SYSC 4005 Simulation Project

Deliverable 1

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1.0 Problem Formulation

The manufacturing facility produces three types of product, each requiring one or more different components. Products are assembled at workstations with each unique product type having its own workstation. Each workstation has one or more buffers for each unique component and the workstation must wait for one of each of the required component(s) before assembling the product. There are two inspectors who must inspect the components before sending the components in the appropriate buffer for a given workstation. The policy for selecting which buffer to send the components from inspector one is to pick the workstation with the shortest buffer. If there is a tie between two buffers, the priority is workstation one, then workstation two, then workstation three. If all the buffers of a given component type become full, then inspector for that component is blocked from sending any more components until a buffer has space available.

There are three different types of products, P_1, P_2, and P_3, each assembled at its own workstation W_1, W_2, and W_3 respectively. There are three different types of components, C_1, C_2, and C_3, required to assemble the products. P_1 requires one C_1, P_2 requires one C_1 and one C_2, and P_3 requires one C_1 and one C_3. There are two inspectors, I_1 and I_2, who inspect the components. I_1 inspects component C_1 and I_2 inspects components C_2 and C_3. The inspected components are placed into the workstation buffers, denoted as $B_{i,j}$, where i is the workstation number and j is the component type of the buffer. This means C_1 can be sent to $B_{1,1}$, $B_{2,1}$, or $B_{3,1}$, C_2 is sent to $B_{2,2}$, and C_3 is sent to $B_{3,3}$.

2.0 Setting of Objectives and Overall Project Plan

2.1 Objectives

The question that we want to answer is:

How should inspector 1 distribute their C_1 components?

Criteria for evaluating alternatives is the throughput of the system and idle time of each workstation and inspector. Our primary objective is to maximize the throughput of the system; other objectives are to minimize the idle time of inspectors and workstations.

The current method inspector 1 uses to place C_1 components is to place them in the buffer with the fewest components. If there is a tie, W_1 has highest priority, then W_2, then W_3. We will consider two alternatives to the current method.

First, we will alter the criteria inspector 1 uses to pick a buffer to place C1 components. Instead of picking the shortest queue the inspector's C1 component into, we will use a fair/round-robin policy (i.e. 1st C_1 to W_1 buffer, 2nd C_1 to W_2 buffer, 3rd C_1 to W_3 buffer, 4th C_1 to W_1 buffer, etc.). This will mean that there is no need for the secondary workstation priorities, and we should see a more even number of each product being created. In the event that a buffer is full when it is the buffer's "turn" to receive a C_1, the buffer will be skipped and C_1 will be placed into the next available buffer. If all buffers for component C_1 are full, then inspector 1 is blocked from sending any more components to the buffers. Once a buffer for component C_1 becomes available, inspector 1 sends the component to that buffer and the selection policy continues from that buffer.

Second, we will change the priority of the workstations in the event of a tie when using the current criteria. The current priority when multiple buffers are equally empty prioritizes W_1, but this may lead to inspector 2 being idle for long periods of time, so we will invert the priority order to W_3, then W_2, then W_1.

Simulation is an appropriate method to answer this question because there are many different criteria and priorities to choose, and it would be too time consuming and resource intensive to actually implement a production line for each C_1 distribution method we want to compare.

