912919832374.

44 Charles Stewart III, "Waiting to Vote in 2012," *Journal of Law and Politics*, 28: 439-464, 2012-2013.

45 BPC/MIT Polling Place Line Study.

46 Ibid.

47 Ibid.

48 Ibid.

Bipartisan Policy Center

1225 Eye St NW, Suite 1000
Washington, DC 20005

bipartisanpolicy.org

202 - 204 - 2400

The Bipartisan Policy Center (BPC) is a Washington, D.C.-based think tank that actively fosters bipartisanship by combining the best ideas from both parties to promote health, security, and opportunity for all Americans. Our policy solutions are the product of informed deliberations by former elected and appointed officials, business and labor leaders, and academics and advocates who represent both ends of the political spectrum.

BPC prioritizes one thing above all else: getting things done.

@BPC_Bipartisan
facebook.com/BipartisanPolicyCenter
instagram.com/BPC_Bipartisan

Policy Areas

- Economy
- Energy
- Finance
- Governance
- Health
- Housing
- Immigration
- Infrastructure
- National Security

Bipartisan Policy Center

1225 Eye Street NW, Suite 1000
Washington, D.C. 20005

IDEAS. ACTION. RESULTS.

April 2019

CURRICULUM VITAE

Name:	Stephen C. Graves	Department:	Sloan School of Management
Date of Birth:	November 1951	Place of Birth:	Pittsfield, MA
Citizenship:	U.S.	Marital Status:	Married

Education:

School	Degree	Date
Dartmouth College	A.B.	1973
Dartmouth College	M.B.A.	1974
University of Rochester	M.S.	1976
University of Rochester	Ph.D.	1977

Title of Doctoral Thesis: The Multiproduct Production Cycling Problem for Stochastic Demand and Finite Production Capacity

Principal Fields of Interest: Operations Management, Applied Operations Research

Name and Rank of Other SSM Faculty in Same Field:

Gabriel R. Bitran	Professor
Joann de Zegher	Assistant Professor
Steven D. Eppinger	Professor
Vivek Farias	Professor
Charles H. Fine	Professor
Negin Golrezaei	Assistant Professor
Jonas Jonasson	Assistant Professor
Retsef Levi	Professor
Georgia Perakis	Professor
Thomas Roemer	Senior Lecturer
Zeynep Ton	Adjunct Professor
Nikolaos Trichakis	Associate Professor
Tauhid Zaman	Associate Professor
Yanchong Karen Zheng	Associate Professor

Non-M.I.T. Experience:

Employer	Position	Date
Educational Testing Service	Management Science Analyst	Summer 1972
Simonds Saw and Steel	Management Science Analyst	Summer 1973
University of Rochester	Research Assistant	Summer 1974
University of Rochester	Instructor	Summers 75-77
University of Rochester	Visiting Research Associate	Summers 79-80
Eastman Kodak	Management Science Analyst	Summers 80-81
Shanghai Institute of Mechanical Engineering	Visiting Professor	July 82-Jan 83
Optiant	Member of Advisory Board	2000 - 2009
Servigistics	Chief Scientist	2001 – 2004
JDA	Chief Science Advisor	2005 - 2011

History of M.I.T. Appointments:

Rank	Beginning	Ending
Assistant Professor, Sloan School of Management	7/77	6/81
Associate Professor, Sloan School of Management	7/81	6/87
Professor, Sloan School of Management	7/87	
Leaders for Manufacturing Professor	7/88	6/93
Deputy Dean	9/90	8/93
Abraham J. Siegel Professor of Management	10/95	
Professor, Engineering Systems Division (joint)	7/99	6/15
Professor, Mechanical Engineering Department (joint)	7/05	
Interim Director, Engineering Systems Division	9/12	12/13

Industrial Consulting Record:

Firm and Dates
Bausch and Lomb, 1976; Shycon Associates, 1980 - 1986; GTE Research Laboratories, 1981 - 1982, 1984, 1986; Illinois Central Gulf Railroad, 1982; C.S. Draper Laboratory, 1982 - 1984; ROLM Corporation, 1984, 1993; Palladian Software, 1986; GM Research Laboratories, 1986 – 1997, 2003 - 2004; W.R. Grace, 1987, 1991; Millipore, 1988; WearGuard, 1988; Alcoa, 1993 – 1994; Amazon.Com, 2001; Invistics, 2002 – 2005; Servigistics, 2001 – 2003; JDA, 2003 – 2011; Honeywell, 2003; FormFactor 2006; McMaster-Carr 2007; Sears Holdings, 2015; New York City, 2017; State of Michigan, 2017; Oniqua 2018.

Institute Activities:

Staff Member of Operations Research Center, 1977 - present
Undergraduate Advisor, 1978 - present
Freshman Advisor, 1991- 1998, 2002 - 2005, 2008 - present
Member of Sloan Program Committees: 1978 – 2013 (SB); 1978-1980 (SM); 1985-1987, 1994 – 1998, 2005 - 2008 (PhD).
Chair of Sloan Undergraduate Education Committee, 2010 - 2013
Member of Committee on Academic Performance, 1984-1986
Member of Committee on Discipline, 1995 – 1997
Chair of Committee on Discipline, 1997 – 2001
Member of Sloan Dean Search Committee, 1987
Member of Freshman Housing Committee, 1989
Acting CoDirector, Leaders for Manufacturing Program, 1989-1990
Chair of Parking and Transportation Committee, 1989-1995
Member of Parking and Transportation Committee, 2016 - 2019
CoDirector, Leaders for Manufacturing Program, 1994 - 2001
CoDirector, System Design and Management Program, 1999 - 2001
Chair of Task Force on ROTC, 1995 – 1996
Chair of Sloan Dean Search Committee, 1998
Chair of MIT Faculty, 2001 – 2003
Chair of Faculty Policy Committee, 2001 – 2003

Member of Task Force on Campus Security, 2001
Member, ad hoc committee on Access to and Disclosure of Scientific Information, 2002
Chair, review committee on Faculty Newsletter, 2002
Faculty Newsletter, Editorial Board, 2003 – 2009
Member of Faculty Advisory Committee for MIT Presidential Search, 2004 - 2005
Member of Committee on Undergraduate Admissions and Financial Aid, 2004 – 2006
Chair of Committee on Undergraduate Admissions and Financial Aid, 2007 – 2008
Member of ad hoc committee on MIT Disciplinary System, 2005
Member of ad hoc committee on MLK Visiting Professor Program, 2006
Member of Stellar faculty advisory committee, 2004 – 2010
Chair of Search Committee for Dean of Graduate Student Office, 2007
Chair of Dean for Graduate Education Search Advisory Committee, 2010
Chair of Committee on Graduate Policy, 2008 – 2011
Member of Commencement Committee, 2007 – 2011, 2018 – 2019
Member of Search Committee for Director of Student Financial Services, 2008- 2009
Chair of Search Committee for Director of Financial Aid, 2009 – 2010
Member of MIT150 Steering Committee, 2008 – 2011
Chair of ad hoc committee: Strategic Review of MIT Sloan's Undergraduate Programs, 2009
Member of Education Working Group of the MIT Planning Task Force, 2009
Member of NGS3 faculty advisory group, 2009- 2011
Member of Independent Activities Period (IAP) Subcommittee of the FPC, 2012
Member of Committee on the Undergraduate Program, 2011 – 2013
Chair of Committee on the Undergraduate Program, 2013 - 2014
Co-chair of Task Force for Graduate Student Professional Development, 2012 – 2013
Member of ROTC Oversight Committee, 2012-2014
Member of Employee Assistance Program (EAP) Advisory Committee, 2015 - 2019
Member of ad hoc Group on the Future of Libraries, 2015 – 2016
Member of Committee on Campus Planning, 2016 – 2017
Chair of Committee on Campus Planning, 2017 - 2018
Member of Committee on Community Giving, 2016 – 2019
Member of ad hoc Committee of Graduate Housing, 2017 – 2018
Member of DAPER Advisory Board, 2017 – 2019
Graduate Officer, IDSS, 2017 - 2019
Member of Educational Effectiveness planning group, MIT Accreditation, 2018 – 2019
Member of Committee on Student Life, 2018 - 2020

Professional Activities:

Associate Editor - *Operations Research,* 1981-1986; *Management Science*, 1983-1986, 2001 - 2003; *Manufacturing & Service Operations Management*, 1997 – 2008, 2015 - 2017
Department Editor - *Management Science*, 1987-1991
Area Editor – *Operations Research*, 2006 – 2008
Editor - *Manufacturing & Service Operations Management*, 2009 - 2014
Functional Area Editor - *Interfaces*, 1985-1986
Editor, Edelman Special Issue, *Interfaces*, 1989 - 2007
Member - INFORMS
Member of Student Affairs Committee for ORSA, 1980-1983
Edelman Award Committee, 1988 – 2007; 2011 & 2012 (Chair)
INFORMS (formerly TIMS/ORSA) Publication Committee, 1990-1998, 2006 - 2008
Vice President, Publications - INFORMS, 1994 – 1995

Awards:

Fellow of the Manufacturing and Service Operations Management Society
Fellow of the Production and Operations Management Society
INFORMS Fellow
1999 Billard Award for service at MIT
2012 MSOM Distinguished Service Award
Zaragoza Logistics Center: Medal of Distinction (2013)
INFORMS Case Competition, First Prize (2005)
M&SOM Best Paper Award (2017)
Member of National Academy of Engineering

Subjects Taught:

15.062	Decision Models for Management
15.761	Operations Management
15.763	Practice of Operations Management
15.764	Theory of Operations Management
15.053	Introduction to Management Science
15.770J	Transportation and Logistics Analysis
15.066J	System Optimization and Analysis for Manufacturing
15.762	Operations Management: Models and Applications
15.762J	Supply Chain Planning
15.763J	Manufacturing Systems and Supply Chain Design
15.A03	Operations Research Can be Fun (freshmen seminar)
EC.733J	D Lab Supply Chains (15.772J)
15.762x	Supply Chains for Manufacturing I (MITx)
15.763x	Supply Chains for Manufacturing II (MITx)

Publications**:**

Books

1. Handbook in Operations Research and Management Science, Volume 4: Logistics of Production and Inventory, edited by S. C. Graves, A. H. G. Rinnooy Kan and P. H. Zipkin, North-Holland, Amsterdam, 1993.

