Analysis of Vote-by-Mail Processing: A Time Study from Salt Lake City

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Abstract

The number of vote-by-mail (VBM) ballots in the 2020 presidential election reached record highs. Reasons for the sudden increase in voters using VBM ballots range from accessibility to social distancing restrictions and other COVID-19 pandemic health and safety concerns. In conjunction with other circumstances encircling the presidential election, the reporting of VBM results was delayed, which led to mistrust and contributed to mis-, dis-, and malinformation surrounding the election results. Ultimately, it was difficult for election officials to predict how long it would take to verify and tabulate VBM ballots, especially due to the rapid adoption and expansion of VBM. To understand the VBM verification and tabulation system, this research utilizes time studies to define rates, distributions, and processing times for VBM processes in order to support election officials in preparing for VBM results reporting in future elections. The data explored in this study were collected from several counties in the greater Salt Lake City region during the 2022 midterm election. These data consisted of time studies on manual and machine-supported VBM process steps, including, but not limited to, ballot arrival, signature verification, ballot extraction, tabulation, and adjudication. Through statistical methods, processing times, processing rates, and representative probability distributions for each VBM process step are defined. These data can assist in predicting the necessary workforce and forecasting the time to report election results with existing equipment. The results aid in supporting election officials and administrators in making data-enabled decisions for future election planning and scheduling.

1 Introduction

Vote-by-mail (VBM) or absentee voting in the United States (U.S.) increased significantly during the presidential election in 2020 (Stewart III, 2020). This response caused some challenges for election officials and administrators (Perry, 2020; Phillips, 2020; Schneider, 2020), but absentee voting is not necessarily new in the U.S. The first absentee voting occurred in the U.S. during the Civil War when soldiers could cast their ballots on the battlefields, which were counted back home (MIT Election Data and Science Lab, 2021). In the late 1800s, states started to pass laws for absentee voting under the specific circumstances of voters being seriously ill on Election Day or far away from home (MIT Election Data and Science Lab, 2021). However, traditionally, this type of absentee voting was relatively small. Until the 1980s, voters in all states could not request no-excuse absentee ballots, with California as the first state to codify this option into law (MIT Election Data and Science Lab, 2021).

Today, the following eight states allow VBM for all elections: California, Colorado, Hawaii, Nevada, Oregon, Utah, Vermont, and Washington, and further states allow VBM for smaller or specific elections (National Conference of State Legislatures, 2022). In the last presidential election in 2020, around half (i.e., 46%) of American voters cast their ballot by mail or absentee. This is more than twice as many compared to the 25% in the 2016 presidential election (Stewart III, 2020). Based on the circumstances of the COVID-19 pandemic, the increased use of VBM was not unpredictable. However, this rise in popularity was overwhelming to many election officials and supporting election infrastructure. Several researchers (e.g., Perry, 2020; Phillips, 2020; Schneider, 2020) announced their concerns before the presidential election. Concerns were related to the slow U.S. Postal Service, possible invalid VBM ballots due to a lack of voter experience, election worker shortages, and no automatic VBM system in states like Wisconsin and Louisiana. Even with some emergency last-minute investments and the sharing of expertise and support, most states were not prepared for the high demand for absentee and VBM voting in the 2020 presidential election. Consequently, issues in processing and tabulating mail ballots led to substantial delays in reporting final election results in states such as Arizona, North Carolina, and Georgia (Perry, 2020; Phillips, 2020; Schneider, 2020; Collier, 2020; Parlapiano and Gamio, 2022). In conjunction, delays in VBM results reporting and other circumstances surrounding the election (i.e., deadline confusion, mis-/dis-communication) led to mistrust by the U.S. population regarding the voting results (**??**). The consequences of such delays are still causing ripple effects throughout elections today. To be more prepared for future elections and to plan them more accurately, it is essential to understand what happens inside a VBM tabulation center and design the system for optimal throughput. In order to do so, data is required to understand what the processing steps are, their order, and how much time each processing step requires. With this information, election administrators and officials can estimate work times, schedule workers, and determine resource allocation.

Existing literature that explores VBM investigates this process from a po-

litical science perspective, with respect to voter turnout (McGhee et al., 2020; Cigno et al., 2023; Barber and Holbein, 2020; Berinsky et al., 2001), voter confidence (Clark, 2021), voting behavior (Southwell, 2010), and financial requirements (Lamb, 2021). Regarding operations and processing inside the VBM tabulation facility, there is limited information that predominately focuses on signatures and rejection rates. Cottrell et al. (2021) investigated the ballot rejection rate in the VBM process during three general elections in Florida throughout the last decade. The authors identified that the ballots were mainly rejected due to signature defects on the envelopes, like missing or not matching signatures or late arrival at the election offices. The authors Cottrell et al. (2021) have also published rejection rates from ballots for in-person and VBM voting. Baringer et al. (2020) looked at the VBM ballot rejection in Florida in the General Election of 2018. The authors focus on the risk of VBM ballot rejection by age, disability status, and geography. Their results show that younger voters, individuals with disabilities, Hispanics, and voters without an affiliation to a major party have a higher risk that of their ballot getting rejected. However, with respect to the overall processing time of the VBM tabulation process, there is one paper recently published study that discusses the start time and it's influence on final reporting results timelines. (Tuch, 2021) indicated in their research analysis that the pre-processing start date of a state influences the time when the election results get published and, thus, the skepticism surrounding late reported election results.

This research is among the first in elections literature to present processing times, rates, and distributions for VBM processing steps. This paper aims to identify accurate processing times, rates, and distributions for VBM voting based on time studies that occurred during the midterm election in the greater Salt Lake City, Utah region. The results of this research will support election officials and administrators in making data-informed decisions for future election planning and work scheduling.

2 Methodology

Through various statistical methods, processing times, rates, and distributions for each observed VBM process step are determined. Firstly, the processing steps are described, which were observed during the midterm election of 2022 in Utah, as well as the time study itself. Then, the data cleaning procedure and the following statistical methods occurred: descriptive statistics, clustering of data from different counties, and fitting distributions.

2.1 Processing Steps for VBM

The processing steps to verify, extract, and tabulate VBM ballots can differ between counties based on size, resources, voter turnout, and legislation. This research focuses on different-sized counties in Utah with different resources to process ballots.

The following is an outline of the typical processing steps for VBM ballots in Utah. First, the ballots arrive in an envelope at the tabulation center by mail or drop box pick-up. The envelopes are sorted into boxes when necessary and counted. Afterward, the workers remove a paper tab on the envelope which covers the voter's signature before it can be scanned for signature verification; however, not every observed county had a tab over the voter's signature. Signature verification is usually done manually by workers who receive special training and can have up to three levels to pass before the voter gets a notification that their ballot cannot be processed due to a signature-related issue (e.g., non-matching signature). In the first level, the workers compare the envelope signature with a signature on file. In the second level, up to six other signatures from the voter are available for comparison, where the specialized worker evaluates these for similarities and differences. In the last level, scanned signatures are sent to a top-tier, specially trained worker who investigates the signature for verification. When they cannot identify a match between the signature on the ballot envelope and the signatures from the databases, depending on the laws, the county notifies the voter. When the signature on the ballot matches the signature from the databases, the next step is to sort the not identified signatures out of the batches. It is followed by opening the envelopes and extracting the ballot. After extraction, the ballots need to be unfolded and flattened before they can be tabulated. Once unfolded, ballots are processed through ballot scanners for tabulation and tallying the votes. If the computer cannot identify the voter's selection on one or more votes, then, depending on the laws, two people can adjudicate the ballot and decide on the voter's intention. Lastly, the ballots are secured and stored in inventory. The process steps that will be considered in the following statistical analysis are:

- Sorting Incoming Ballots
- Counting Envelopes
- Signature Tab Removal
- Signature Scanning with Machine or by Hand
- Signature Verification Level 1
- Signature Verification Level 2
- Signature Verification Level 3
- Sorting Envelopes into Batches
- Opening Envelopes and Extracting Ballot
- Unfolding the Ballots
- Tabulation
- Adjudication

Not every process step occurred in every county, depending on the size and standard operating procedure. Also, some counties pair other processing steps together depending on their resources and equipment.

2.2 Time Study

Prior to and during the midterm election of 2022, a time study occurred to observe the VBM processing steps in the region of Utah. Members of The University of Rhode Island Voter OperaTions and Election Systems (URI VOTES) observed the VBM process in four different-sized counties:

- Small County: 28,570 Registered Voters (Summit County, 2022)
- Medium County: 191,890 Registered Voters (Davis County, 2022)
- Large County 1: 337,223 Registered Voters(Utah County, 2022b)
- Large County 2: 591,999 Registered Voters(Salt Lake County, 2022)

One County published that 94.75 % of the voters cast their ballots by mail (Utah County, 2022a). In this time study, over six days, a total of 2,945 observations and around 579 minutes (9.5 hours) of video observations were collected.

2.3 Data Cleaning

Data cleaning is necessary to ensure consistency and accuracy in the collected data. Firstly, all data points with a zero value for the duration were eliminated from the data set. Also, processing steps with an observation number of three or fewer were removed. These data points were mostly observations of transportation or loading and unloading of a process step or machine. Further, the names of the process steps were standardized through all observers, and the batch size was added in an additional column.[1] The batch size is used to determine the duration of the process step per ballot, which allows for accurate process comparisons and generalizability of processing times. For the process step 'Signature Tab Removal,' the average batch size from the process step 'Counting Envelopes' is taken because the batch size was not noted during the time study for 'Signature Tab Removal' but the 'Counting Envelopes' feed directly into that process. In addition, the batch size varied from batch to batch because counties did not sort them into equal-sized batches after their arrival.