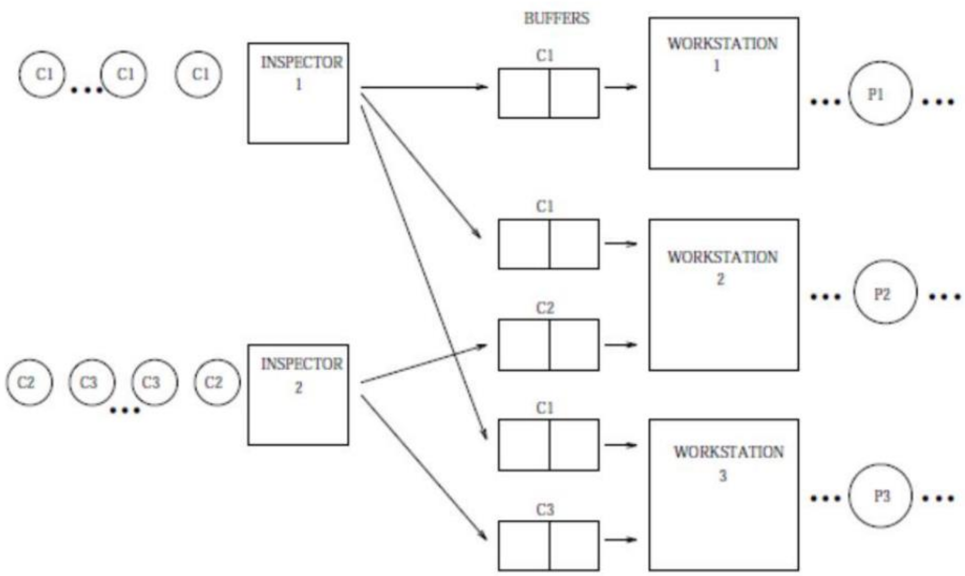
2.2 Project Plan

Our group will meet every Monday from 11:00am to 12:00pm and Tuesday 10:30 to 11:30am to work on the project. These times should work well because they are the scheduled times for the labs each group member is registered in, so we will always be free and will have access to the TA if needed. Depending on progress, additional meetings may be required to ensure completion on time.

The schedule for completing each task is not predictable as it depends on the progress we make in class, but during each weekly meeting the goal is to apply the new knowledge from the previous week's classes so that the project stays up to date.

3.0 Model Conceptualization

Below is the provided schematic of the manufacturing facility from which the entities, relationships among these entities, abstractions, and assumptions that are being made about the system will be listed.



3.1 Entities

Component: The lowest level piece of the system which is used by every other part of the manufacturing system. There is an infinite inventory of components available and taking components from the inventory happens instantaneously. There are three types of components.

Inspector: An inspector is an individual that inspects specific components for some time and then sends the component off to a buffer before starting to inspect the next component. There are two different inspectors.

Buffer: A queue which holds only a specific type of component for a given work station. At most, a queue will hold two items. There are five buffers among all workstations.

Workstation: The part of the system which takes in components as inputs to general different products as outputs. There are three workstations total and each workstation only assembles on type of product. Workstations can only begin to assemble products once they have the required components in their buffers.

Product: The final output of the system obtained from a workstation. There are three different products created and output by the system.

3.2 Entity Interactions

Components and Inspectors: Inspectors take a single component (C1 to inspector 1 and C2/C3 to inspector 2) and inspect the component for some amount of time. Once completed, the inspector will send the component to a specific buffer and instantaneously retrieve take another component for inspection.

Components and Buffers: Components are placed into buffers of the same component type and are only removed from the buffer when the workstation begins assembly.

Components and Workstations: Workstations require a specific combination of components before constructing a product out of the components.

Components and Products: Components are used in the assembly of products.

Inspectors and Buffers: Inspectors place the inspected components into a buffer of the same component type. The buffer chosen depends on the specific routing policy being used. Additionally, buffers can block inspectors from sending additional components if the buffers for that component type are full.

Workstations and Buffers: Each workstation has one buffer per component type that is used in the assembly the product associated with the specific workstation. The workstation will remove one of each of the required components from the workstation's buffer(s) in order to assemble a product.

Workstation and Product: Workstations will assemble a specific product over some amount of time once the required components exist in the workstation's buffers.

3.3 Essential Features

The essential features of this simulation are the inspectors, the buffers, and the workstations. The inspectors are essential because the amount of time taken to inspect the components directly affects how long it takes to go from component to finished product. The buffers are essential because it is important to observe whether the buffers are being filled up too often, or not often enough, to determine if there is a bottle neck in the speed of inspecting a given component. Finally, the workstations are essential for a similar reason as the inspectors in determining the total time taken to go from components to final products.