2. Handbook in Operations Research and Management Science, Volume 11: Supply Chain Management: Design, Coordination and Operation, edited by A. G. De Kok and S. C. Graves, Elsevier, Amsterdam, 2003.

<u>Papers</u>

3. Optimal Storage Assignment in Automatic Warehousing Systems, (with W.H. Hausman and L.B. Schwarz), *Management Science*, February 1976, Vol. 22, 629-638.

4. Single Cycle Continuous Review Policies for Arborescent Production/Inventory Systems, (with L.B. Schwarz), *Management Science*, January 1977, Vol. 23, 529-540.

5. Storage-Retrieval Interleaving in Automatic Warehousing Systems, (with W.H. Hausman and L.B. Schwarz), *Management Science*, May 1977, Vol. 23, 935-945.

6. A Note on 'Critical Ratio Scheduling: An Experimental Analysis', *Management Science*, August 1977, Vol. 23, 1358-1359.

7. On 'Production Runs for Multiple Products: The Two-Product Heuristic', (with R.W. Haessler), *Management Science*, July 1978, Vol. 24, 1194-1196.

8. Scheduling Policies for Automatic Warehousing Systems: Simulation Results, (with W.H. Hausman and L.B. Schwarz), *AIIE Transactions,* September 1978, Vol. 10, 260-270.

9. A Note on the Deterministic Demand Multi-Product Single-Machine Lot Scheduling Problem, *Management Science*, March 1979, Vol. 25, 276-280.

10. A Methodology for Studying the Dynamics of Extended Logistics Systems, (with J. Keilson), *Naval Research Logistics Quarterly,* July 1979, Vol. 26, 169-197.

11. An n-Constraint Formulation of the (Time Dependent) Traveling Salesman Problem, (with K.R. Fox and B. Gavish), *Operations Research*, July-August 1980, Vol. 28, 1018-1021.

12. The Multi-Product Production Cycling Problem, *AIIE Transactions*, September 1980, Vol. 12, 233-240.

13. A One-Product Production/Inventory Problem with Continuous Review Policy, (with B. Gavish), *Operations Research,* September-October 1980, Vol. 28, 1228-1236.

14. Production/Inventory Systems with a Stochastic Production Rate Under a Continuous Review Policy, (with B. Gavish), *Computers and Operations Research,* 1981, Vol. 8, 169-183.

15. Multistage Lot-Sizing: An Iterative Procedure, in TIMS Studies in Management Science, *Multi-Level Production/Inventory Systems: Theory and Practice*, edited by L.B. Schwarz, 1981, Vol. 16, 95-109.

16. The Compensation Method Applied to a One-Product Production Inventory Model, (with J. Keilson), *Mathematics of Operations Research*, May 1981, Vol. 6, 246-262.

17. A Review of Production Scheduling, *Operations Research*, July-August 1981, Vol. 29, 646-675.

18. Problem Formulations and Numerical Analysis in Integer Programming and Combinatorial Optimization, (with J.F. Shapiro), in *Mathematical Programming with Data Perturbations I*, edited by A.V. Fiacco, 1982, 131-148.

19. Using Lagrangean Techniques to Solve Hierarchical Production Planning Problems, *Management Science*, March 1982, Vol. 28, 260-275.

20. The Application of Queueing Theory to Continuous Perishable Inventory Systems, *Management Science*, April 1982, Vol. 28, 400-406.

21. A Multiple-Item Inventory Model with a Job Completion Criterion, *Management Science*, November 1982, Vol. 28, 1134-1137.

22. System Balance for Extended Logistic Systems, (with J. Keilson), *Operations Research*, March-April 1983, Vol. 31, 234-252.

23. An Integer Programming Procedure for Assembly System Design Problem, (with B. Lamar), *Operations Research*, May-June 1983, Vol. 31, 522-545.

24. Scheduling of Re-entrant Flow Shops, (with H.C. Meal, D. Stefek, and A.H. Zeghmi), *Journal of Operations Management,* August 1983, Vol. 3, 197-207.

25. A Simple Stochastic Model for Facility Planning in a Mental Health Care System, (with H.S. Leff, J. Natkins, and M. Senger), *Interfaces*, October 1983, Vol. 13, 101-110.

26. Deep-Draft Dredging of U.S. Coal Ports: A Cost-Benefit Analysis, (with M. Horwitch and E.H. Bowman), *Policy Sciences*, Vol. 17, 1984.

27. A Study of Production Smoothing in a Job Shop Environment, (with A.B. Cruickshanks and R.D. Drescher), *Management Science*, March 1984, Vol. 30, 368-380.

28. A Minimum Concave-Cost Dynamic Network Flow Problem with an Application to Lot-Sizing, (with J.B. Orlin), *Networks*, Vol. 15, 1985.

29. Description and Field Test of a Mental Health System Resource Allocation Model, (with H.S. Leff, J. Natkins, and J. Bryan), *Administration in Mental Health*, Fall 1985, Vol. 13, 43-68.

30. Continuous-Review Policies for a Multi-Echelon Inventory Problem with Stochastic Demand, (with M. DeBodt), *Management Science*, October 1985, Vol. 31, 1286-1299.

31. A Multi-Echelon Inventory Model for a Repairable Item with One-for-One Replenishment, *Management Science*, October 1985, Vol. 31, 1247-1256.

32. An LP Planning Model for a Mental Health Community Support System, (with H.S. Leff and M. Dada), *Management Science*, February 1986, Vol. 32, 139-155.

33. Overlapping Operations in Material Requirements Planning, (with M.M. Kostreva) *Journal of Operations Management,* Vol. 6, No. 3, May 1986, 283-294.

34. Two-Stage Production Planning in a Dynamic Environment, (with H.C. Meal, S. Dasu, Y. Qiu), in Lecture Notes in Economics and Mathematical Systems, *Multi-Stage Production Planning and Inventory Control,* edited by S. Axsater, Ch. Schneeweiss, and E. Silver, Springer-Verlag, Berlin, 1986, Vol. 266, 9-43.

35. A Tactical Planning Model for a Job Shop, *Operations Research*, July-August 1986, Vol. 34, 522-533.

36. Equipment Selection and Task Assignment for Multiproduct Assembly System Design, (with C.A. Holmes Redfield) *International Journal of Flexible Manufacturing Systems,* 1988, Vol. 1, No. 1, pp. 31-50.

37. Safety Stocks in Manufacturing Systems, *Journal of Manufacturing and Operations Management,* 1988, Vol. 1, No. 1, pp. 67-101.

38. Determining the Spares and Staffing Level for a Repair Depot, *Journal of Manufacturing and Operations Management,* 1988*,* Vol. 1, No. 2, pp. 227-241.

39. A Composite Algorithm for the Concave-Cost Network Flow Problem, (with A. Balakrishnan) *Networks*, Vol. 19, 1989, pp. 175-202.

40. A Tactical Planning Model for Manufacturing Subcomponents of Mainframe Computers, (with C. Fine), *Journal of Manufacturing and Operations Management,* 1989, Vol. 2, No. 1, pp. 4-34.

41. A Model for the Configuration of Incoming WATS Lines, (with R. H. Blake and P. C. Santos), *Queueing Systems*, 1990, Vol. 7, No. 1, pp. 3-21.

42. Principles on the Benefits of Manufacturing Process Flexibility, (with W. C. Jordan), *Management Science*, April 1995, Vol. 41, No. 4, pp. 577 - 594.

43. A Multi-Echelon Inventory Model with Fixed Replenishment Intervals, *Management Science*, January 1996, Vol. 42, No. 1, pp. 1-18.

44. Cyclic Scheduling in a Stochastic Environment, (with H. Zhang), *Operations Research*, November-December 1997, Vol. 45, No. 6, pp. 894-903.

45. A Dynamic Model for Requirements Planning with Application to Supply Chain Optimization, (with D. B. Kletter and W. B. Hetzel) *Operations Research*, May-June 1998, Vol. 46, Supp. No. 3, pp. S35-S49.

46. OMAC: A System for Operations Modeling and Analysis, (with K. N. McKay and D. B. Kletter), *Annals of OR*, Vol. 72, 1997, pp. 241-264.

47. Reducing Flow Time in Aircraft Manufacturing, (with Jackson Chao), *Production and Operations Management*, Spring 1998, Vol. 7, No. 1, pp. 38-52.

48. A Single-Item Inventory Model for a Non-Stationary Demand Process, *Manufacturing & Service Operations Management*, 1999, Vol. 1, No. 1, pp. 50-61.

49. Optimizing Strategic Safety Stock Placement in Supply Chains, (with S. P. Willems), *Manufacturing & Service Operations Management*, 2000, Vol. 2, No. 1, pp. 68 – 83.

50. Manufacturing Planning and Control, in Handbook of Applied Optimization, edited by P. Pardalos and M. Resende, Oxford University Press, New York, 2002, pp. 728 - 746.

51. Technology Portfolio Management: Optimizing Interdependent Projects over Multiple Time Periods, (with M. Dickinson and A. Thornton), *IEEE Transactions on Engineering Management*, Vol. 48, No. 4, November 2001, pp. 518-527.

52. Creating an Inventory Hedge for Markov-Modulated Poisson Demand: Application and Model, (with H. S. Abhyankar), *Manufacturing & Service Operations Management*, Fall 2001, Vol. 3, No. 4, pp. 306 - 320.

53. Process Flexibility in Supply Chains, (with B. T. Tomlin), *Management Science*, July 2003, Volume 49, Number 7, pp. 907 - 919.

54. Supply Chain Design: Safety Stock Placement and Supply Chain Configuration, (with S. Willems), Chapter 3 in Handbook in Operations Research and Management Science, Volume 11: Supply Chain Management: Design, Coordination and Operation,, edited by A. G. De Kok and S. C. Graves, Elsevier, Amsterdam, 2003, pp. 95 - 132.

55. Optimizing the Supply-Chain Configuration for New Products, (with S. Willems), *Management Science*, August 2005, Vol. 51, No. 8, pp. 1165 – 1180.

56. Logistics Network Design with Supplier Consolidation Hubs and Multiple Shipment Options, (with M.L.F. Cheong, R. Bhatnagar), *Journal of Industrial and Management Optimization*, Volume 3, Number 1, February 2007, pp. 51–69.

57. A Single-Product Inventory Model for Multiple Demand Classes, (with H. Arslan, T. Roemer) *Management Science*, September 2007, Vol. 53, No. 9, pp. 1486 – 1500.