Additional data points could be received through the recorded videos. Two people watched and marked the videos for different process steps. The marked video sequences were exported and added to the data set from the observations. To ensure that both observers marked the processing steps in the same way, an inter-rater reliability was performed, which shows an accuracy rate of 99.9% among the two independent video observers.

[1]The oberseved VBM processes often process ballots or envelopes in batches, sometimes hundreds at a time.

Ultimately, the sample size decreased from 2,945 data points to 2,893 observations after the cleaning process. Due to the video analysis, 480 data points could be added to the data set. In total, 3,373 observations of the VBM processing steps could be used for the following statistical analysis. There is an additional reduction to 2,870 data points because some observations cover transportation, pre- and unloading time of machines, and between processing steps which are not considered in this paper. Table 1 gives an overview of the considered processing steps and the amount of data that is used for the statistical analysis.

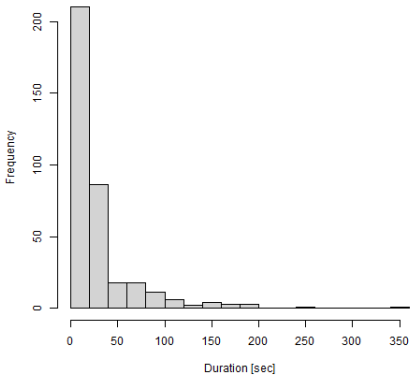
Table 1: Overview of the Processing Steps in the Different Counties

Processing Steps	Small	Medium	Large1	Large2
Sorting Incoming Ballots			22	37
Counting Envelopes				77
Signature Tab Removal	12	282		62
Signature Scanning with Machine		12		6
Signature Scanning by Hand	7			
Signature Verification 1	44	468	196	169
Signature Verification 2		30		59
Signature Verification 3				94
Sorting Envelopes into Batches		15	12	6
Opening Envelopes and Extracting Ballots		26	2	103
Opening Envelopes	10			
Extracting Ballots and Unfolding	15			
Unfolding the Ballots		118	3	24
Tabulation DS450	9	18		
Tabulation DS200			146	
Tabulation DS850			9	
Tabulation DRG2140				105
Adjudication		87	222	363

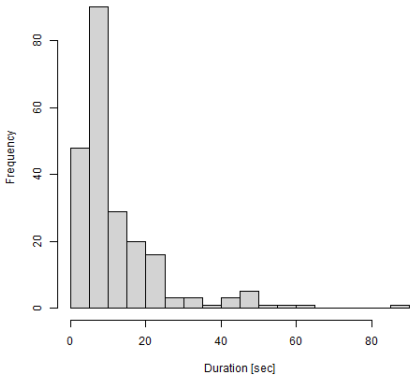
2.4 Descriptive Statistics and Histograms

The descriptive statistics for each process step from every county separately are shown in Table 2. Additionally, the histograms for every process step for each county are drawn to get a first impression of possible distributions. Figure 1 shows four different histograms, which all look different and likely follow different distributions, which will be identified later in this paper. Histograms for each process are included in Appendix A.

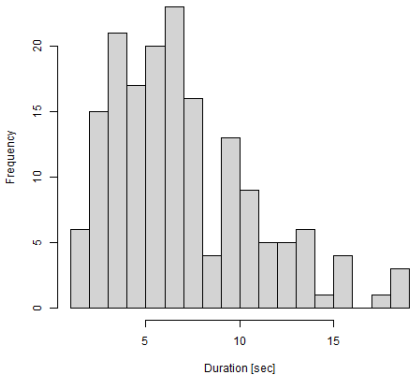
(a) Histogram Adjudication Large2



(b) Histogram Adjudication Large1



(c) Histogram Signature Verification 1 Large2



(d) Histogram Signature Verification 1 Large2

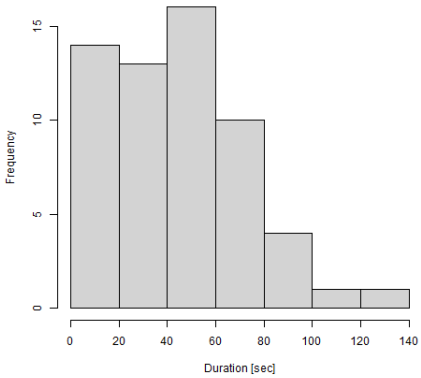


Figure 1: Histogram Examples

Table 2: Descriptive Analysis for each Processing Steps by County

Process Step	Location	n	Mean	SE Mean	Std.	Q1	Median	Q3	Min	Max	Sum of Squares
Sorting Incoming Ballots	Large1	22	1.16	0.38	1.78	0.56	0.72	0.91	0.48	9.00	66.88
Sorting Incoming Ballots	Large2	37	0.79	0.04	0.24	0.62	0.76	0.98	0.30	1.25	2.05
Counting Envelopes	Large2	77	0.29	0.01	0.12	0.21	0.28	0.35	0.07	0.76	1.16
Signature Tab Removal	Medium	282	5.11	0.28	4.64	2.40	3.60	5.90	1.20	42.90	6053.53
Signature Tab Removal	Large2	62	3.54	0.40	3.11	2.00	2.41	4.04	1.10	21.80	590.52
Signature Scanning with Machine	Medium	12	0.22	0.03	0.09	0.18	0.21	0.23	0.07	0.46	0.09
Signature Scanning with Machine	Large2	6	0.14	0.03	0.07	0.09	0.15	0.21	0.05	0.22	0.03
Signature Scanning by Hand	Small	7	2.29	0.34	0.90	1.87	2.03	2.16	1.66	4.29	4.86
Signature Verification 1	Small	44	8.81	1.17	7.74	4.57	6.00	13.25	0.30	46.27	2575.91
Signature Verification 1	Medium	468	3.71	0.23	4.96	2.00	2.40	3.20	0.70	63.10	11502.13
Signature Verification 1	Large1	196	6.79	0.75	10.50	3.00	3.00	6.00	2.00	82.00	21480.42
Signature Verification 1	Large2	169	7.02	0.30	3.84	4.10	6.20	9.50	1.50	19.00	2476.04
Signature Verification 2	Medium	30	53.13	4.86	26.61	41.73	56.15	71.70	1.60	95.40	20542.12
Signature Verification 2	Large2	59	44.06	3.50	26.92	22.50	45.30	61.95	3.10	124.60	42017.88
Signature Verification 3	Large2	94	22.19	1.19	11.52	11.35	20.75	30.43	4.30	50.60	12346.62
Sorting Envelopes into Batches	Medium	15	0.56	0.23	0.89	0.21	0.33	0.38	0.18	3.69	10.99
Sorting Envelopes into Batches	Large1	12	0.24	0.05	0.17	0.18	0.19	0.20	0.17	0.77	0.31
Sorting Envelopes into Batches	Large2	6	0.13	0.03	0.07	0.08	0.14	0.16	0.05	0.23	0.02
Opening Envelopes and Extracting Ballots	Medium	26	1.93	0.17	0.86	1.27	1.96	2.70	0.30	3.32	18.66
Opening Envelopes and Extracting Ballots	Large1	2	1.34	0.04	0.06	1.32	1.34	1.36	1.30	1.38	0.00
Opening Envelopes and Extracting Ballots	Large2	103	1.89	0.05	0.50	1.59	1.73	2.01	1.06	3.99	25.47
Opening Envelopes	Small	10	1.54	0.28	0.87	1.17	1.28	1.84	0.14	3.28	6.87
Extracting Ballots and Unfolding	Small	15	13.99	0.47	1.81	12.78	13.92	15.21	10.47	16.94	46.03
Unfolding the Ballots	Medium	118	5.29	0.21	2.25	3.73	5.20	6.30	1.00	12.80	590.92
Unfolding the Ballots	Large1	3	4.86	1.23	2.13	3.63	3.65	5.49	3.61	7.32	9.08
Unfolding the Ballots	Large2	24	13.48	1.22	5.99	11.16	15.23	17.07	0.10	23.27	826.09
Tabulation DS450	Small	9	27.40	1.42	4.26	25.50	28.20	29.60	18.20	33.00	144.98
Tabulation DS450	Medium	18	1.23	0.12	0.53	1.19	1.27	1.47	0.35	2.38	4.74
Tabulation DS200	Large1	146	9.26	0.27	3.25	8.40	9.05	9.50	0.40	37.60	1533.54
Tabulation DS850	Large1	9	1.48	0.10	0.30	1.35	1.47	1.69	0.88	1.86	0.73
Tabulation DRG2140	Large2	105	1.85	0.18	1.81	0.83	0.96	2.20	0.12	11.30	338.86
Ajudication	Medium	87	24.21	1.30	12.10	16.05	20.70	28.20	11.70	86.30	12594.80
Ajudication	Large1	222	12.37	0.80	11.95	5.30	8.30	14.60	1.70	87.60	31581.18
Ajudication	Large2	363	30.62	2.05	39.13	9.90	16.90	31.50	0.60	347.50	554224.00

2.5 Comparison of Data

The next step is to investigate if it is possible to merge processing step data from two or more counties to have more data for one processing step available. The Kruskal-Wallis-Test inspects if there is a statistical significance between the respective medians of three or more different counties for the same processing step.

The Kruskal-Wallis-Test shows that the processing steps 'Sorting Incoming Ballots,' 'Scanning Signature,' 'Signature Verification 2,' and 'Opening Envelopes & Extraction Ballots' have a p-value above 0.05; therefore, the null hypothesis failed to reject. All results from the Kruskal-Wallis-Test are shown in Table 3.