3.4 Assumptions

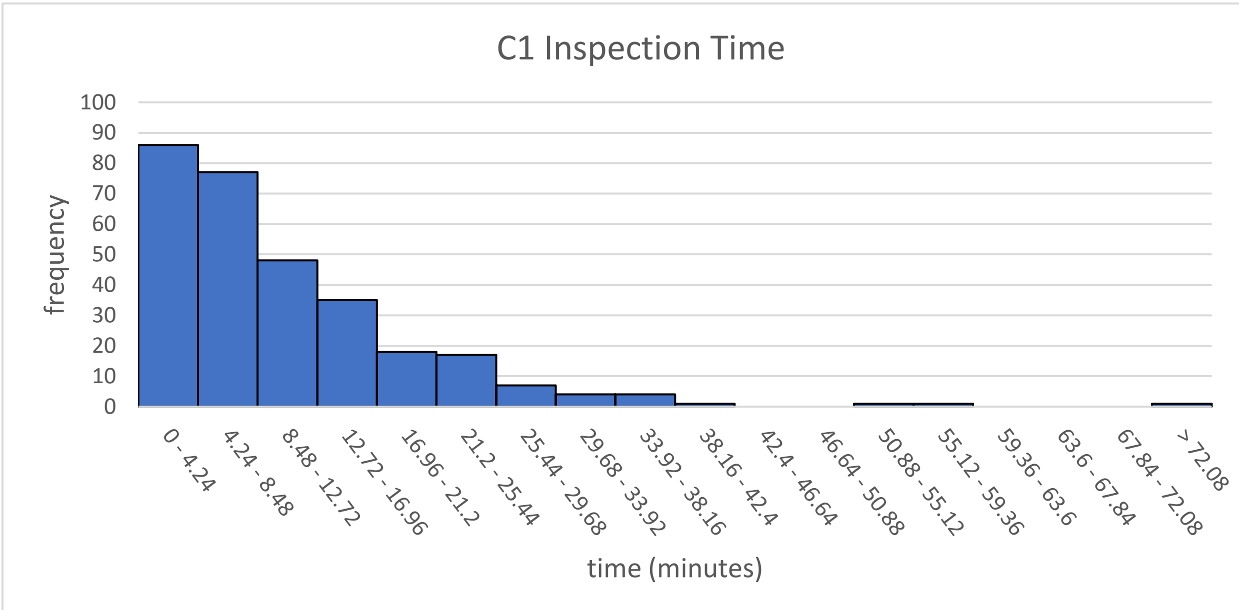
When an inspector gets blocked from placing a component into a buffer on account of the buffer being full, it is assumed that the inspector will keep that component and will able to instantly send that component to a buffer once a buffer becomes available. The reason for this assumption is that the component will eventually be needed, and it would be a waste of time to dispose of the component and then inspect another one later.

4.0 Data Collection and Input Modelling

Data has been collected for 6 different aspects of the environment: Inspection time for C1, Inspection time for C2, Inspection time for C3, W1 assembly time, W2 assembly time, and W3 assembly time.

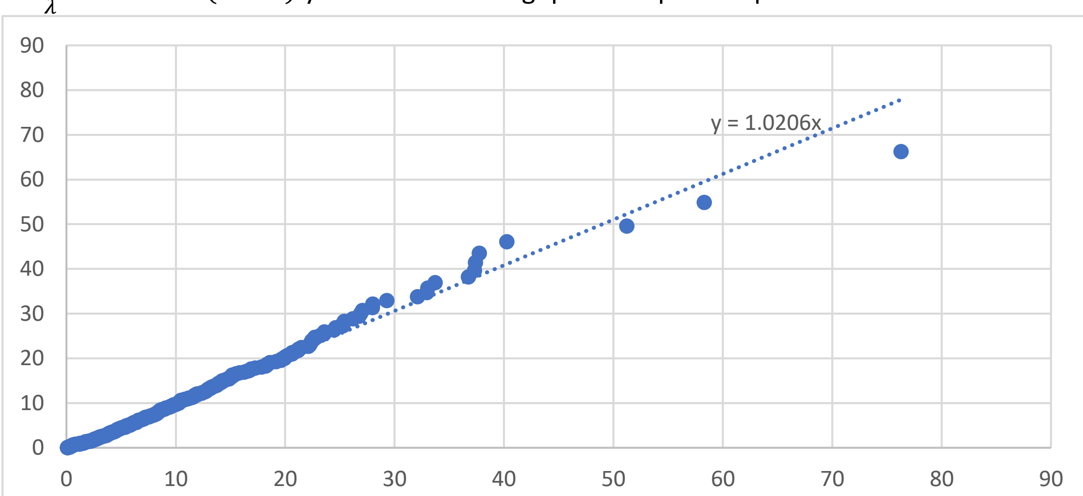
4.1 Inspection Time for C1

Given that the data represents service times and is a continuous variable, it likely follows an exponential distribution. As there are 300 data points, $\lceil \sqrt{300} \rceil = 18$ bins will be used to produce the histogram below:



Based on the shape of this plot, the sample data does seem to fit an exponential distribution, but quantile-quantile plot and chi-squared test must be used before we can say with certainty that this is the distribution that fits.