58. Flexibility Principles, Chapter 3 in Building Intuition: Insights from Basic Operations Management Models and Principles, edited by D. Chhajed and T. J. Lowe, Springer Science+Business Media, LLC, New York, 2008, pp. 33 – 49.

59. Little's Law, (with J. D. C. Little), Chapter 5 in Building Intuition: Insights from Basic Operations Management Models and Principles, edited by D. Chhajed and T. J. Lowe, Springer Science+Business Media, LLC, New York, 2008, pp. 81 – 100.

60. Strategic Inventory Placement in Supply Chains: Non-Stationary Demand, (with S. Willems) *Manufacturing & Service Operations Management*, Spring 2008, Vol. 10, No. 2, pp. 278 – 287.

61. The Benefits of Re-Evaluating Real-Time Order Fulfillment Decisions, (with P. Xu and R. Allgor), *Manufacturing & Service Operations Management,* Spring 2009, Vol. 11, No. 2, pp 340-355.

62. Strategic Safety Stocks in Supply Chains with Evolving Forecasts, (with Tor Schoenmeyr) *Manufacturing & Service Operations Management,* Fall 2009, Vol. 11, No. 4, pp 657-673.

63. Optimal Planning Quantities for Product Transition, (with Hongmin Li and Donald Rosenfield), *Production and Operations Management*, March-April 2010, Vol. 19, No. 2, pp 142 – 155.

64. Uncertainty and Production Planning, in Production and Inventories in the Extended Enterprise , edited by Karl G. Kempf, Pınar Keskinocak, and Reha Uzsoy, *International Series in Operations Research & Management Science* Volume 151, Springer US, 2011, pp 83 – 101.

65. Setting Planned Lead Times for a Make-To-Order Production System under Master Schedule Smoothing, (with C. C. Teo and R. Bhatnagar), *IIE Transaction*, 2011, Vol. 43, No. 6, pp. 399-414.

66. How to Catch a Tiger: Understanding Putting Performance on the PGA Tour, (with Douglas Fearing and Jason Acimovic), *Journal of Quantitative Analysis in Sports*, 2011, Vol. 7: Issue 1, Article 5. DOI: 10.2202/1559-0410.1268.

67. Pricing Decisions during Inter-generational Product Transitions, (with Hongmin Li) *Production and Operations Management*, January-February 2012, Vol. 21, No. 1, pp 14-28.

68. Remanufacturing and Energy Savings, (with T. Gutowski, S. Sahni, and A. Boustani), *Environmental Science & Technology*, 2011, Vol. 45, pp. 4540-4547.

69. An Application of Master Schedule Smoothing and Planned Lead Time Control, (with C. C. Teo and R. Bhatnagar), *Production and Operations Management,* March-April 2012, Vol. 21, No. 2, pp 211 - 223.

70. Ship-Pack Optimization in a Two-Echelon Distribution System, (with Naijun Wen and Justin Ren), *European Journal of Operational Research*, August 2012, Vol. 220, Issue 3, pp. 777-785.

71. Optimal Capacity Conversion for Product Transitions under High Service Requirements, (with Hongmin Li and Woonghee Tim Huh), *Manufacturing & Service Operations Management*, Winter 2014, Vol. 16, No. 1, pp. 46-60.

72. A Forecast-driven Tactical Planning Model for a Serial Manufacturing Systems, (with Pallav Chhaochhria) *International Journal of Production Research*, December 2013, 51:23-24, pp. 6860-6879.

73. Water Desalination Supply Chain Modeling and Optimization: The Case of Saudi Arabia, (with Malak T. Al-Nory) *IDA Journal of Desalination and Water Reuse,* Vol. 5, No. 2 (2013) pp 64 - 74.

74. Supply Chain Design for the Global Expansion of Manufacturing Capacity in Emerging Markets, (with Stefan Weiler, Dayán Páez, Jung-Hoon Chun, Gisela Lanza), *CIRP Journal of Manufacturing Science and Technology*, Vol. 4, No. 3 (265-280), 2011.

75. A Network Flow Approach for Tactical Resource Planning in Outpatient Clinics, (with Thu Ba T. Nguyen, Appa Iyer Sivakumar), *Health Care Management Science*, Vol. 18, No. 2 (2015): pp.124-136.

76. Desalination Supply Chain Decision Analysis and Optimization, (with Malak T. Al-Nory, Alexander Brodsky, Burçin Bozkaya), *Desalination* Vol. 347 (2014), pp. 144-157.

77. Making Better Fulfillment Decisions on the Fly in and Online Retail Environment, (with J. Acimovic), *Manufacturing & Service Operations Management,* Winter 2015, Vol. 17, No. 1, pp 34-51.

78. Setting Optimal Production Lot Sizes and Planned Lead Times in a Job Shop System, (with Rong Yuan), *International Journal of Production Research*, (2016), Vol. 54, Issue 20, pp 6105 - 6120. DOI: 10.1080/00207543.2015.1073859.

79. OM Forum - Practice-Based Research in Operations Management: What It Is, Why Do It, Related Challenges, and How to Overcome Them, (with Jeremie Gallien and Alan Scheller-Wolf) *Manufacturing & Service Operations Management*, Winter 2016, Vol. 18, No. 1, pp 5 - 14. http://dx.doi.org/10.1287/msom.2015.0566

80. Strategic Safety Stock Placement in Supply Chains with Capacity Constraints (with Tor Schoenmeyr) *Manufacturing & Service Operations Management*, Summer 2016, Vol. 18, No. 3, pp 445 - 460. http://dx.doi.org/10.1287/msom.2016.0577.

81. Inventory Management in a Consumer Electronics Closed-Loop Supply Chain, (with Andre Calmon), *Manufacturing & Service Operations Management,* Fall 2017, Vol. 19, No. 4, pp 568 - 585. https://doi.org/10.1287/msom.2017.0622

82. Scheduling Rules to Achieve Lead-time Targets in Outpatient Appointment Systems, (with Thu Ba T. Nguyen, Appa Iyer Sivakumar), *Health Care Management Science*, December 2017, Vol. 20, No. 4, pp 578-589. http://dx.doi.org/10.1007/s10729-016-9374-2.

83. No Magic Bullet: A Theory-based Meta-analysis of Markov Transition Probabilities in Studies of Service Systems for Persons with Serious Mental Illness, (with H. Stephen Leff, Clifton Chow) *Psychiatric Services* (2017), Vol. 68, No. 3, pp 278-287, http://dx.doi.org/10.1176/appi.ps.201500523.

84. Mitigating Spillover in Online Retailing via Replenishment, (with J. Acimovic), *Manufacturing & Service Operations Management*, Summer 2017, Vol. 19, No. 3 pp. 419-436. https://doi.org/10.1287/msom.2016.0614 . Available at https://ssrn.com/abstract=2459097.

85. Stowage Decisions in Multi-zone Storage Systems, (with Rong Yuan and Tolga Cezik), *International Journal of Production Research* (2018) Vol. 56, No. 1-2, pp 333-343. https://doi.org/10.1080/00207543.2017.1398428 Available at SSRN: https://ssrn.com/abstract=2990432

86. Performance Evaluation of Material Separation in a Material Recovery Facility using a Network Flow Model, (with Karine Ip, Mariapaola Testa, Anne Raymond and Timothy Gutowski), *Resources, Conservation and Recycling* 131 (2018): 192-205

87. Capacity Planning with Demand Uncertainty for Outpatient Clinics, (with Thu Ba T. Nguyen, Appa Iyer Sivakumar), *European Journal of Operational Research* 267, no. 1 (2018): 338-348.

88. Velocity-based Storage Assignment in Semi-automated Storage Systems, (with Rong Yuan and Tolga Cezik), *Production and Operations Management* (2019), Vol. 28, No. 2, Feb. 2019, pp. 354 – 373. https://doi.org/10.1111/poms.12925 Available at: SSRN: https://ssrn.com/abstract=2889354.

89. Integrated planning for design and production in two-stage recycling operations, (with Jiyoun C. Chang, Randolph E. Kirchain and Elsa A. Olivetti.) *European Journal of Operational Research*, Vol. 273, no. 2 (2019): 535-547. https://doi.org/10.1016/j.ejor.2018.08.022

Proceedings

1. A Mathematical Programming Procedure for Equipment Selection and System Evaluation in Programmable Assembly, (with D.E. Whitney), *Proceedings of the 18th IEEE Conference on Decision and Control,* Fort Lauderdale, Florida, December 1979, 531-536.

2. Extensions to a Tactical Planning Model for a Job Shop, *Proceedings of the 27th IEEE Conference on Decision and Control*, Austin, Texas, December 1988, pp. 1850-1855.

3. Using Simulated Annealing to Select Least-Cost Assembly Sequences, (with J. M. Milner and D. E. Whitney), *Proceedings of IEEE Conference on Robotics and Automation*, May 1994.

4. Spatial Yield Modeling for Semiconductor Wafers, (with A. I. Mirza, G. O' Donoghue, and A. W. Drake), *Proceedings of IEEE/SEMI Advanced Semiconductor Manufacturing Conference*, November 1995

5. Strategic Safety Stock Placement in Supply Chains, (with S. Willems) *Proceedings of the 1996 MSOM Conference*, Dartmouth College, Hanover NH, June 1996, pp. 299 - 304.

6. Optimizing Monsanto's Supply Chain under Uncertain Demand, (with C. Gutierrez, M. Pulwer, H. Sidhu and G. Weihs), *Annual Conference Proceedings - Council of Logistics Management*, Orlando FL, October 1996, pp. 501-516.

7. Optimizing the Supply-Chain Configuration for New Products, (with S. P. Willems), *Proceedings of the 2000 MSOM Conference*, Ann Arbor, MI, 2000, 8 pp.

8. Tactical Shipping and Scheduling at Polaroid with Dual Lead-Times, (with Kermit Threatte), *Proceedings of the 2002 SMA Conference*, Singapore, 2002, 8 pp.

9. A Base Stock Inventory Model for a Remanufacturable Product, *Proceedings of the 2003 SMA Conference*, Singapore, 2003, 7 pp.

10. Optimizing Safety Stock Placement in General Network Supply Chains, (with K. Lesnaia), *Proceedings of the 2004 SMA Conference*, Singapore, 2004, 7 pp.

11. Traditional Inventory Models in an E-Retailing Setting: A Two-Stage Serial System with Space Constraints, (with R. Allgor and P. Xu), *Proceedings of 2004 SMA Conference*, Singapore, 2004, 6 pp.