Table 3: Kruskal-Wallis-Test

Process Step	Small	Medium	Large1	Large2	χ^2	df	p-value
Sorting Incoming Envelopes			X	X	0.15	1	0.695
Signature Tab Removal	X	X		X	22.86	2	0.000
Scanning Signatures		X		X	2.54	1	0.111
Signature Verfication 1	X	X	X	X	213.61	3	0.000
Signature Verfication 2		X		X	2.88	1	0.090
Sorting Envelopes		X	X	X	14.72	2	0.001
Opening & Extraction		X	X	X	4.05	2	0.132
Unfolding Ballots		X	X	X	34.59	2	0.000
Tabulation DS450	X	X			17.36	1	0.000
Adjudication		X	X	X	137.12	2	0.000

To investigate if any two datasets of different counties are equal to each other for the same processing step, the Mann-Whitney U-Test was performed in addition to the Kruskal-Wallis-Test. In Table 4, all results from the Mann-Whitney U-Test are illustrated. In addition to the four processing steps from the Kruskal-Wallis-Test, the data from the counties of the process steps 'Signature Verification 1 (Small & Large2),' 'Sorting Envelopes (Large2 & Medium) and (Large1 & Medium),' and 'Unfolding Ballots (Large1 & Medium)' can also be combined for further statistical analysis (p-value $\succ$ 0.05).

Table 4: Mann-Whitney U-Test

Process Step	County 1	County 2	P-Value
Sorting Incoming Ballots	Large2	Large1	0.703
Signature Tab Removal	Small	Large2	0.042
Signature Tab Removal	Small	Medium	0.000
Signature Tab Removal	Large2	Medium	0.001
Scanning Signatures	Large2	Medium	0.122
Signature Verfication 1	Small	Large2	0.412
Signature Verfication 1	Small	Large1	0.000
Signature Verfication 1	Small	Medium	0.000
Signature Verfication 1	Large2	Large1	0.000
Signature Verfication 1	Large2	Medium	0.000
Signature Verfication 1	Large1	Medium	0.000
Signature Verfication 2	Large2	Medium	0.091
Sorting Envelopes	Large2	Large1	0.027
Sorting Envelopes	Large2	Medium	0.851
Sorting Envelopes	Large1	Medium	0.305
Opening & Extraction	Large2	Medium	0.946
Opening & Extraction	Large2	Large1	0.028
Opening & Extraction	Medium	Large1	0.305
Unfolding Ballots	Large2	Large1	0.028
Unfolding Ballots	Large2	Medium	0.000
Unfolding Ballots	Large1	Medium	0.745
Tabulation DS450	Small	Medium	0.000
Adjudication	Large2	Large1	0.000
Adjudication	Large2	Medium	0.003
Adjudication	Large1	Medium	0.000

2.6 Descriptive Statistics and Histograms of Combined Counties

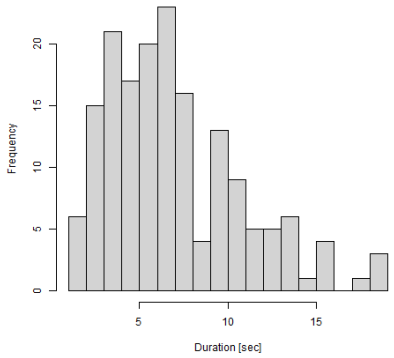
[!hbp] The Kruskal-Wallis and Mann-Whitney U-Test indicate that the data can be combined for further analysis for seven processing steps. The benefit of combining the data is that more data for one processing step can determine the distribution more accurately. Table 5 presents the descriptive statistics for the seven processing steps with combined data.

Also, the histograms for this data are considered for fitting distributions. For the processing steps 'Signature Verification 1 and 2,' it is visible that one county follows a different distribution than the other county and the data combined (see Figure 2). A more accurate determination of the distribution is possible through more data points, and the possibility of a combination of data indicates that the counties are comparable for selected processing steps.

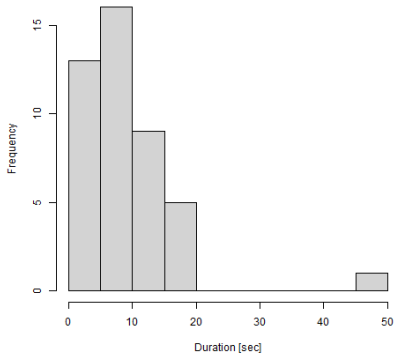
Table 5: Descriptive Analysis of the Combined Data

Process Step	Location	n	Mean	SE Mean	Std.	Q1	Median	Q3	Min	Max	Sum of Squares
Sorting Incoming Ballots	Large2 - Large1	59.00	0.93	0.14	1.11	0.61	0.75	0.96	0.30	9.00	70.88
Signature Scanning with Machine	Large2 - Medium	18.00	0.19	0.02	0.09	0.17	0.19	0.23	0.05	0.46	0.14
Signature Verification 1	Large 2 - Small	213.00	7.39	0.34	4.94	4.10	6.10	9.70	0.30	46.27	5163.71
Signature Verification 2	Large2 - Medium	89.00	47.12	2.86	27.01	29.20	47.30	62.90	1.60	124.60	64196.30
Opening & Extraction	Large1 - Medium	28.00	1.88	0.16	0.85	1.28	1.83	2.70	0.30	3.32	19.30
Opening & Extraction	Large2 - Medium	129.00	1.90	0.05	0.59	1.57	1.74	2.12	0.30	3.99	44.15
Unfolding the Ballots	Large1 - Medium	121.00	5.28	0.20	2.24	3.70	5.20	6.30	1.00	12.80	600.55

(a) Histogram Signature Verification 1 Large2



(b) Histogram Signature Verification 1 Small



(c) Histogram Signature Verification 1 Large2-Small

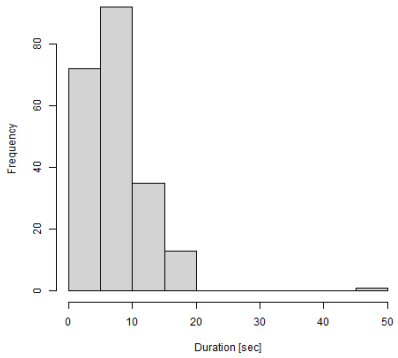


Figure 2: Histograms Combined Data

2.7 Fitting Distribution

The last statistical analysis step was to determine the process distributions, which were tested through the *fitdistrplus* package in *R*. The distributions of Lognormal, Log Logistics, Gamma, and Weibull were tested in this statistical analysis. For example, Figure 3 shows the test of all four distributions on the combined data set of 'Unfolding the Ballots'; thus, the Gamma distribution could be selected as it follows the histogram the best (lower left diagram). The distribution fit for each process is included in Appendix B. Additionally, the Gamma distribution follows the quantile, percentile, and cumulative distribution function graphs most suitable for this processing step with the selected Utah counties. Fits were also assessed statistically through the comparison of fit statistics (e.g., the Kolmogorov–Smirnov statistic). Overall, a best-fit distribution was determined for every processing step with more than twelve observations.[2]

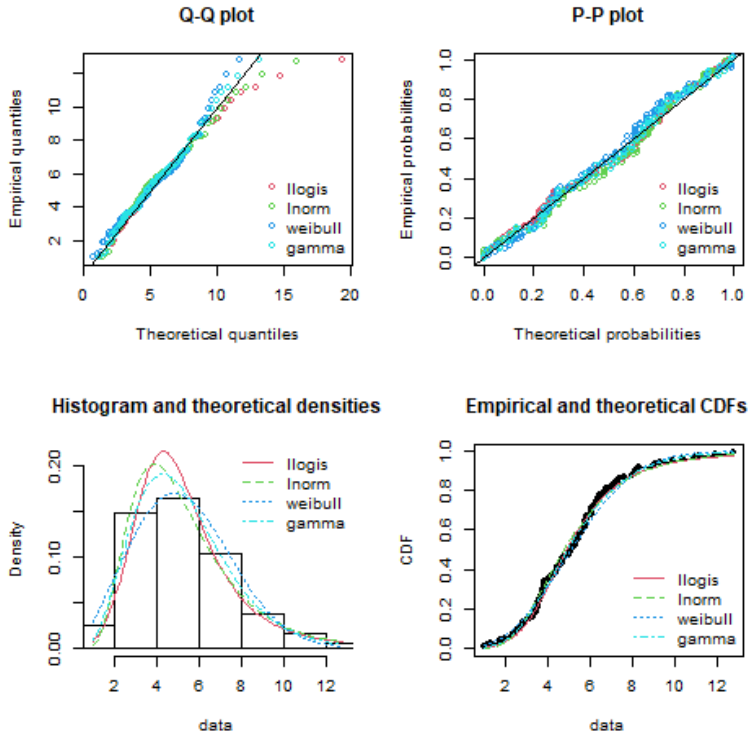


Figure 3: Example: Unfolding the Ballots (Large1-Medium) for Fitting the Distribution

[2]Process steps with fewer than 12 observations failed to fit any distribution due to the limited sample size.

3 Results

The statistical analysis results from the collected data are presented in this section. Through the Kruskal-Wallis and Mann-Whitney U-Test, it was possible to combine seven process steps from different counties to have more data available. For example, for the 'Signature Scanning' process step in the Medium and Large2 county, the sample size was not big enough to define a distribution for each county alone; however, when combined, a distribution fit was possible. Overall, 13 processing steps, some with different resources and procedures, are statistically described. These processes may be useful for various applications in planning elections with a VBM system.

The defined processing rates, distributions, and times for each processing step are illustrated in Table 6. The table represents the rates in the form of ballots processed per hour, processing times are displayed through mean, minimum, and maximum durations, and distributions are presented with the best-fit distribution and their corresponding distribution parameters.

4 Discussion and Limitation

The performed time studies of the VBM processes in the region of Salt Lake City, Utah, and the following statistical analysis results of this paper are among the first published processing times, processing rates, and representative probability distributions for the VBM process. Altogether, statistical values could be defined for 13 processing steps, some being variants of one another. This study shows that through regulations and experiences, the VBM steps are executed differently from county-to-county. Nevertheless, some processing steps are similar between different counties, whereby a data merge was possible to generate more accurate results.