Using $\lambda = \frac{1}{\bar{X}}$ as the parameter estimation and the quantile function $F^{-1}(x) = \frac{-ln(1-x)}{\lambda} = -\bar{X}ln(1-x)$ yields the following quantile-quantile plot:



The linearity of this plot further confirms that an exponential distribution for C1 inspection time is a good fit, and the parameter estimation is accurate since the slope of the plot is almost exactly one.

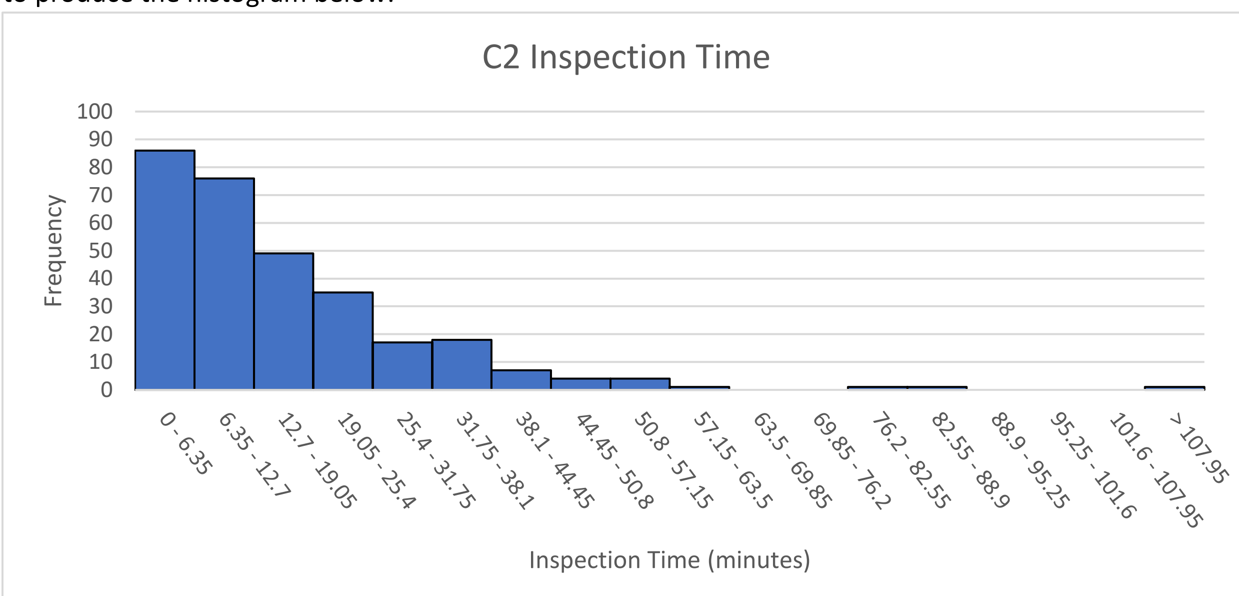
To finalize this choice of distribution, a chi-squared test must be performed. This is an appropriate test to use in these circumstances since there are a large number of data points and there are estimated parameters.

H_0 = the inspection time for C1 follows an exponential distribution with $\lambda = \frac{1}{\bar{X}}$ =0.096545

With 18 bins and one variable estimated, the assumed chi-square distribution has $18 - 1 - 1 = 16$ degrees of freedom. Using a significance level of 0.05, the threshold value obtained from tables is $z_o{}^2{}_{0.05,\,16} = 26.3$. By calculating expected frequencies from the hypothesized exponential distribution (see Appendix 1.1), $z_o{}^2 = 15.0409$. Since this is below the threshold value, the hypothesis can be confidently accepted, and we can say with certainty that the inspection time for C1 components follows an exponential distribution with $\lambda =$ 0.096545.