12. Logistics Network Design with Differentiated Delivery Lead-Time: Benefits and Insights, (with M.L.F. Cheong, and R. Bhatnagar), *Proceedings of 2005 SMA Conference*, Singapore, 20 pp.

13. An Extension to the Tactical Planning Model for a Job Shop: Continuous-Time Control, (with C. C. Teo, and R. Bhatnagar), *Proceedings of 2005 SMA Conference*, Singapore, 8 pp.

14. The Complexity of Safety Stock Placement in General-Network Supply Chains, (with K. Lesnaia, and I. Vasilescu), *Proceedings of the 2005 SMA Conference*, Singapore, 5 pp.

15. The Benefits of Re-Evaluating Real Time Fulfillment Decisions, (with P. Xu and R. Allgor), *Proceedings of 2005 SMA Conference*, Singapore, 7 pp.

16. Performance Analysis of Order Fulfillment for Low Demand Items in E-tailing, (with P. Chhaochhria), *Proceedings of 2007 SMA Conference*, Singapore, 5 pp.

17. Capacity Planning in a General Supply Chain with Multiple Contract Types, (with X. Huang), *Proceedings of 2007 SMA Conference*, Singapore, 6 pp.

18. Reusing Personal Computer Devices – Good or Bad for the Environment?, (with S. Sahni, A. Boustani and T. Gutowski) IEEE/International Symposium on Sustainable Systems and Technology, Washington D.C, 2010

19. Appliance Remanufacturing and Life Cycle Energy and Economic Savings, (with S. Sahni, A. Boustani and T. Gutowski) IEEE/International Symposium on Sustainable Systems and Technology, Washington D.C, 2010.

20. Water Desalination Supply Chain Modeling and Optimization, (with Malak T. Al-Nory), Data Engineering Workshops (ICDEW), 2013 IEEE 29th International Conference, April 2013.

<u>Working Papers and Technical Reports</u>

W1. The Travelling Salesman Problem and Related Problems, (with B. Gavish), Operations Research Center, M.I.T., Working Paper No. 078-78, July 1978, revised and retitled, March 1981.

W2. A Research Agenda for Models to Plan and Schedule Manufacturing Systems, (with C. Abraham, B. Dietrich, W. Maxwell, and C. Yano), Sloan School of Management, M.I.T., Working Paper No. 1689-85, revised July 1985.

W3. Principles on the Benefits of Manufacturing Process Flexibility, (with W. C. Jordan), Sloan School of Management, M.I.T. Working Paper No. 3296-91-MSA, May 1991 (GM Research Laboratories Research Publication GMR-7310).

W4. An Analytic Approach for Demonstrating the Benefits of Limited Flexibility, (with W. C. Jordan), Sloan School of Management, M.I.T. Working Paper No. 3297-91-MSA, May 1991 (GM Research Laboratories Research Publication GMR-7341).

W5. Creating an Inventory Hedge for Markov-Modulated Poisson Demand: Application and Model, (with H. S. Abhyankar), January 2000, long version. (short version published in M&SOM.

W6. Optimizing Strategic Safety Stock Placement in Supply Chains, (with S. Willems), August 1998, long version. (short version published in M&SOM).

W7. Strategic Inventory Placement in Supply Chains: Nonstationary Demand, (with S. Willems), August 2002 working paper (substantially revised version published in M&SOM).

W8. A Constant-Inventory Tactical Planning Model for a Job Shop, (with J. S. Hollywood), working paper, January 2001, revised March 2004, January 2006, 36 pp.

W9. A Dual-Channel Vendor-Buyer System with Minimum Purchase Commitment, with (Y. Wang and R. Bhatnagar), working paper, June 2008, 33 pp.

W10. Capacity Planning in a General Supply Chain with Multiple Contract Types – Single Period Model, (with Xin Huang), June 2008, revised September 2008, 41 pp

W11. Ship-pack Optimization in a Two-echelon Distribution System with Product Obsolescence, (with Elnaz Karimi and Z. Justin Ren). *Available at SSRN 3242756* (2018).

W12. Coordination of Multi-Echelon Supply Chains Using the Guaranteed Service Framework, (with Tor Schoenmeyr). *Available at SSRN 3243806* (2018).

W13. Warranty Matching in a Consumer Electronics Closed-Loop Supply Chain, (with Andre P. Calmon and Stef Lemmens). *Available at SSRN 3357683* (2019).

Teaching Cases

1. Steel Works, Inc, prepared by David Kletter, 1996

2. Meditech Surgical, prepared by Bryan Gilpin, 1995.

3. Apollo Paper Company, prepared by Charles DeWitt, 1995.

4. Use of a Queuing Model to Design a Lean System, prepared by Jamie Flinchbaugh, 2002

5. The Challenge at Instron, prepared by Dan Wheeler, 2000.

6. H. C. Starck, Inc., prepared by Thomas J. Carroll, 2000.

7. Ford Pan-European Durable Containers, prepared by Carmelo Anthony Palumbo, 2002.

8. Reebok NFL Replica Jerseys: A Case for Postponement, prepared by John C. W. Parsons, 2005.

9. American Axle and Manufacturing: Determining the Optimal Number of Bar Lengths for Axle Shaft Production, prepared by Heath Holtz, 2005.

10. Production Planning for Chemical Manufacturing, prepared by Shardul Phadnis, 2007.

Invited Presentations (Partial List up to 1992):

1. "Improved Scheduling for Automatic Warehousing Systems: Simulation Tests," (with W.H. Hausman and L.B. Schwarz), Joint ORSA/TIMS National Meeting, New York, New York, May 1978.

2. "Logistic Failure vs. Mission Failure in Reliability Specifications," (with J. Keilson), Department of Defense Acquisition Research Symposium, Hershey, Pennsylvania, June 1978.

3. "A Methodology for Studying the Dynamics of Extended Logistics Systems," (with J. Keilson), Conference on Multi-Echelon Inventory Systems, George Washington University, November 1978.

4. "Multistage Lot-Sizing: An Iterative Procedure," Joint ORSA/TIMS Meeting, New Orleans, May 1979 (Also Purdue, April 1979).

5. "The Introduction of Feedback into a Hierarchical Production Planning System," TIMS XXIV International Meeting, Honolulu, June 1979.

6. "Production Scheduling: Theory and Practice," TIMS XXIV International Meeting, Honolulu, June 1979.

7. "System Balance for Extended Logistics Systems," (with J. Keilson), Conference on Multi-Echelon Inventory Systems, Philadelphia, Pennsylvania, November 1979.

8. "Base Stock Systems for Multistage Planning," Conference on Multi-Echelon Inventory Systems, Chapel Hill, North Carolina, June 1980.

9. "Optimization-Based Approaches to Vehicle Routing Problems," (with T.L. Magnanti), Joint ORSA/TIMS National Meeting, Colorado Springs, Colorado, November 1980.

10. "A Mathematical Programming Heuristic for Manufacturing System Design and Evaluation," (with B.W. Lamar) CORS/TIMS/ORSA National Meeting, Toronto, May 1981.

11. "The Dynamics of a Multiechelon Inventory System for a Repairable Item," (with J. Keilson), ORSA/TIMS National Meeting, Houston, October 1981.

12. "A Study of Production Smoothing in a Job Shop," (with A.B. Cruickshanks and R.D. Drescher), TIMS/ORSA National Meeting, Detroit, April 1982.

13. "Scheduling of Re-entrant Flow Shops," (with H.C. Meal, D. Stefek, A.H. Zeghmi), TIMS/ORSA National Meeting, Chicago, May 1983.

14. "An LP Planning Model for a Mental Health Community Support System," (with M. Dada and H.S. Leff), ORSA/TIMS National Meeting, Orlando, November 1983.

15. "Operational Analysis of a Job Shop," TIMS/ORSA National Meeting, San Francisco, May 1984.

16. "Two-Stage Production Planning in a Dynamic Environment," (with H.C. Meal), ORSA/TIMS National Meeting, Dallas, November 1984.

17. "Determining the Spares and Staffing Levels for a Repair Depot," TIMS/ORSA National Meeting, Boston, May 1985.

18. "Developing and Use of a Production Flow Plan," ORSA/TIMS National Meeting, Atlanta, November 1985.

19. "Safety Stocks in Manufacturing Systems," ORSA/TIMS National Meeting, Miami, October 1986.

20. "Equipment Selection and Task Assignment for Multiproduct Assembly System Design," (with C.A. Holmes), ORSA/TIMS National Meeting, St. Louis, October 1987.

21. "A Multiechelon Inventory Model for Fixed Reorder Intervals," TIMS/ORSA National Meeting, Washington, DC, April 1988.

22. "Production Planning in a Dynamic Environment," ORSA/TIMS National Meeting, Denver, October 1988. (Also, Yale, November 1988, Carnegie-Mellon, April 1989.)

23. "Cyclic Schedules in Stochastic Environments," CORS/TIMS/ORSA National Meeting, Vancouver, Canada, May 1989.

24. "Production Planning over a Multiplant Operation," ORSA/TIMS National Meeting, Philadelphia, October 1990.

25. "Principles on the Benefits of Manufacturing Flexibility," (with W. C. Jordan), TIMS/ORSA National Meeting, Nashville, May 1991. (Also, University of Minnesota, February 1991, Ohio State, November 1991).

26. "Some Thoughts on Inventory Modeling and Diagnostics," UCLA Conference in Honor of El Buffa, Los Angeles, November 1991.

27. "Reducing Flow Time in Aircraft Manufacturing," (with Jackson Chao), ORSA/TIMS National Meeting, San Francisco, October 1992.

Thesis Supervision (Partial List):

R. Blake, Allocation of Items under Fixed Capacity, S.M., June 1978 (reader).

M. Pendrock, A Hierarchical Approach to Integrated Production and Distribution Planning, S.M. June 1978 (reader).

A. Dutra, The Impact of Multiple Objectives on Strategic Decision Making: A Case Analysis of the *Sloan Management Review,* S.M., June 1979.

N. Zarin, A Mathematical Model of the Deinstitutionalization of the Cambridge-Somerville Mental Health Region, S.M., June 1979.

M. Cross, Business Planning for Small Manufacturing Companies, S.M., June 1980.

B. Lamar, Optimal Machine Selection and Task Assignment in an Assembly System Design Problem, S.M., September 1980.

M. Ibrahim, Modeling and Analysis of Automated Manufacturing Systems with Focus on Equivalence and Computational Complexity, S.M., May 1981.