The results of this study form a basis for election officials and administrators to plan and schedule their election with the VBM process, especially when they are rolling out or ramping up a VBM system in their county or state. Also, these results can be used to reflect and improve current VBM systems, especially if there were delays or bottlenecks in past elections. The defined data can be used for static process evaluation or dynamic process modeling with simulation tools like discrete-event simulation to get more accurate results on where the bottlenecks in the process are and how they can be eliminated.

Limitations in this study need to be considered when using the data. The time studies describe four counties in one state. While Utah has a high rate of VBM turnout, examining VBM processes from different states would provide broader insights into VBM processing times, since states and jurisdictions can have differing regulations and processing steps. Also, there can be different regulations and laws between the counties and states, which makes nearly every VBM process unique. The four counties in Utah had some differences in their processing steps through the equipment used, procedures, regulations, and experiences in doing the task.

Table 6: Rates, Distribution, and Times for VBM Process Steps

Process Step	Location	n	Mean	Ballots/hr	Min	Max	Range	BestFit Dis.	Dis. Parameters
Sorting Incoming Ballots	Large1	22	1.16	3091	0.48	9.00	8.52	Log Logistics	3.704 , 0.746
Sorting Incoming Ballots	Large2	37	0.79	4566	0.30	1.25	0.96	Gamma	10.5671 , 13.4013
Sorting Incoming Ballots	Large2 - Large1	59	0.93	3876	0.30	9.00	8.70	Log Logistics	4.6917 , 0.7524
Counting Envelopes	Large2	77	0.29	12231	0.07	0.76	0.69	Log Logistics	4.4293 , 0.2729
Signature Tab Removal	Medium	282	5.11	704	1.20	42.90	41.70	Log Logistics	2.5872 , 3.7628
Signature Tab Removal	Large2	62	3.54	1016	1.10	21.80	20.70	Log Logistics	3.2204 , 2.7276
Signature Scanning with Machine	Medium	12	0.22	16415	0.07	0.46	0.38	NA	NA
Signature Scanning with Machine	Large2	6	0.14	24950	0.05	0.22	0.17	NA	NA
Signature Scanning with Machine	Large2 - Medium	18	0.19	18528	0.05	0.46	0.41	Weibull	2.3303 , 0.219
Signature Scanning by Hand	Small	7	2.29	1570	1.66	4.29	2.63	NA	NA
Signature Verification 1	Small	44	8.81	408	0.30	46.27	45.97	Log Logistics	2.0371 , 6.6715
Signature Verification 1	Medium	468	3.71	970	0.70	63.10	62.40	Log Logistics	3.7367 , 2.6341
Signature Verification 1	Large1	196	6.79	530	2.00	82.00	80.00	Log Logistics	2.5283 , 3.7449
Signature Verification 1	Large2	169	7.02	512	1.50	19.00	17.50	Gamma	3.4798 , 0.4953
Signature Verification 1	Large2 - Small	213	7.39	487	0.30	46.27	45.97	Log Logistics	2.7586 , 6.2321
Signature Verification 2	Medium	30	53.13	68	1.60	95.40	93.80	Log Logistics	1.9604 , 49.2024
Signature Verification 2	Large2	59	44.06	82	3.10	124.60	121.50	Weibull	1.6755 , 49.2621
Signature Verification 2	Large2 - Medium	89	47.12	76	1.60	124.60	123.00	Weibull	1.6761 , 52.1986
Signature Verification 3	Large2	94	22.19	162	4.30	50.60	46.30	Gamma	3.3234 , 0.1497
Sorting Envelopes in Batches	Medium	15	0.56	6441	0.18	3.69	3.51	Log Logistics	2.8123 , 0.3128
Sorting Envelopes into Batches	Large1	12	0.24	15147	0.17	0.77	0.60	NA	NA
Sorting Envelopes into Batches	Large2	6	0.13	27224	0.05	0.23	0.18	NA	NA
Opening & Extraction	Medium	26	1.93	1869	0.30	3.32	3.02	Gamma	3.7793 , 1.9616
Opening & Extraction	Large1	2	1.34	2689	1.30	1.38	0.08	NA	NA
Opening & Extraction	Large2	103	1.89	1900	1.06	3.99	2.93	Log Logistics	7.9952 , 1.798
Opening & Extraction	Large1 - Medium	28	1.88	1910	0.30	3.32	3.02	Gamma	3.9418 , 2.0916
Opening & Extraction	Large2 - Medium	129	1.90	1893	0.30	3.99	3.69	Log Logistics	5.9999 , 1.816
Opening Envelopes	Small	10	1.54	2330	0.14	3.28	3.15	NA	NA
Extraction & Unfolding	Small	15	13.99	257	10.47	16.94	6.47	Log Logistics	13.4071 , 13.9858
Unfolding the Ballots	Medium	118	5.29	680	1.00	12.80	11.80	Gamma	5.3829 , 1.0174
Unfolding the Ballots	Large1	3	4.86	741	3.61	7.32	3.71	NA	NA
Unfolding the Ballots	Large2	24	13.48	267	0.10	23.27	23.17	Log Logistics	1.9961 , 12.7138
Unfolding the Ballots	Large1 - Medium	121	5.28	682	1.00	12.80	11.80	Gamma	5.4317 , 1.0287
Tabulation DS450	Small	9	27.40	131	18.20	33.00	14.80	NA	NA
Tabulation DS450	Medium	18	1.23	2920	0.35	2.38	2.03	Weibull	2.6081 , 1.3859
Tabulation DS200	Large1	146	9.26	389	0.40	37.60	37.20	Log Logistics	8.2925 , 8.9456
Tabulation DS850	Large1	9	1.48	2426	0.88	1.86	0.99	NA	NA
Tabulation DRG2140	Large2	105	1.85	1944	0.12	11.30	11.18	Log Logistics	2.3163 , 1.2447
Adjudication	Medium	87	24.21	149	11.70	86.30	74.60	Log Logistics	4.3608 , 21.3974
Adjudication	Large1	222	12.37	291	1.70	87.60	85.90	Log Logistics	2.4268 , 8.6907
Adjudication	Large2	363	30.62	118	0.60	347.50	346.90	Lognormal	2.9608 , 0.8917

For example, the four counties used four different machines to tabulate the ballots. Thereby, the same processing step sometimes differs between different counties, which the Kruskal-Wallis and Mann-Whitney U-Test verify; therefore, identifying different distributions describing the same process step is possible. In addition, the sample sizes of some observed processing steps were too small to determine distributions. Also, transportation and waiting times between the processing stations, as well as loading and unloading the machines, were not considered in this paper.

However, the results of this paper build a basis to plan elections with the VBM system more accurately than based on past experiences. The trend of the last election and from states offering VBM without excuse shows that the VBM system is becoming more popular. Also, the VBM system differs from in-person voting based on the amount and type of processing steps and their equipment as well as expenditure, resources, and staffing. Therefore, more research is necessary for a balanced, detailed, planned VBM system without delays in reporting election results.

5 Conclusion

This paper aims to define processing times, processing rates, and representative probability distributions for the VBM process steps of different-sized counties in the larger Salt Lake City region from time studies that took place during the midterm election in 2022. In total, 2,945 observations and around 579 minutes of video material were collected over six days during the midterm election in 2022, with 2,870 data points were used for the statistical analysis. Through the statistical analysis, rates, distributions, and times were defined for 13 VBM process steps with different resources and procedures to receive the same result. The determined processing rates, distributions, and times aim to support election officials and administrators in making data-informed decisions for future election planning and scheduling. The statistically analyzed data can assist in predicting the necessary workforce and forecasting the time to report election results with existing equipment. The presented rates, distributions, and times are among the first published values for VBM process steps and contain some limitations which need to be considered when the data is used. However, the determined rates, distributions, and times can give an estimate of the process and necessary time and resources.

In the future, more time studies should occur to get more data for each processing step as well as data from other states and counties with their specific laws to include more processing steps and their variations. Further research can use the collected and analyzed data to set up simulations for specific counties to examine their processes to detect bottlenecks and improvement potential. These simulations can also be used for resource allocation and scheduling of workers and processing steps.