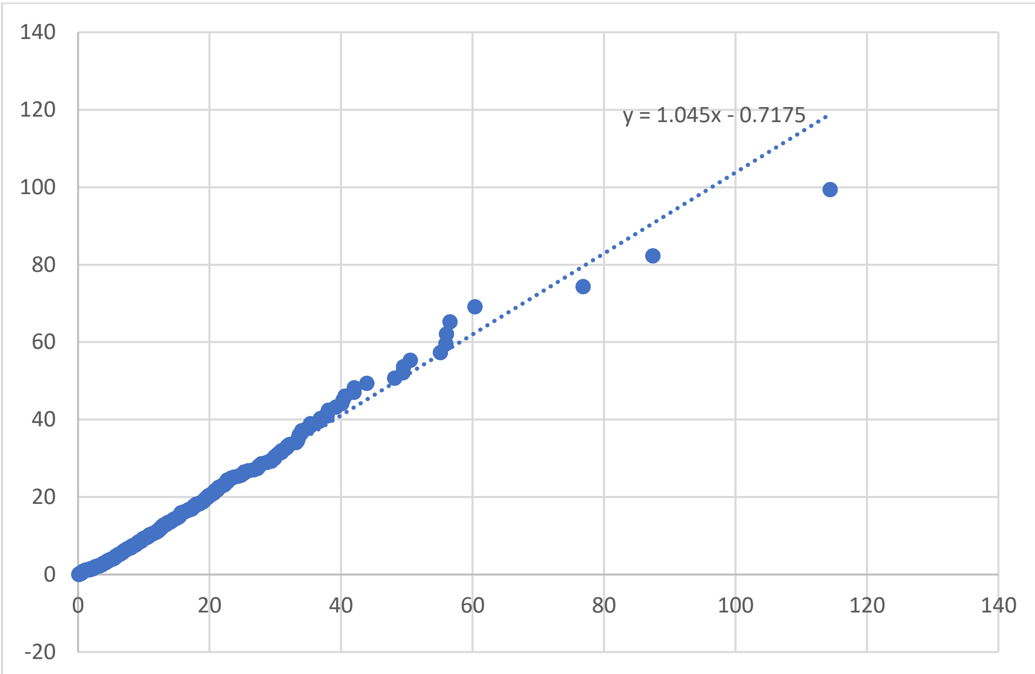
4.2 Inspection Time for C2

Given that the data represents service times and is a continuous variable, it likely follows an exponential distribution. As there are 300 data points, $\lceil\sqrt{300}\,\rceil = 18$ bins will be used to produce the histogram below:



Based on the shape of this plot, the sample data does seem to fit an exponential distribution, but quantile-quantile plot and chi-squared test must be used before we can say with certainty that this is the distribution that fits.

Using $\lambda = \frac{1}{\bar{X}}$ as the parameter estimation and the quantile function $F^{-1}(x) = \frac{-ln(1-x)}{\lambda} = -\bar{X}ln(1-x)$ yields the following quantile-quantile plot:



The linearity of this plot further confirms that an exponential distribution for C2 inspection time is a good fit, and the parameter estimation is accurate since the slope of the plot is almost exactly one. A few of the largest values do not adhere to this linear trend as strongly, but this is fairly typical of the extrema in q-q plot.