M. Neel, A Contract Engineering Model, A Work Force Management Tool, S.M., April 1981.

T. Quinlan, Management Information and Control Systems for Hospital Supplies: A Case Study, S.M., June 1981.

A.B. Cruickshanks and R.D. Drescher, A Case Study of Production Smoothing in a Job Shop Environment, Joint S.M., February 1982.

D. Stefek, A Periodic Production Scheduling Problem, S.M., June 1982.

C. Olson, A Prototype System for Hierarchical Production Planning, S.M., June 1983.

D. Choing, The Role of Buffer Stocks in a Re-Entrant Flow Shop, S.M., June 1983.

R. Gould, Quantitative Tools for the Optimization of Selling Efforts in Metropolitan Cable Television Systems, S.M., February 1984.

P.C. Santos, An Optimization Model for the Configuration of Incoming WATS Lines, S.M., June 1984.

A.H. Zeghmi, Inventory Buffers for a Production Line with Controllable Production Rates, Ph.D., September 1985.

C.A. Holmes, Equipment Selection and Task Assignment for Multiproduct Assembly System Design, S.M., January 1987.

S.H. Parrish, Extensions to a Model for Tactical Planning in a Job Shop Environment, S.M., June 1987.

S. Mihara, A Tactical Planning Model for a Job Shop with Unreliable Work Stations and Capacity Constraints, S.M., January 1988.

J. Wagner, Stochastic Programming with Recourse Applied to Groundwater Quality Management, Ph.D., June 1988.

G. Sy-Quia, A Study of Production Loading in a Job Shop, S.M., June 1988.

L. Dickey, Where Should Safety Stock be Held to Minimize Costs and Maximize Flexibility? S.M., May 1989.

G. Amblard, Rationale for the Use of Subassemblies in Production Systems: A Comparative Look at Sequential and Arborescent Systems, S.M., May 1989.

C. Cooprider, Equipment Selection and Assembly System Design Under Multiple Cost Scenarios, S.M., June 1989.

E. Reifschneider, Scheduling Jobs in a Multi-Station Plant, B.S., June 1989.

S. Pappu, A Dual-Ascent Algorithm for Finding the Optimal Testing Strategy, S.M., June 1989.

H. Zhang, Cyclic Scheduling in a Stochastic Environment, Ph. D., May 1990.

C. Fu, An Investigation of the Development of Product Design Specifications: A Conceptual Development and a Case Study, S.M., June 1990.

R. Munroe, A Framework for Product Development Based on Quality Function Deployment, Traditional Decision-Making Theory, and Design Practice, S.M., June 1990.

R. M. Coleman, The Effects of Design, Manufacturing Processes, and Operations Management on the Assembly of Aircraft Composite Structure, S.M., June 1991.

C. Papouras, Lead Time and Inventory Reduction in Batch Chemical Manufacturing, S.M., June 1991.

T. Taylor, Evaluating and Selecting Manufacturing Flexibility, S.M., June 1991.

K. Elsesser, The Validation of a Simulation Model for the Allocation of Mental Health Services, S.M., June 1991.

J. Chao, Analysis of Variance Impact on Manufacturing Flow Time, S.M., June 1991.

B. Koetje, Improving Cycle Times in Batch Chemical Operations, S.M., June 1991.

C. Athaide, Capacity Allocation and Safety Stocks in Manufacturing Systems, Ph. D., June 1992.

M. Burke, Optimizing Product Life Cycles in the U. S. Auto Industry, S.M., June 1992.

C. Dennison, Electric Shock Risks in an Electric Vehicle, S.M., June 1992.

D. Hager, Applying Continuous-Flow Manufacturing Principles to a Low-Volume Electronics Manufacturer, S.M., June 1992.

L. Hsu, The Design of an Assembly Line with Stochastic Task Times, S.M., June 1992.

C. Jutte, Lead Time Reduction for Multiple Step Batch Chemical Processes, S.M., June 1992.

T. Mock, Reducing Process Variability in Chemical Batch Manufacturing, S.M., June 1992.

S. Pappu, Production Planning with Due-Date Constraints, Ph. D., June 1992.

L. Spiridigliozzi, Precision Laser Micromachining of Ceramics, S.M., June 1992.

K. D. Bartelson, Analysis and Redesign of the Production System Structure for 757 and 737 Aircraft Doors, S.M., June 1993.

M. J. Blatz, Designing Measurement Systems in a Manufacturing Environment, S.M., June 1993.

M. Chrzanowski, Development of a Manufacturing & Business Planning Tool to Aid in Forward Planning, S.M., June 1993.

W. B. Hetzel, Cycle Time Reduction and Strategic Inventory Placement Across a Multistage Process, S.M., June 1993.

J. A. Rennert, Measuring Customer-Driven Manufacturing Process Improvement in a Multidivisional Corporation, S.M., June 1993.

D. J. Seitelman, Scheduling Employees of a Manufacturing Facility, S.M., June 1993.

S. K. Jacobsmeyer, Implementing Flow Time Reduction Using Process Mapping and Innovation, S.M., June 1994.

D. B. Kletter, Determining Production Lot Sizes and Safety Stocks for an Automobile Stamping Plant, S.M., June 1994.

J. Ku, Microprocessor Manufacturing Throughput Time Variability, S.M., June 1994.

L. R. Oliver, Process and Productivity Improvements through Bottleneck Reduction and Design of Experiments, S.M., June 1994.

B. K. Parks, Cost and Lead Time Reduction in the Manufacture of Injection Molding Tools, S.M., June 1994.

M. A. Raftery, Using the Seven-Step Method to Reduce Defects in a Polymer Sheet Making Process, S.M., June 1994.

K. Y. Tan, Minimizing the Impact of Model Changeover at a Medium-Mix High-Volume Cellular-Telephone Production Line, S.M., June 1994.

C. M. Dewitt; A Holistic Approach to Automotive Powder Coating, S.M., June 1995.

K. L. Homsi, Information Flow and Demand Forecasting Issues in a Complex Supply Chain, S.M., June 1995.

P. Gallagher, Molding Process Development for Fuel Cell Components, S.M., May 1995.

A. E. Koszarek, Module Based Configuration Definition to Enable Design Re-Use and Manufacturing System Simplification in the Commercial Aircraft Industry, S.M., June 1995.

A. I. Mirza, Spatial Yield Modeling for Semiconductor Wafers, S.M., May, 1995.

T. R. Wadewitz, Analysis of Investments in Process Control Tools: Laser Scanners Used For On-Line Inspection in a Polyester Sheet Production Process, S.M., June, 1995.

M. I. Zeni, Five Axis Machining of Stamping Dies, S.M., May 1995.

Roberta Bailey, A Data-Driven Approach to Improving Capacity Utilization of Semiconductor Test Equipment, S.M., June 1996.

James Beuerle, A Study of Electrostatically Applied Powder Paint in the Automotive Industry, S.M., June 1996.

Michael Carnette, Implementing Internal Supply Chain Improvements, S.M., June 1996.

Barrett Crane, Cycle Time and Cost Reduction in a Low Volume Manufacturing Environment, S.M., May 1996

Audrey Dima, Improving the Recovery Process of Circuit Boards in a One-Time-Use Camera, S.M., June 1996

Mark MacLean, Implementing Lean Manufacturing in an Automobile Plant Pilot Project, S.M., June 1996

Cristian Gutierrez, Development and Application of a Linear Programming Model to Optimize Production and Distribution of a Manufacturing Company, S.M., February 1996

Sumer Johal, A Simulation-Based Study of the Cost and Performance Trade-Offs in a Semiconductor IC Manufacturing Facility, S.M., May 1996

Sean Willems, Strategic Safety Stock Placement in Integrated Production/Distribution Systems, S.M., May 1996

Rebecca D'Amato, Allocating Housing Resources for a Psychiatric Program, S.M., June 1996

David B. Kletter, Planning and Control of an Unreliable Machine in a Multi-Item Production-Inventory System, Ph.D., June 1996

Jeffrey Alcalde, The Design and Implementation of a Synchronous Manufacturing System In a Job-Shop Environment, S.M., June 1997.

Liana Alvarez, Design and Implementation of Cellular Manufacturing in a Job Shop Environment, S.M., June 1997.

Daniel Crocker, Analysis of Global Manufacturing Strategies for High Volume High Technology Products, S.M., June 1997.

Jennifer Felch, Supply Chain Modeling for Inventory Analysis, S.M., June 1997.

Joetta L. George, Applying the Theory of Constraints in a High Volume Manufacturing System to Increase Throughput and Performance, S.M., June 1997.

Steven Harman, Implementation of Lean Manufacturing and One-Piece Flow at Allied Signal Aerospace, S.M., June 1997.

Thomas Jacob, Root Cause Analysis of Low On-Time Delivery Performance at a Computer Manufacturing Plant, S.M., June 1997.

Michael Miller, Business System Improvements Through Recognition of Process Variability, S.M., June 1997.

Brian E. Black, Utilizing the Principles and Implications of the Base Stock Model to Improve Supply Chain Performance, S.M., June 1998.

Douglas Bohn, Computer Modeling of a Continuous Manufacturing Process, S.M., June 1998.

R. Lawrence Coughlin, III, Optimization and Measurement of a World-Wide Supply Chain, S.M., June 1998.

Judson Graham, Application of Theory of Constraints and Process Control Theory to Multi-Stage Manufacturing Systems, S.M., June 1998.

Brian Hintzman, Capacity Analysis for Multi-Product, Parallel-Site Aluminum Ingot Production, S.M., June 1998.

Brent Johnson, The Soft Side of the Toyota Production Systems is The Hard Side, S.M., June 1998.

Brian Klippel, A Design Methodology for Automotive Component Manufacturing Systems, S.M., June 1998.

David Medrow, Cost Modeling of a Manufacturing Process, S.M., June 1998.

Nicholas Purzer, Managing the Supply, Release, and Machining of Material Within an Aerospace Component Shop, S.M., June 1998.

John D. Ruark, Implementing Reusable Solvers: An Object-Oriented Framework for Operations Research Algorithms, Ph.D., June 1998.

Sean P. Willems, Two Papers in Supply Chain Design: Supply Chain Configuration and Part Selection in Multigeneration Products, Ph.D., February 1999.