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6 Appendix

A Histograms for all Voting Processes and Counties

Figure A1: Sorting Incoming Ballots - Large2

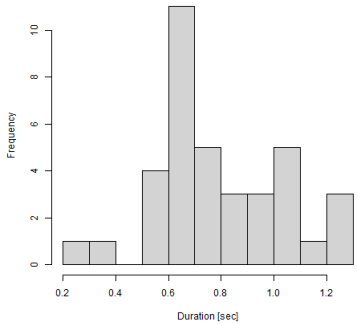


Figure A2: Sorting Incoming Ballots - Large1

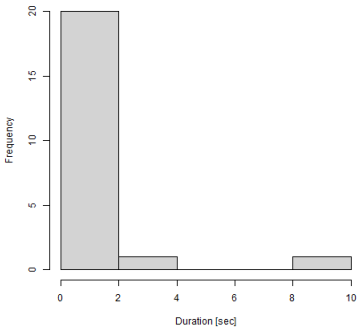


Figure A3: Sorting Incoming Ballots - Large2-Large1

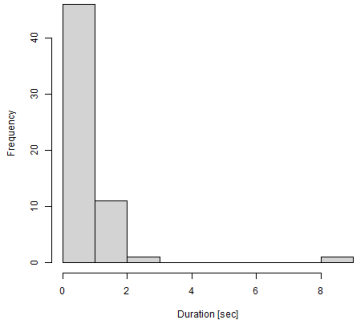


Figure A4: Counting Envelopes - Large2

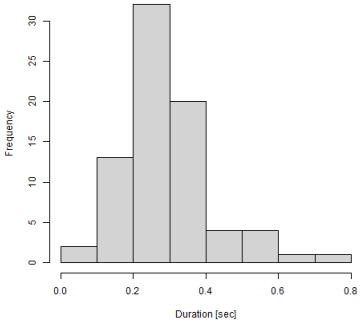


Figure A5: Signature Tab Removal - Large2

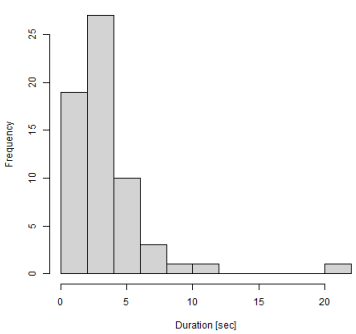


Figure A6: Signature Tab Removal - Medium

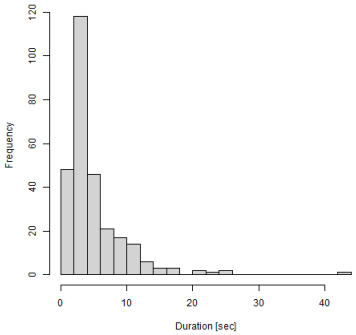


Figure A7: Sorting Signature Tab Removal - Small

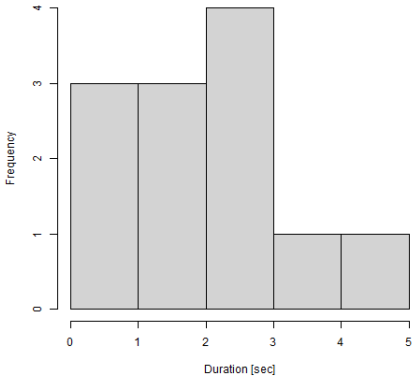


Figure A8: Signature Scanning with Machine - Large2

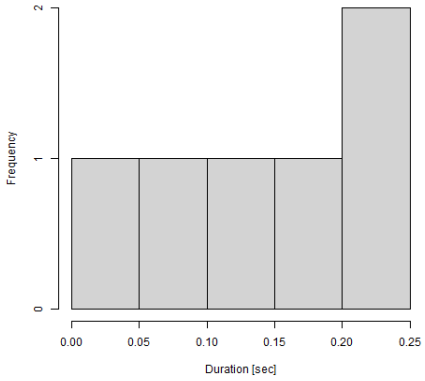


Figure A9: Signature Scanning with Machine - Medium

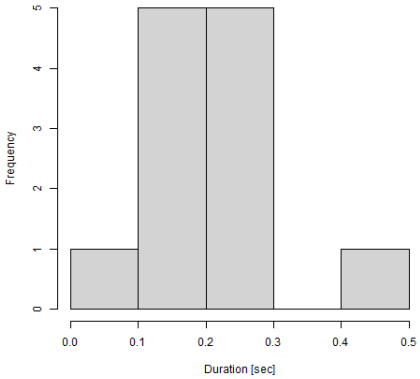


Figure A10: Signature Scanning with Machine - Large2-Medium

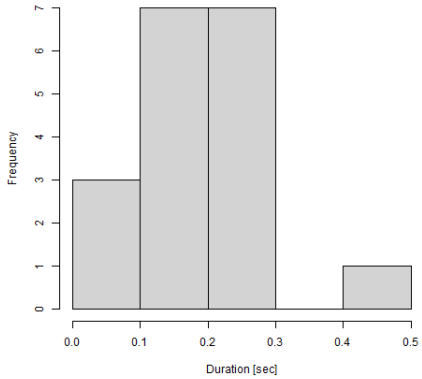


Figure A11: Signature Scanning by Hand - Small

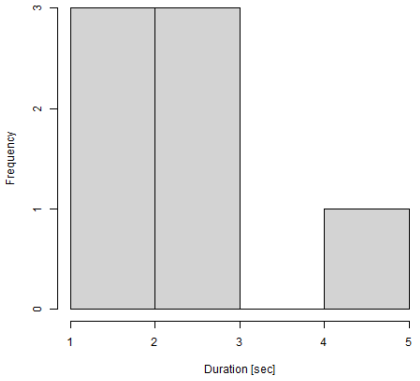


Figure A12: Signature Verification 1 - Large1

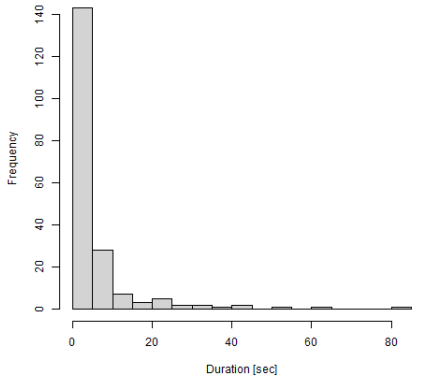


Figure A13: Signature Verification 1 - Medium

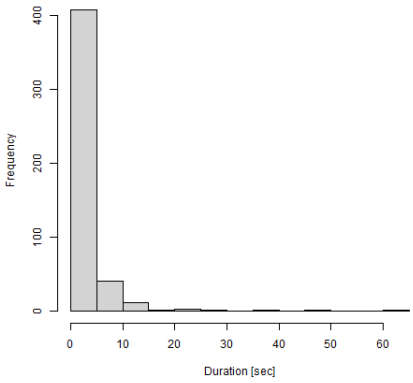


Figure A14: Signature Verification 2 - Medium

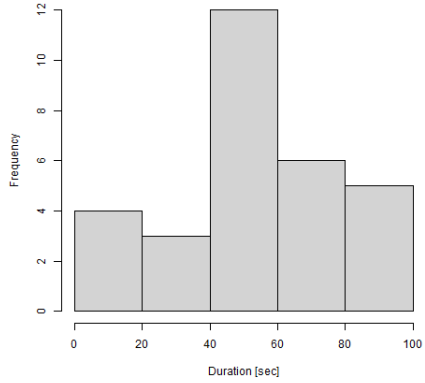


Figure A15: Signature Verification 2 - Large2-Medium

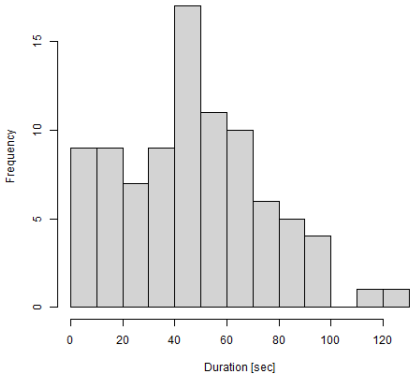


Figure A16: Signature Verification 3 - Large2

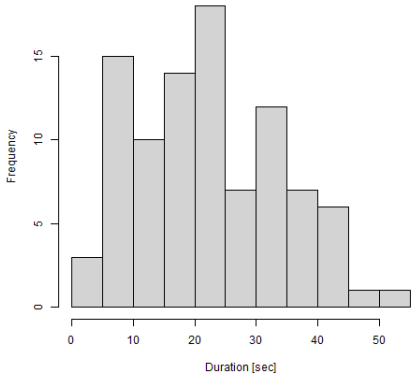


Figure A17: Sorting Envelopes - Large2