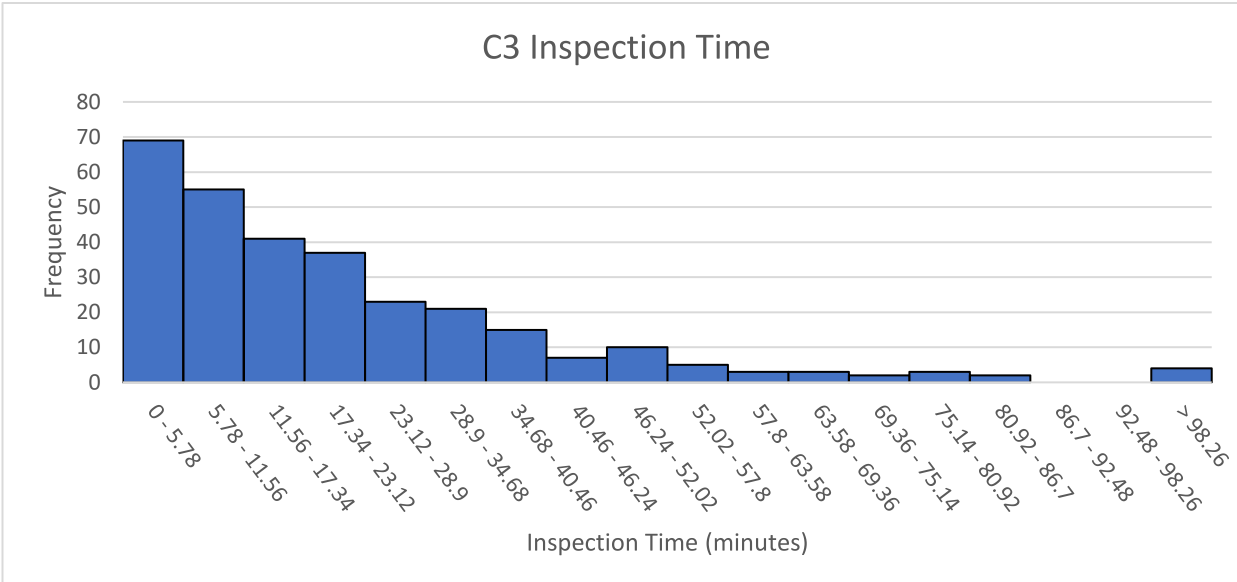
To finalize this choice of distribution, a chi-squared test must be performed. This is an appropriate test to use in these circumstances since there are a large number of data points and there are estimated parameters.

H_0 = the inspection time for C2 follows an exponential distribution with $\lambda = \frac{1}{\bar{X}}$ =0.0644

With 18 bins and one variable estimated, the assumed chi-square distribution has $18 - 1 - 1 = 16$ degrees of freedom. Using a significance level of 0.05, the threshold value obtained from tables is $z_o{}^2_{0.05,\,16}$ = 26.3. By calculating expected frequencies from the hypothesized exponential distribution (see Appendix 1.2), $z_o{}^2$ = 15.663. Since this is below the threshold value, the hypothesis can be confidently accepted, and we can say with certainty that the inspection time for C2 components follows an exponential distribution with $\lambda =$ 0.0644.

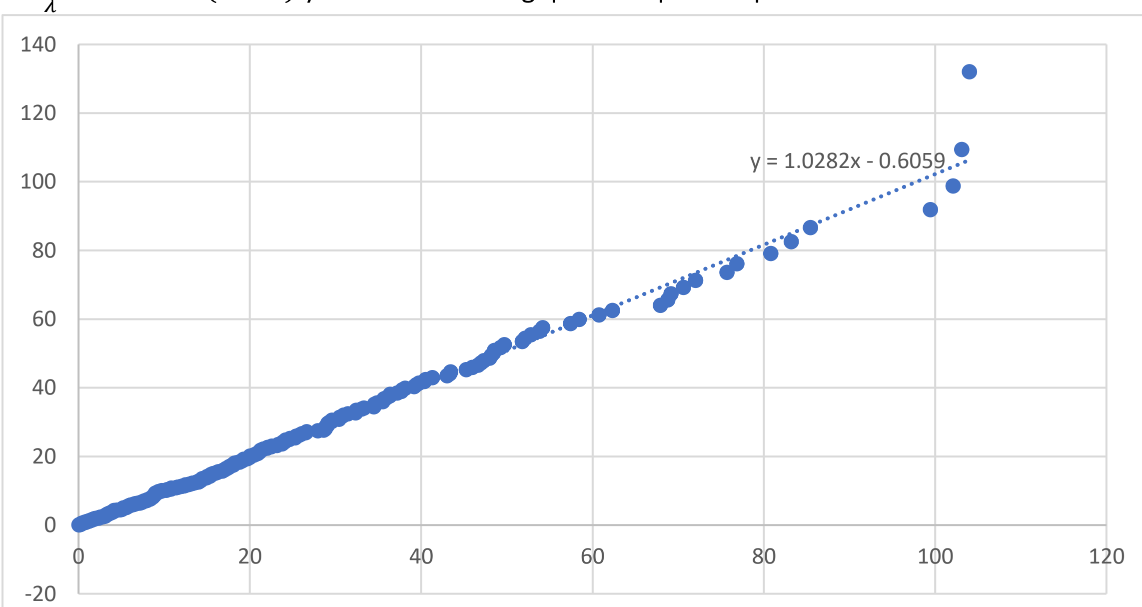
4.3 Inspection Time for C3

Given that the data represents service times and is a continuous variable, it likely follows an exponential distribution. As there are 300 data points, $\lceil\sqrt{300}\,\rceil = 18$ bins will be used to produce the histogram below:



Based on the shape of this plot, the sample data does seem to fit an exponential distribution, but quantile-quantile plot and chi-squared test must be used before we can say with certainty that this is the distribution that fits.