Michael Dickinson, Technology Portfolio Management: Optimizing Interdependent Projects Over Multiple Time Periods, S.M., June 1999.

Thomas Furey, Decision Elements in the Design of a Consumer Electronics Assembly Plant, S.M., June 1999.

Mark Graban, An Inventory Planning Methodology for a Semiconductor Manufacturer with Significant Sources of Variability, S.M., June 1999.

Louis Herena, Application of Manufacturing Tools to the DNA Sequencing Process, S.M., June 1999.

C. Gregory Kandare, Production/Inventory Policies for a Parallel Machine Manufacturing System, S.M., June 1999.

John Kang, Applying Six Sigma to Tenneco Automotive Manufacturing, S.M., June 1999.

Michael Kimber, Definition and Implementation of a Visual Inventory Management System, S.M., June 1999.

Adam King, A Method of Comparing the Costs of Platform and Unique Product Design, S.M., June 1999.

Nestor Macias, Engineering Design Leadtime Drivers Analysis, S.M., June 1999.

Michael Milby, Methodology for Sizing Finished Goods Inventories for a Vinyl Siding Extrusion Plant, S.M., June 1999.

Leslie Rudolph, Development of a Decision Framework and a Knowledge Management System for Make/Buy Determinations in Manufacturing, S.M., June 1999.

Thor Sewell, Understanding and Controlling Risk in Product Development, Specifically in New Technology Procurement, at an Automatic Test Equipment Manufacturer, S.M., June 1999.

Hemant Taneja, A Tactical Planning Model for a Semiconductor Wafer Fabrication Facility, S.M., June 1999.

Hari S. Abhyankar, Inventory Control for High Technology Capital Equipment Firms, Ph.D. February 2000.

Matthew F. Bromberg, Modeling Design Rework in a Product Development Process, S.M., June 2000.

Thomas J. Carroll, Using Postponement to Move from Job-Shop to a Mixed MRP/Job Shop Environment S.M., June 2000.

John S. Hollywood, Performance Evaluation and Optimization Models for Processing Networks with Queue-Dependent Production Quantities, Ph. D., June 2000.

James Ryan Horn, Design and Operational Enhancements for a Batch Process Driven Supply Chain, S.M., June 2000.

Mitchell A. Malone, Analysis of a High-End Memory Supply Chain? Dram Vendors to Final Assembly, S.M., June 2000.

Scott M. Pagendarm, The Use of Strategic Inventory and Packaging Postponement to Address Daily Demand Variability and Seasonal Demand Patterns in a Demand Flow Environment, S.M., June 2000.

Olapeju A. Popoola, Development of a Methodology for the Rapid Implementation of a Sustainable Lean Manufacturing System, S.M., June 2000.

Brian T. Tomlin, Supply Chain Design: Capacity, Flexibility and Wholesale Price Strategies, Ph.D., February 2000.

Brian A. Urkiel, The Analysis and Optimization of the Alcoa Mill Products Supply Chain for European Customers, S.M., June 2000.

James A. Wolters, II, Optimizing the Assembly Sequence of an Aerospace Manufacturing Process, S.M., June 2000.

Aviv Cohen, Order Assignment Heuristic in a Build to Order Environment, S.M., June 2001.

Lynn S. Delisle, Breaking Through the Quality Ceiling, S.M., June 2001.

Greg K. Gerstenzang, A Computer Model to Facilitate the Implementation of Lean Manufacturing Principles in Aluminum Products Manufacturing S.M., June 2001.

Jonathan E. Howe, Minimizing the Risk Qualification Test Wafers Have On The Manufacturing Readiness of a New Microprocessor Fabrication Site Through Data Driven Processes, S.M., June 2001.

Jayson S. Kunzler, Order Fulfillment Model for Medical Equipment Installation Materials, S.M., June 2001.

Alison L. Page, Forecasting Mix-Sensitive Semiconductor Fabrication Tool Set Requirements Under Demand Uncertainty, S.M., June 2001.

Matthew W. Street, Quick Response Inventory Replenishment for a Photographic Material Supplier, S.M., June 2001.

Kalyan R. Tadikonda, Fuel Cells - Manufacturing Strategy for Emerging Technologies, S.M., June 2001.

Kermit Threatte, Tactical Shipping and Scheduling at Polaroid with Dual Lead Times, S.M., June 2001.

Andrea L. Vlasak, Integration of Third Party Logistics Providers within the Distribution Network, S.M., June 2001.

Julie L. Wilhelmi Analyzing the Boeing 777 Link the Flow Process for Value Stream Flow Reduction Against the Lean Aerospace Initiative's Enterprise Level Roadmap, S.M., June 2001.

Esther W. Wong Reducing Demand Variability By Improving Information and Material Flows, S.M., June 2001.

Qian Wu A Supply Chain Strategy for Digital Camera Products, S.M., June 2001.

Gregory S. Chalker, The Use of Modeling and Critical Operations Data To Optimize Plant Performance, S.M., May 2002.

Dan Grotsky, A New Framework for Making Sourcing Decisions Regarding Low-Volume, High-Complexity Products, S.M., June 2002.

Emanuele F. Gillio, Lean Principles Applied to a Supply Chain with Demand Uncertainty, S.M., June 2002.

Eric W. Partlan, An Alternative Method of Long Lead-Time Tool Purchases, S.M., June 2002.

Clinton J. Rockwell, A Framework for Optimizing the Supply Chain: A Case Study as Kodak, S.M., June 2002.

Robert L. Scholtz III, Strategies for Manufacturing Low Volume Semiconductor Products in a High Volume Manufacturing Environment, S.M., June 2002.

Eric Jan, Supply Chain Performance Improvement Through Forecasting, S.M., June 2002.

Sheila J. Bragg, Analysis of Sorting Techniques in Customer Fulfillment Centers, S.M., June 2003.

M. Carla Eustache, Integrating Cost Consciousness into a High Quality Manufacturing Environment, S.M., June 2003.

Eric D. Green, Optimization of Photochemical Production Using Lean Manufacturing Philosophies, S.M., June 2003.

Mark Kamal, Management of Regional Local Content Regulations at Dell Computer Corporation, S.M., June 2003.

Don J. Lee, End-of-Life Supply Chain Strategy for High-Performance Servers, S.M., June 2003.

Scott A. Rosenberg, Managing a Data Analysis Production Line: An Example from the Whitehead/MIT Center for Genomic Research, S.M., June 2003.

Eric A. White, Lean Enterprise Distribution Tactics with Customer Supply Chain Integration, S.M., June 2003.

Mark Hagan, Process for Evaluating Options for Materials Management Outsourcing, S.M., June 2004.

Stephen G. King, Using Value Stream Mapping to Improve Forging Processes, S.M., June 2004.

Michael A. Zeppieri, Predictive Capacity Planning Modeling with Tactical and Strategic Application, S.M., June 2004.

Haitao Liu, The Development and Implementation of a Production Information Collection and Reporting System, S.M., June 2004.

William Kwong, Reducing Variability in Equipment Availability at Intel using Systems Optimization, S.M., June 2004.

Padmaja S. Vanka, Line Coordination in a Rapid Change, High Volume Environment, S.M., June 2004.

Ekaterina Lesnaia, Optimizing Safety Stock Placement in General Network Supply Chains, Ph.D., September 2004.

John C.W. Parsons, Using a Newsvendor Model for Demand Planning of NFL Replica Jerseys, M. Eng., June 2004.

Jeffrey D. Johnson, Managing Variability in the Semiconductor Supply Chain, S.M., February 2005.

Jason Walker Connally, Introducing Pull Methodologies in a Semiconductor Fab, S.M., June 2005.

G. Thomas Heaps-Nelson, Analyzing and Improving Throughput of Automated Storage and Retrieval Systems in Personal Computer Manufacturing, S.M., June 2005.

Heath M. Holtz, Re-sourcing Manufacturing Processes in Metal Forming Operations, S.M., June 2005.

Carlos Mazariegos, Bath Sizing Strategy and Production Load Leveling in a Multi-Step Chemical Manufacturing Process, S.M., June 2005.

Kevin McKenney, Development and Application of Management Tools within a High-Mix, Low-Volume Lean Aerospace Manufacturing Environment, S.M., June 2005.

John M. Palmer, Level Loading and Cross Docking in a Global Logistics Network, S.M., June 2005.

Mira K. Sahney, Building Operational Excellence in a Multi-Node Supply Chain, S.M., June 2005.

Ronak R. Shah, A Systems Approach to the Evaluation of Radio Frequency Identification (RFID) in the Defense Industry, S.M., June 2005.

Roy C. Wildeman, Jr., An Application of Lean Principles within a Semiconductor Manufacturing Environment, S.M., June 2005.

Claudia Wu, Total Supply Chain Cost Model, S.M., June 2005.

Ping Josephine Xu, Order Fulfillment in Online Retailing: What Goes Where, Ph.D., September 2005.

Cheong Lee Fong, Michelle, New Models in Logistics Network Design and Implications for 3PL Companies, Ph.D., NTU, August 2005.

Teo Chee Chong, A Tactical Planning Model for Make-To-Order Environment under Demand Uncertainty, Ph.D., NTU, May 2006.

Craig B. Abler, Material Evaluation and Selection Processes to Enable Design for Manufacture, S.M., May 2006.

Yue (Cathy) Chang, Getting Ahead in Sourcing Through Benchmarking and System Dynamics Analysis: An Aerospace Industry Perspective, S.M., June 2006.

Rebecca Cassler Fearing, Managing Preventative Maintenance Activities at Intel Corporation, S.M., June 2006.

Matthew J. Hasik, Developing a Framework to Evaluate the Existence of a Complexity Threshold, S.M., June 2006.

Sean Holly, Lean Manufacturing in a Semiconductor Environment: Use of Variation Analysis to Focus Continuous Improvement Efforts, S.M., June 2006.

Brooke Kahl, Developing and Implementing Standard Logistics Solutions for Eastman Kodak Company's Inbound Supply Chain, S.M., June 2006.

Sandeep Khattar, An Approach to Sourcing Optimization at a High Volume Soft Drink Manufacturer, S.M., June 2006.

D Ramaswamy, The Role of Lean Manufacturing Principles and Strategic Alternatives in Achieving Business Goals, S.M., June 2006.

Todd Robinson, Cost Modeling in the Integrated Supply Chain Strategic Decision Process, S.M., June 2006.

Howard H. Shen, A Radio Frequency Identification (RFID) Evaluation Strategy for Customer Fulfillment Centers, S.M., June 2006.