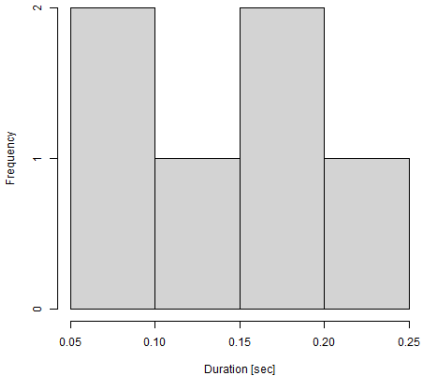


Figure A18: Sorting Envelopes - Large1

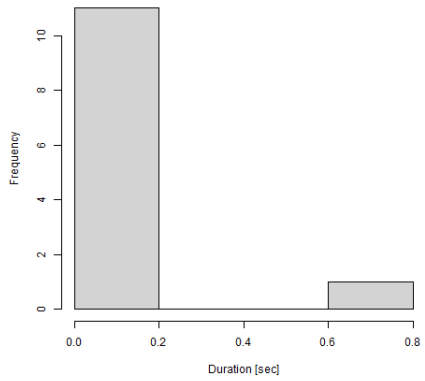


Figure A19: Sorting Envelopes - Medium

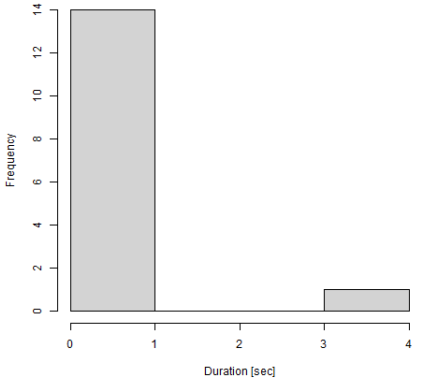


Figure A20: Opening & Extraction - Large2

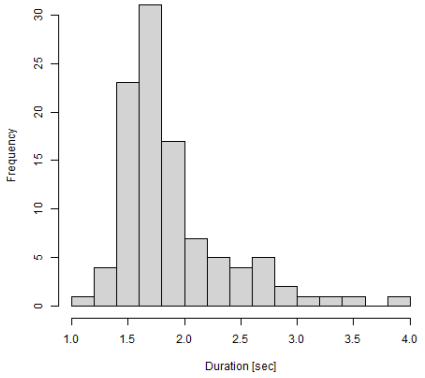


Figure A21: Histogram Opening & Extraction - Large1

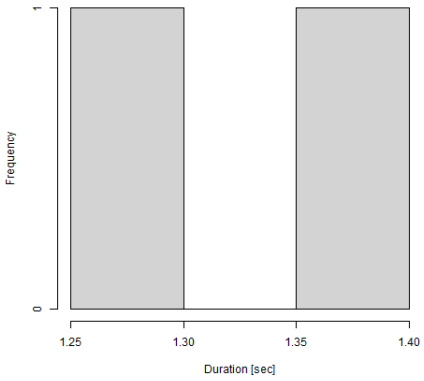


Figure A22: Histogram Opening & Extraction - Medium

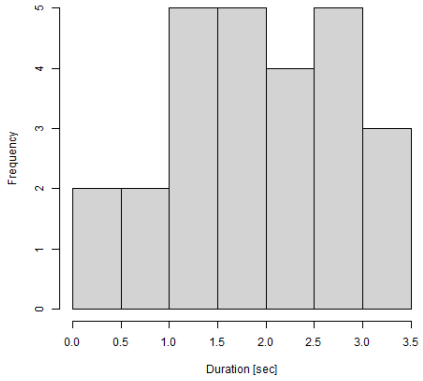


Figure A23: Opening & Extraction - Large2-Medium

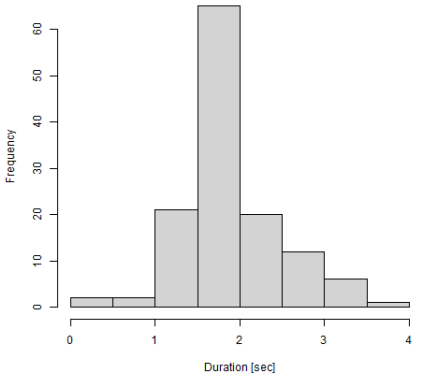


Figure A24: Opening & Extraction - Large1-Medium

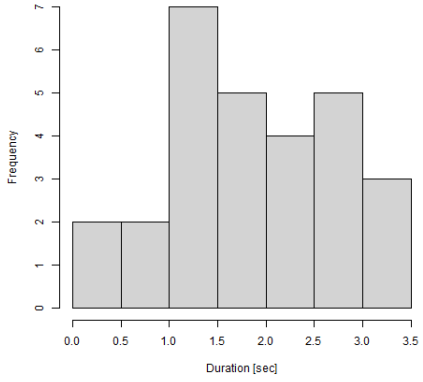


Figure A25: Opening Envelopes - Small

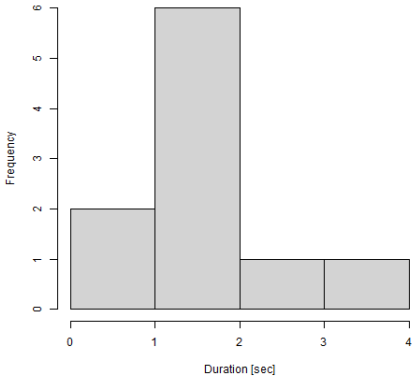


Figure A26: Extraction & Unfolding - Small

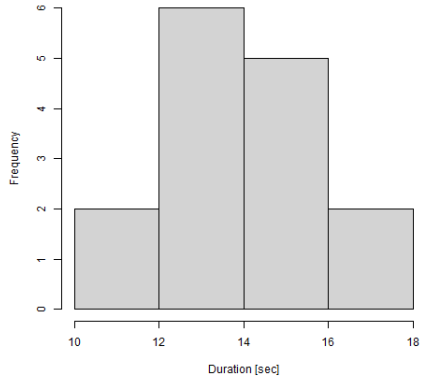


Figure A27: Unfolding Ballots - Large2

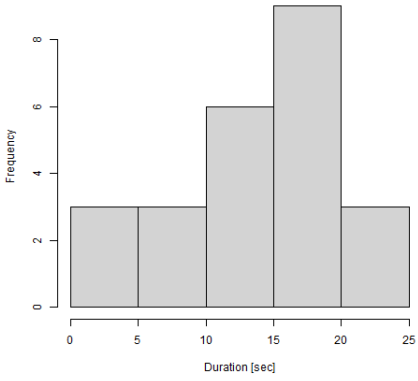


Figure A28: Unfolding Ballots - Large1

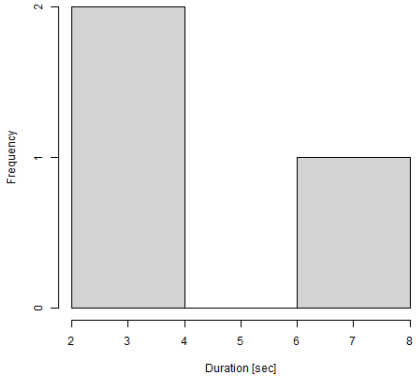


Figure A29: Unfolding Ballots - Medium

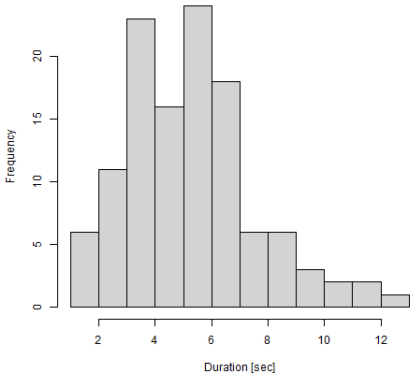


Figure A31: Tabulation DS450 - Medium

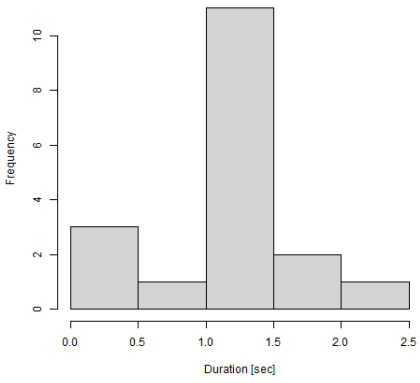


Figure A30: Unfolding Ballots - Large1-Medium

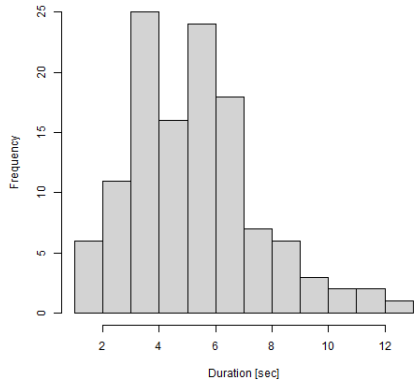


Figure A32: Tabulation DS450 - Small

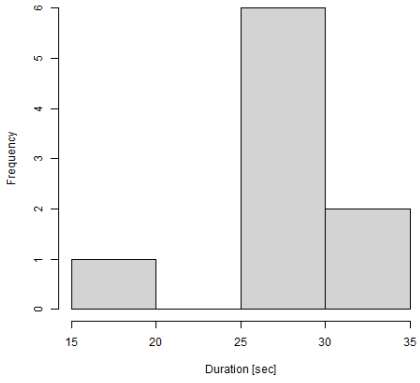


Figure A33: Tabulation DS200 - Large1

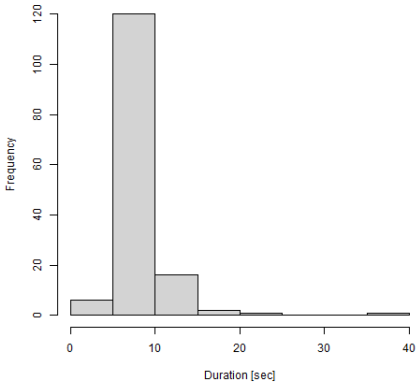


Figure A34: Tabulation DS850 - Large1

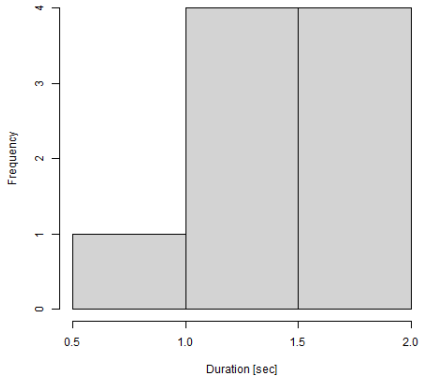


Figure A35: Tabulation DRG2140 - Large2

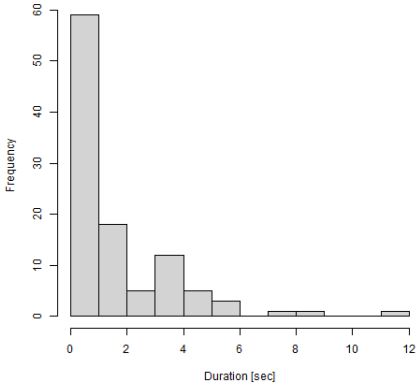
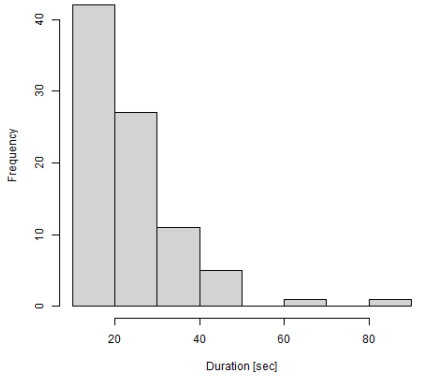