Dimitrios Andritsos and Anthony Craig, Vendor Managed Inventory vs. Order Based Fulfillment in a Specialty Chemical Company, joint M.Eng., June 2006.

Chien Yung Tan, Inventory Management of Steel Plates at an Oil Rig Construction Company, M.Eng., September 2006.

Chin Jiat Tan, Workload Analysis and Scheduling Policies for a Document Processing Centre, M.Eng., September 2006.

Ni Yang, Optimization of Service Parts Planning for InFocus, M.Eng., September 2006.

Pallav Chhaochhria, Inventory Planning for Low Demand Items in Online Retailing, S.M., May 2007.

Kevin M. Myers, Building Flexibility in the Volatile Aftermarket Parts Supply Chains of the Defense Aerospace Industry, S.M., June 2007.

Cassian Naughton, Costs of Complexity in Hewlett-Packard's Inkjet Printer Business, S.M., June 2007.

Kurt Campbell, A Core Competency Model for Aligning Information Technology with Business Objectives, S.M., June 2007.

Nima Subramanian, Lean Manufacturing in a Semiconductor Environment: Production Leveling, S.M., June 2007.

Matthew J. Ward, Fab Cycle Time Improvement through Inventory Control: A Wafer Starts Approach, S.M., May 2007.

Curtis J Underwood and Jacob R Wood, Applying an Analytical Framework to Production Process Improvement, Joint S.M., June 2007.

Shardul S. Phadnis, Inventory Segmentation and Production Planning for Chemical Manufacturing, M.Eng., June 2007.

J. Sean Walkenhorst, Quantifying the Value of Reduced Lead Time and Increased Delivery Frequency, M.Eng., June 2007.

Si Ming Thomas Khor, The Study of Inventory Management of Raw Materials for a Pharmaceutical Company, M.Eng., September 2007.

Yixiong Kok, The Production Planning and Inventory Management of Intermediate Products for a Pharmaceutical Company, M.Eng., September 2007.

Sumit Gupta, The Production Planning and Inventory Management of Finished Goods for a Pharmaceutical Company, M.Eng., September 2007.

Yi Qian, Reduce Cycle Time and Work In Process in a Medical Device Factory: The Problem and a Proposed Solution, M.Eng., September 2007.

Jing Yao, Reduce Cycle Time and Work In Process in a Medical Device Factory: Scheduling of Needle Hub Molding Machines, M.Eng., September 2007.

Kai Meng, Reduce Cycle Time and Work In Process in a Medical Device Factory: Scheduling Policies for Needle Assembly Machine, M.Eng., September 2007.

Yong Ning Foo, A Diagnostic Analysis of Retail Out-of-Stocks, S.M., September 2007.

Wang Ye Xin, Logistics Coordination in Vendor-Buyer Systems, Ph.D., NTU, September 2007.

Christopher Siow, Analysis of Batching Strategies for Multi-Item Production with Yield Uncertainty, S.M., February 2008.

Kristopher Carter, Analysis of Email and Phone Queuing Systems in a World-wide Contact center Network, S.M., June 2008.

Kaine C. Gill, Lean Concepts in Customer Care: Adding Value and Reducing Waste with Proactive Order Status Messaging, S.M., June 2008.

Phillip J. Hodge and Joshua D. Lemaitre, A Multi-Echelon Supply Chain Model for Strategic Inventory Assessment through the Deployment of Kanbans, joint M.Eng., June 2008.

Hannah McClellan, Applying Lean Enterprise Principles to Optimize Delivery of Customer Service, S.M., June 2008.

Victor A. Mroczkowski, Integrated Decision Support Model for Global Sourcing, S.M., June 2008.

Sriram Ranganath, Inventory Management for Drug Discovery, S.M., June 2008.

Andrew Storm, Leveraging Global Operations Innovation to Create Sustainable Competitive Advantage, S.M., June 2008.

Sanjay Subramanian, Supply Chain Strategy for a Compressed Flow-Time Retrofitting Manufacturing Process, S.M., June 2008.

Sam Wang, Cycle Time Reduction Through Wafer Starts Control, S.M., June 2008.

Xin Huang, Capacity Planning in a General Supply Chain with Multiple Contract Types, Ph.D., June 2008.

Tor Schoenmeyr, Strategic Inventory Placement in Multi-Echelon Supply Chains: Three Essays, Ph.D., June 2008.

Yizhe Cen, Improve the Efficiency and Effectiveness of Material Handling for a Pharmaceutical Factory, M.Eng., September 2008.

Xiaowen Chen, Optimizing the Planning of IBC Usage in Pharmaceutical Industry, M.Eng., September 2008.

He Hu, IBC Management: An Application of WIP Control for a Pharmaceutical Company, M.Eng., September 2008.

Changhui Zhao, Strategic and Operational Plan for Better Material Handling, M.Eng., September 2008.

Sebastian Ortiz Duran and Richard Hawks, Analysis of an International Distribution Hub for Fast Moving Consumer Goods, joint M.Eng., June 2009.

Grant Elliott, Improving Customer Service Contact Root-cause Analysis, S.M., June 2009.

David Johnson, Standardizing and Improving Test Wafer Processes: Inventory Optimization and a Days of Inventory Pull System, S.M., June 2009.

David Larson, Mitigating the Risk of a New Workforce by Reducing Rework and Rightsizing On Hand Inventory, S.M., June 2009.

Adam Nelson, Evaluating an Ocean Shipment Strategy within Dell's Direct Model Supply Chain, S.M., June 2009.

Nathan Peck, Evolving a Global Armaments Logistics Strategy, S.M., June 2009.

Clayton Poppe, Using Critical Chain Project Management Methodologies to Build a Production Schedule, S.M., June 2009.

YongLiang Manfred Lin, Improving Information Flow for Molding Maintenance Operations in a Medical Device Manufacturing Facility, M.Eng., September 2009.

Yuen Chun Gerard Lim, Setting Optimal Inventory Policy for Mold Spare Components In A Medical Device Production Facility, M.Eng., September 2009.

Mohammed Faizal Mohd Fauzi, Preventive Maintenance Scheduling based on Failure Data in a Medical Device Manufacturing Facility, M.Eng., September 2009.

Yuwei Hu and Chin Soon Lim, Scheduling of Biological Samples for DNA Sequencing, S.M., September 2009.

Jie Wang, Multi-period Optimal Network Flow and Pricing Strategy for Commodity Online Retailer, S.M., September 2009.

Dayan Paez, Discrete, Recursive Model for Solar Panel Manufacturing, S.M., January 2010.

Avid Boustani, Remanufacturing and Energy Savings, S.M., January 2010.

Scott Seidel, Planning Combat Outposts to Maximize Population Security, S.M., June 2010.

Marta Lew, Modeling Supply Chain Benefits of Efficient Assortment, M.Eng., June 2010.

Alexander Martchouk, Distribution Network Modeling and Optimization for Rapid Deployment of Oilfield Drilling Equipment, M.Eng., June 2010.

Ryan Rahim, Rapid Deployment of Oil-Drilling Tools Utilizing Distribution Network and Inventory Strategies, M.Eng., June 2010.

Ely Colon-Jimenez, CO_2 Price Impact on Dell's Supply Chain: A Framework for Carbon Footprint Economic Analysis, S.M., June 2010.

Margo de Naray, Fulfillment Supply Chain Strategy Evaluation: Understanding Cost Drivers through Comprehensive Logistics Modeling, S.M., June 2010.

Lucas Sutterer, Development of a Tool for Forecasting a Warehouse Facility Footprint and Enabling Rapid Scenario Analysis, S.M., June 2010.

He Xi, An Optimization Grouping Method in A Multi-line Manufacturing System, M.Eng., September 2010

Kevan Yong Cai Chim, Control of WIP and Reduction of Lead Time in a Food Packaging Company, M.Eng., September 2010

Jean Jingying Liu, Inventory Control Through a Conwip Pull Production System, M.Eng., September 2010

Shao Chong Oh, Manpower Planning and Cycle-Time Reduction of a Labor-Intensive Assembly Line, M.Eng., September 2010

Ricolas Wongso, An Application of Value Stream Mapping to Reduce Lead Time and WIP in a Make-to-Order Manufacturing Line, M.Eng., September 2010

Wei Yung Tan, Developing an Improved Production Planning Method for a Machining Cell using an Active-Nondelay Hybrid Scheduling Technique, M.Eng., September 2010

Naijun Wen, Optimization of Ship-Pack in a Two-Echelon Distribution System, S.M., September 2010.

Shuo Tian, Logistic Regression for a Better Matching of Buyers and Suppliers in E-Procurement, S.M., September 2010.

Bin Huang, A Tactical Planning Model for a Serial Flow Manufacturing System, S.M., September 2010.

Robin Rose, Future Offshore Support Vessel Characteristics, S.M., January 2011.

Nanette Thi Le and Melanie Ann Sheerr, Collaborative Direct to Store Distribution: The Consumer Packaged Goods Network of the Future, M.Eng., June 2011.

Min Fang Hsieh, Applying a MEIO Approach to Manage Intel's VMI Hub Supply Chain, S.M., June 2011.

Diego A. Mendez de la Luz, Improving Supply Chain Responsiveness for Large Diesel Engine Remanufacturing, S.M., June 2011.

David J. Segrera, A Holistic Approach to Finished Goods Inventory in a Global Supply Chain: Analysis and Trade-Offs, S.M., June 2011.

David Barry Wible, Methods for Extension of Ground Shipment Windows through a Supplier Collaboration Initiative, S.M., June 2011.

Cynthia M. Wilson, Development of Operations Based Long Range Network Capacity Planning Models for Vaccine Manufacturing, S.M., June 2011.

Sumant Raykar, Lean Manufacturing in a Mass Customization Plant: Inventory Correction and Shortage Measurement, M.Eng., September 2011.

Moojan Daneshmand, Lean Manufacturing in a Mass Customization Plant: Improved Efficiencies in Raw Material Presentation, M.Eng., September 2011.

Wu Chen, Lean Manufacturing in a Mass Customization Plant: Improvement of Kanban Policy and Implementation, M.Eng., September 2011.

Pallav Chhaochhria, Forecast-driven Tactical Planning Models for Manufacturing Systems, Ph.D., September 2011.

Braden Ball, Simulation as a Method for Determining Inventory Classifications for Allocation, S.M. June 2012.