Figure A36: Adjudication - Medium



B Distribution Fitting for All Voting Processes and Counties

Figure B.1: Sorting Incoming Ballots - Large2

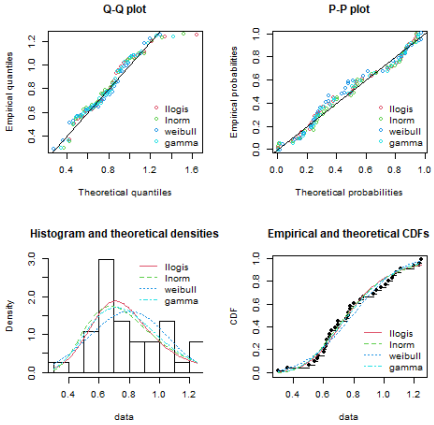


Figure B.2: Sorting Incoming Ballots - Large1

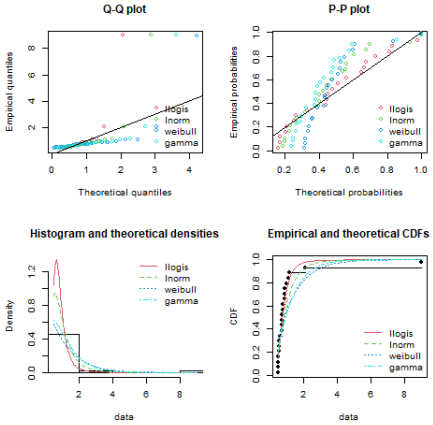


Figure B.3: Sorting Incoming Ballots - Medium

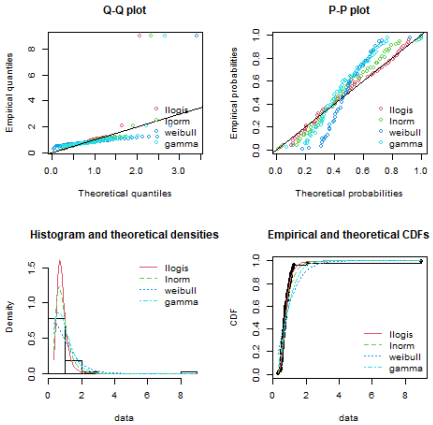


Figure B.4: Counting Envelopes - Large2

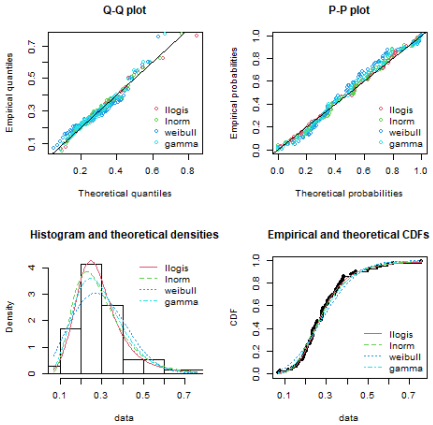


Figure B.5: Signature Tab Removal - Large2

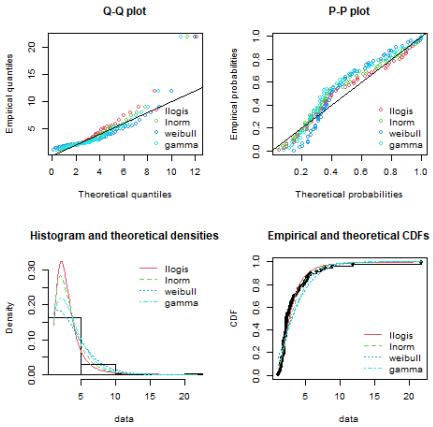


Figure B.6: Signature Tab Removal - Medium

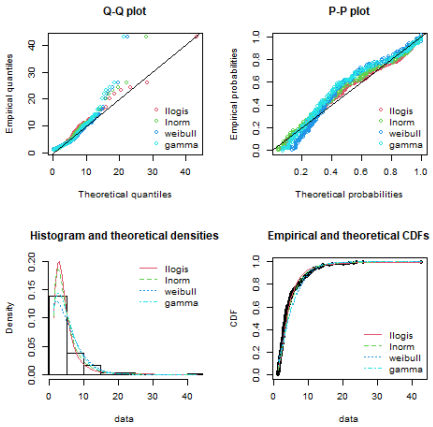


Figure B.7: Signature Scanning with Machine - Large2-Medium

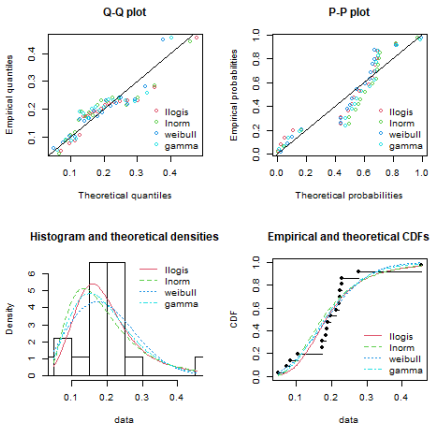


Figure B.8: Signature Verification 1 - Large2

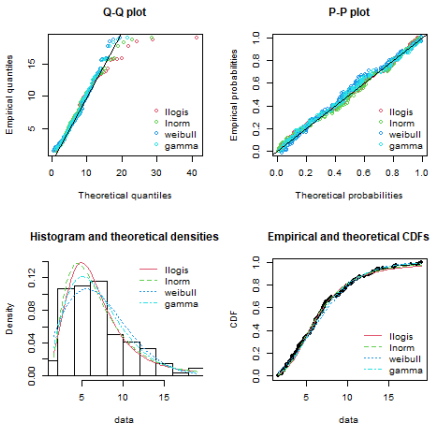


Figure B.9: Signature Verification 1 - Large1

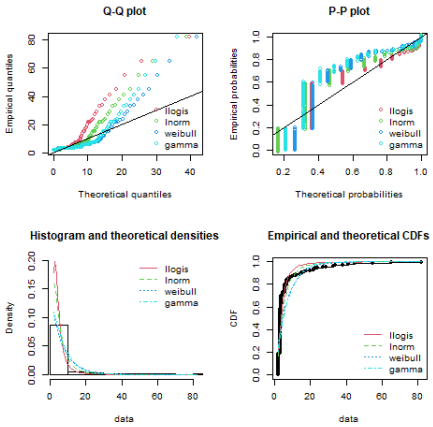


Figure B.10: Signature Verification 1 - Medium

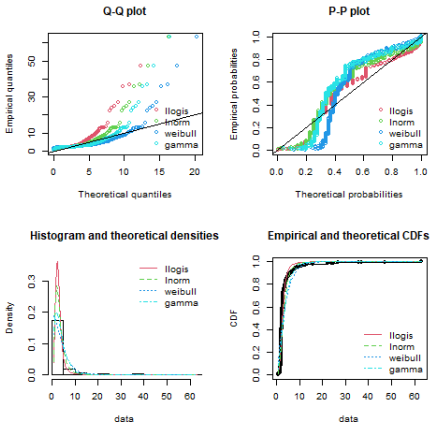


Figure B.11: Signature Verification 1 - Small

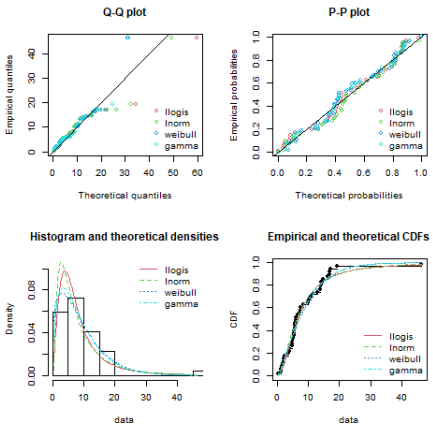


Figure B.12: Signature Verification 1 - Large2-Small

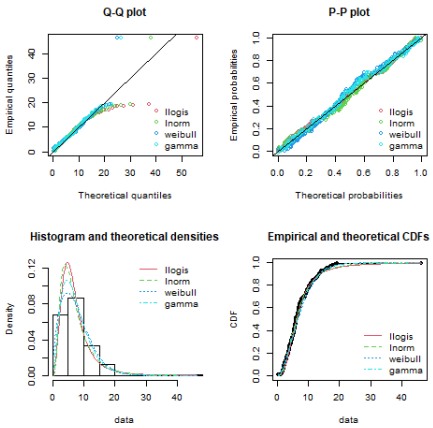


Figure B.13: Signature Verification 2 - Large2

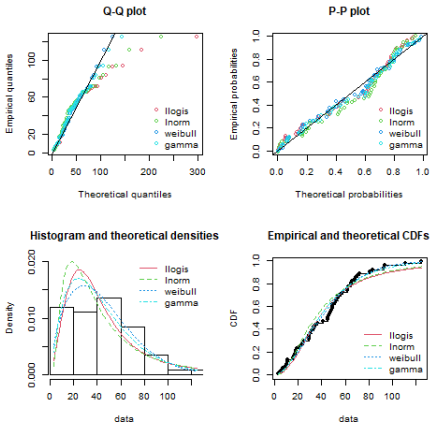


Figure B.14: Signature Verification 2 - Medium

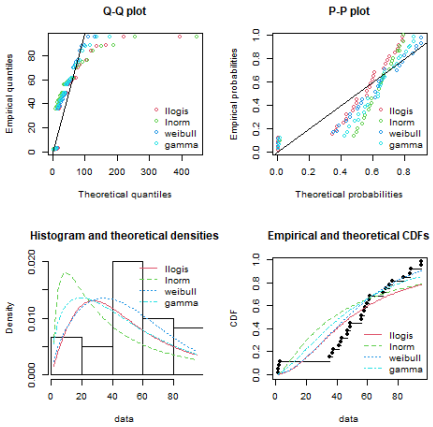