Bryan Drake, Enabling Strategic Fulfillment: A Decision Support Tool For Fulfillment Network Optimization S.M. 2012.

Brandon Rowan, Study of the Role of Strategically Managed Inventory (SMI) in the Caterpillar Supply Chain, S.M. June 2012.

Choong Keat Ng, Inbound Supply Chain Optimization and Process Improvement S.M. June 2012.

Poi Chung Tjhin and Rachita Pandey, Inventory Management Strategy for the Supply Chain of a Medical Device Company, M.Eng., June 2012.

Michael Giordano, The Impact of Out-of-Theater Supply Flow Visibility on In-Theater Logistics, S.M., June 2012.

Jason Acimovic, Lowering Outbound Shipping Costs in an Online Retail Environment by Making Better Fulfillment and Replenishment Decisions, Ph.D., September 2012.

Abdulaziz AlEisa, Production system improvement at a medical devices company: floor layout reduction and manpower analysis, M.Eng., September 2012

Jennifer Jeanne Peterson, Production system improvement: floor area reduction and cycle time analysis, M.Eng., September 2012

Tianying Yang, Production system improvement: floor area reduction and inventory optimization, M.Eng., September 2012

Zhuling Chen, Production system improvement: floor area reduction and visual management, M.Eng., September 2012.

Chen Song, Improving the Efficiency of an Automated Manufacturing System through a Tri-Part Approach, S.M., June 2013.

Rong Yuan, Setting Optimal Production Lot Sizes and Planned Lead Times in a Job Shop System, S.M., June 2013.

Ketan Nayak, Planning and Scheduling Models for Display Manufacturing, S.M., June 2013.

David Guasch Rodriguez, Reducing Total Fulfillment Costs through Distribution Network Design Optimization, S.M. June 2013

Carlo Gabriel Quinonez, Development of a Criteria Based Strategic Sourcing Model, S.M. June 2013

Marie Wolbert, Predictive Analytics for Inventory in a Sporting Goods Organization, S.M. June 2013

Amy Lee, Cost-Optimized Warehouse Storage Type Allocations, S.M. June 2013

Sophia Scipio, Strategic Sourcing in a Direct Import Supply Chain with Increasing Globalization Trends while Mitigating Risk, S.M. June 2013

Robert Giacomantonio, Multi-Echelon Inventory Optimization in a Rapid-Response Supply Chain, S.M. June 2013

Obehi Ukpebor, Materials lead time reduction in a semiconductor equipment manufacturing plant: warehouse design and layout, M.Eng. September 2013

Ryan Surveski, Materials lead time reduction in a semiconductor equipment manufacturing plant: process flow planning, M.Eng. September 2013

Prachyathit Kanburapa, Prioritization and control of order picking system, M.Eng. September 2013

Matthew Mogensen, Service network design optimization for Army Aviation lift planning, S.M. June 2013

Benjamin Polak, Multi-Echelon Inventory Strategies for Retail Replenishment Business Model, S.M. June 2014

Tacy Napolillo, Using Analytics to Improve Delivery Performance, S.M. June 2014

Jane Guertin, Practical Example of Developing and Implementing an Optimization & Scenario Planning Tool, S.M. June 2014

Ashish Koul, Device-Oriented Telecommunications Customer Call Center Demand Forecasting, S.M. June 2014.

Andre Calmon, Reverse Logistics for Consumer Electronics: Forecasting Failures, Managing Inventory, and Matching Warranties, Ph.D., December 2014.

Blake William Clark Sedore, Assembly Lead Time Reduction in a Semiconductor Capital Equipment Plant through Constraint Based Scheduling, M.Eng., September 2014.

Sonam Jain, Assembly Lead Time Reduction in a Semiconductor Capital Equipment Plant through Improved Material Kitting, M.Eng., September 2014.

Anubha Singh Bhadauria, Production Lead Time Reduction in a Semiconductor Capital Equipment Plant through Improved Testing Protocols, M.Eng., September 2014.

Hugh Churchill, Cycle-time Analysis and Improvement Using Lean Methods within a Retail Distribution Center, S.M. June 2015.

John Kang, Inventory Optimization Model for NIKE's Long Lifecycle Highly Seasonal Replenishment Products, S.M. June 2015.

Ryan Jacobs, Methods for Predicting Inventory Levels in a Segmented Retail Supply Chain, S.M. June 2015.

David Jacobs, Practical Example of Base Source Optimization – Footwear Profiling at Nike, Inc. S.M. June 2015.

Yalu Wu, A Framework for Analyzing Forecast Accuracy Metrics, S.M. June 2015.

Mariapaola Testa, Modeling and Design of Material Recovery Facilities: Genetic Algorithm Approach, S.M. June 2015.

Hui Ni Grace Fong, Improving and Maintaining the Operational Efficiency of a Semiconductor Equipment Manufacturing Warehouse, M.Eng., September 2015.

Stephen Douglas Racca, Improving Operational Efficiency of a Semiconductor Equipment Manufacturing Warehouse Through Effective Utilization of Vertical Lift Modules, M.Eng., September 2015.

Paramveer Singh Toor, Improving Operational Efficiency of a Semiconductor Equipment Manufacturing Warehouse through Strategic Allocation of Parts, M.Eng., September 2015.

Ana María Ortiz García, Evaluating Inventory Ordering Policies: a Methodology and Application, S.M. June 2016.

Andrew J. Gabris, Size Curve Optimization for Replenishment Products, S.M. June 2016.

Clararose Faith Voigt, Rapid Supply Chain Strategy Simulation Development for Enhanced Cross-Functional Collaboration in High Growth Environments, S.M. June 2016.

Christian Schneider, Modeling End-to-End Order Cycle-Time Variability to Improve On-Time Delivery Commitments and Drive Future State Metrics, S.M. June 2016.

Eric Young, Amazon UK Transshipment Stow Process Analysis through Discrete Event Simulation, S.M. June 2016.

Amanda Rikki Lurie, Accelerating the Onboarding of a New Factory Partner, S.M. June 2016.

Rong Yuan, Velocity-based Storage and Stowage Decisions in a Semi-automated Fulfillment System, Ph.D. July 2016.

Nelson Lee, Product Availability Improvement for Analytical Column Supply Chain: Inventory Optimization and Lot Sizing, M.Eng., September 2016.

Yu Hua, Optimizing Inventory and Standardizing Planning Procedure in a Multipart Manufacturing System, M.Eng., September 2016.

Yan Han, Product Availability for an Analytical Consumable Supply Chain: Distribution and Transportation, M.Eng., September 2016.

Jordan Charles, Improving Multi-Channel Retail Delivery Performance in Key Market Cities, S.M. June 2017.

Federico Markowicz, Optimizing Order-Routing Decisions: Leveraging Omni-Channel Supply Chain Fulfillment, S.M. June 2017.

Stephen Laskowski, Capacity Utilization and Lean Manufacturing at a Plastic Medical Device Components Manufacturer, S.M. June 2017.

Carla Li-Carrillo, Optimal Staffing Recommendation for Inbound Operations, S.M. June 2017.

Russell Forthuber, Inbound Container Queuing Optimization Model for Distribution Centers, S.M. June 2017.

Annie I-An Chen, Large-Scale Optimization in Online-Retail Inventory Management, Ph.D. June 2017.

Amy Liu, Velocity-Based Stowage Policy for Semi-Automated Fulfillment Systems, S.M., June 2018.

Yijin Wei, Analysis of Additive Manufacturing in an Automobile Service Part Supply Chain, S.M., June 2018.

Ty Ingram, Evaluating the Feasibility of using Screw Conveyors as a Means to Continuously Grow Black Soldier Fly Larvae, S.B., June 2018.

Clinton Rendall, Enhancing the Design and Procurement of Single-Use Assemblies in Biomanufacturing by Implementing Modular Specifications, S.M. June 2018.

Matthew Wallach, Reducing Wave Cycle Time at a Multi-Channel Distribution Center, S.M. June 2018.

Jeffrey Birenbaum, Inbound Supply Chain Optimization with Ship-Mode Variation in a Fixed-Capacity Fulfillment Center, S.M. June 2018.

Ryan Morrison, Unlocking DC Throughput Capacity through Improved Flow, S.M. June 2018.

Dora Aldama, Lean Principles in an Aircraft Assembly Process, S.M. June 2018.

Keval Babu, New Product Forecasting of Appliance and Consumables: Bass Model, M.Eng, September 2018.

Yangyang Li, New Product Forecasting of Appliance and Consumables: SARIMA Model, M.Eng, September 2018.

Pengming Sun, New Product Forecasting of Appliance and Consumables: Moving Average Model, M.Eng, September 2018.

CERTIFICATE OF SERVICE

I hereby certify that on this, the 16th day of December 2019, I electronically filed the foregoing **EXPERT REPORT OF STEPHEN C. GRAVES** with the Clerk of Court using the CM/ECF system, which will automatically send notification of such filing to Counsel of Record:

Chris Carr, Esq.
Attorney General
Dennis Dunn, Esq.
Deputy Attorney General
Russell Willard, Esq.
Senior Assistant Attorneys General
Georgia Office of the Attorney General
40 Capitol Square
Atlanta, GA 30334
Telephone: (404) 656-3300
Fax: (404) 657-8733
ccarr@law.ga.gov
ddunn@law.ga.gov
rwillard@law.ga.gov

Joshua Barrett Belinfante, Esq.
Brian Edward Lake, Esq.
Carey Allen Miller, Esq.
Vincent Robert Russo, Jr., Esq.
Andrew Swindle, Esq.
Robbins Ross Alloy Belinfante Littlefield, LLC -Atl
500 Fourteenth Street, NW
Atlanta, GA 30318
Telephone: (678) 701-9381
Fax: (404) 856-3250
jbelinfante@robbinsfirm.com
blake@robbinsfirm.com
cmiller@robbinsfirm.com
vrusso@robbinsfirm.com

Bryan P. Tyson, Esq.
Special Assistant Attorneys General
Bryan P. Tyson, Esq.
Special Assistant Attorneys General
Bryan Jacoutot, Esq.
Taylor English Duma LLP
1600 Parkwood Circle
Suite 200
Atlanta, GA 30339
Telephone: (678) 336-7249
Fax: (404) 856-3250
btyson@taylorenglish.com
bjacoutot@taylorenglish.com

/s/ Leslie J. Bryan

Allegra J. Lawrence
Georgia Bar No. 439797