Figure B.15: Signature Verification 2 - Large2-Medium

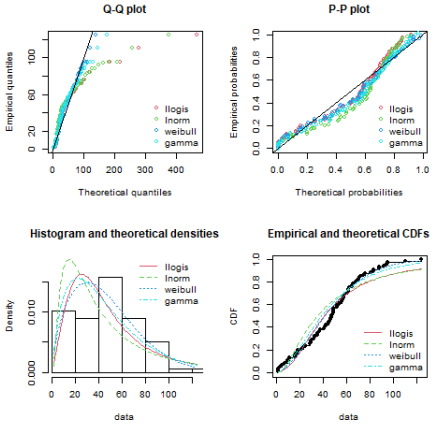


Figure B.16: Signature Verification 3 - Large2

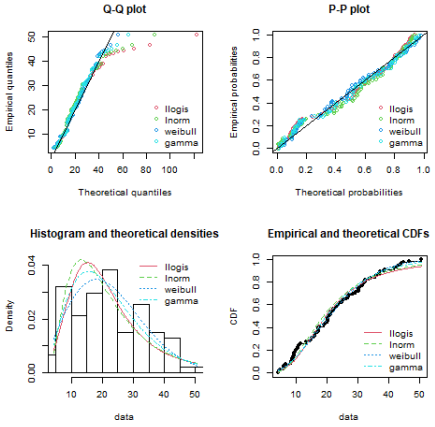


Figure B.17: Sorting Envelopes - Medium

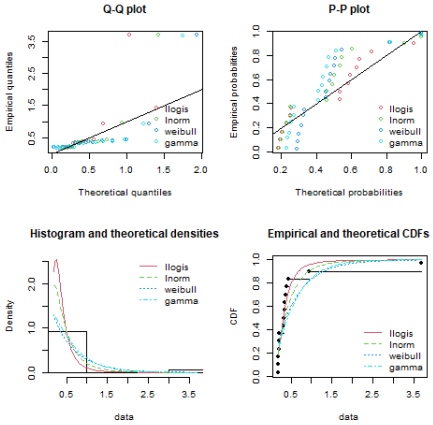


Figure B.18: Opening & Extraction - Large2

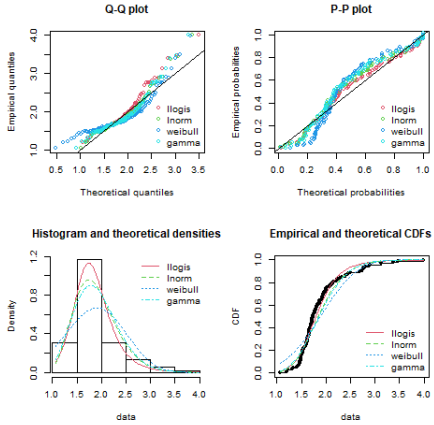


Figure B.19: Opening & Extraction - Medium

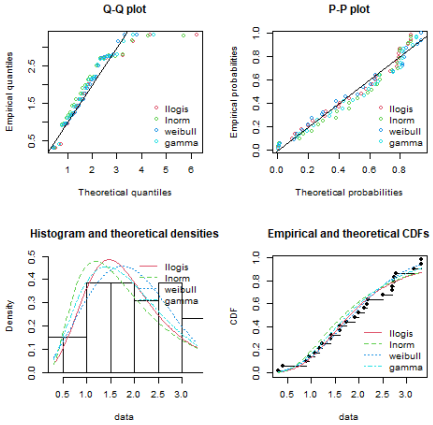


Figure B.20: Opening & Extraction - Large2-Medium

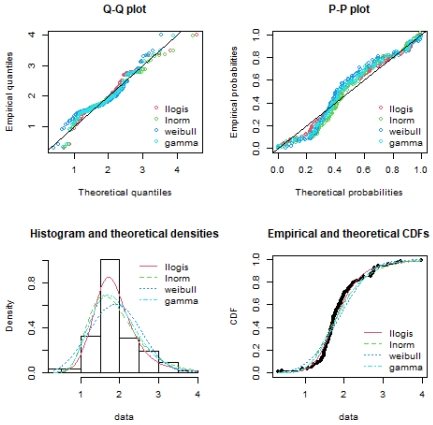


Figure B.21: Opening & Extraction - Large1-Medium

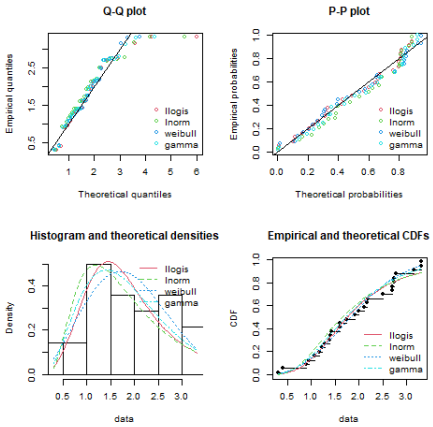


Figure B.22: Extraction & Unfolding - Small

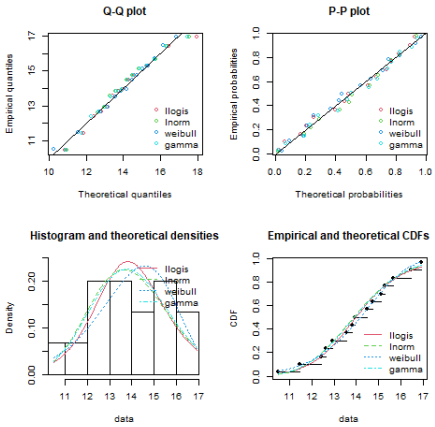


Figure B.23: Unfolding Ballots - Large2

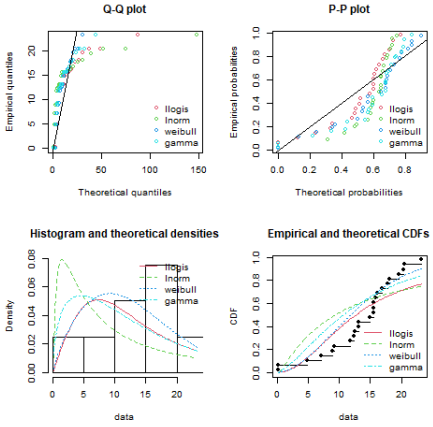


Figure B.24: Unfolding Ballots - Medium

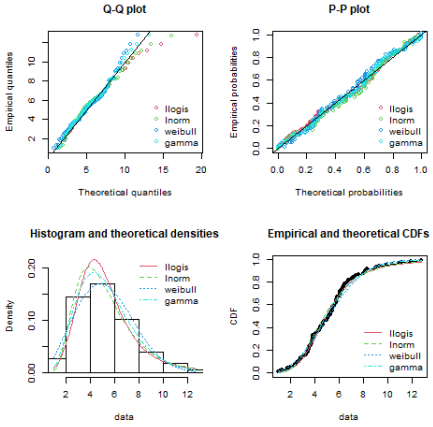


Figure B.25: Tabulation DS450 - Medium

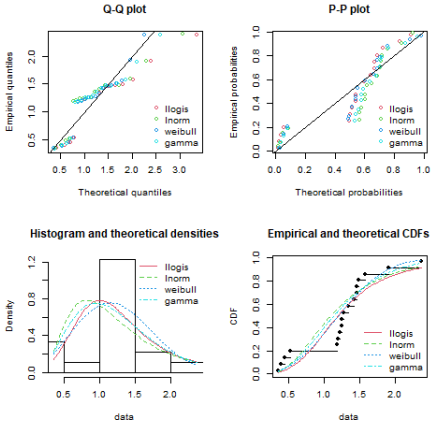


Figure B.26: Tabulation DS200 - Large1

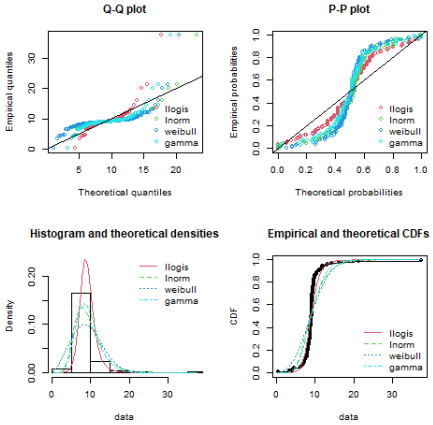


Figure B.27: Tabulation DRG2140 - Large2

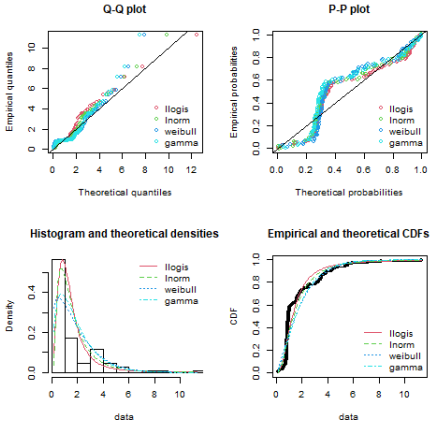


Figure B.28: Adjudication - Large2

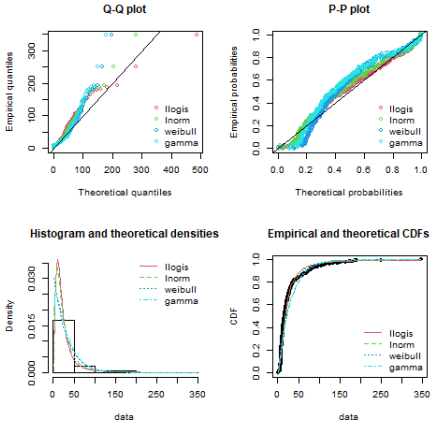


Figure B.29: Adjudication - Large1

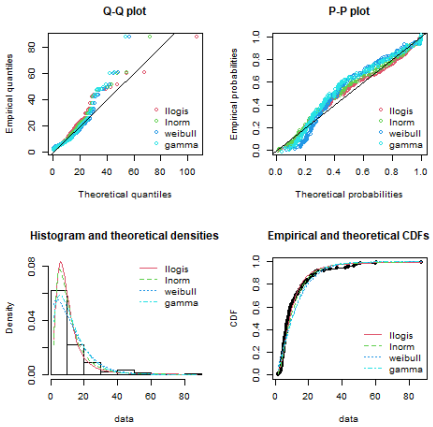


Figure B.30: Adjudication - Medium