Using $\lambda = \frac{1}{\bar{X}}$ as the parameter estimation and the quantile function $F^{-1}(x) = \frac{-ln(1-x)}{\lambda} = -\bar{X}ln(1-x)$ yields the following quantile-quantile plot:



The linearity of this plot further confirms that an exponential distribution for C3 inspection time is a good fit, and the parameter estimation is accurate since the slope of the plot is almost exactly one. A few of the largest values do not adhere to this linear trend as strongly, but this is fairly typical of the extrema in q-q plot.

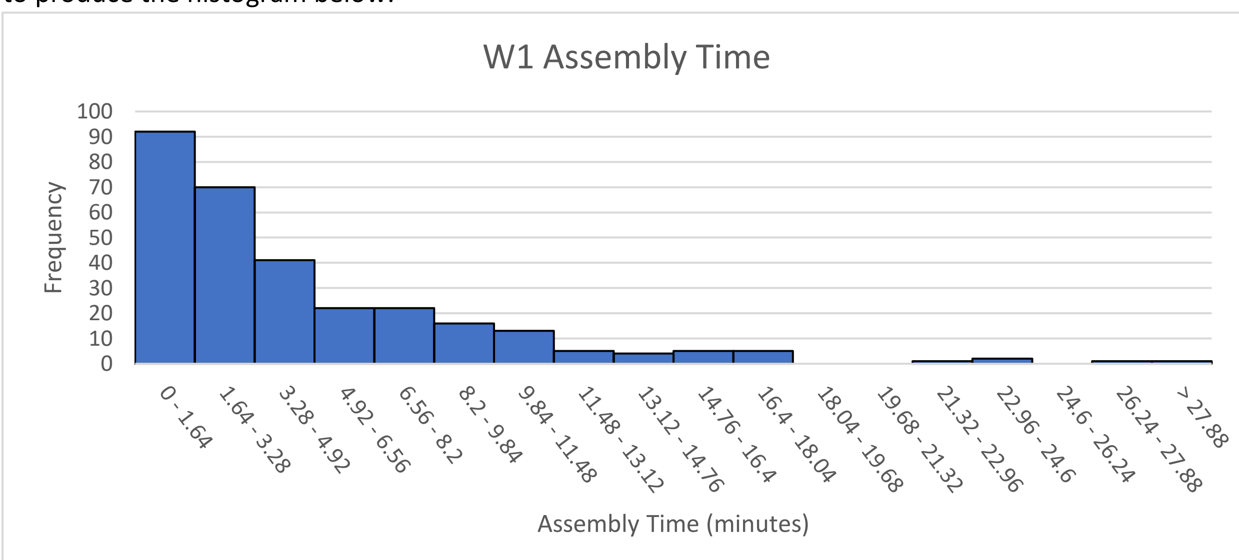
To finalize this choice of distribution, a chi-squared test must be performed. This is an appropriate test to use in these circumstances since there are a large number of data points and there are estimated parameters.

H_0 = the inspection time for C3 follows an exponential distribution with $\lambda = \frac{1}{\bar{X}}$ =0.048467

With 18 bins and one variable estimated, the assumed chi-square distribution has $18 - 1 - 1 = 16$ degrees of freedom. Using a significance level of 0.05, the threshold value obtained from tables is $z_o{}^2_{0.05,\,16}$ = 26.3. By calculating expected frequencies from the hypothesized exponential distribution (see Appendix 1.3), $z_o{}^2$ = 17.48892. Since this is below the threshold value, the hypothesis can be confidently accepted, and we can say with certainty that the inspection time for C3 components follows an exponential distribution with $\lambda =$ 0.048467.

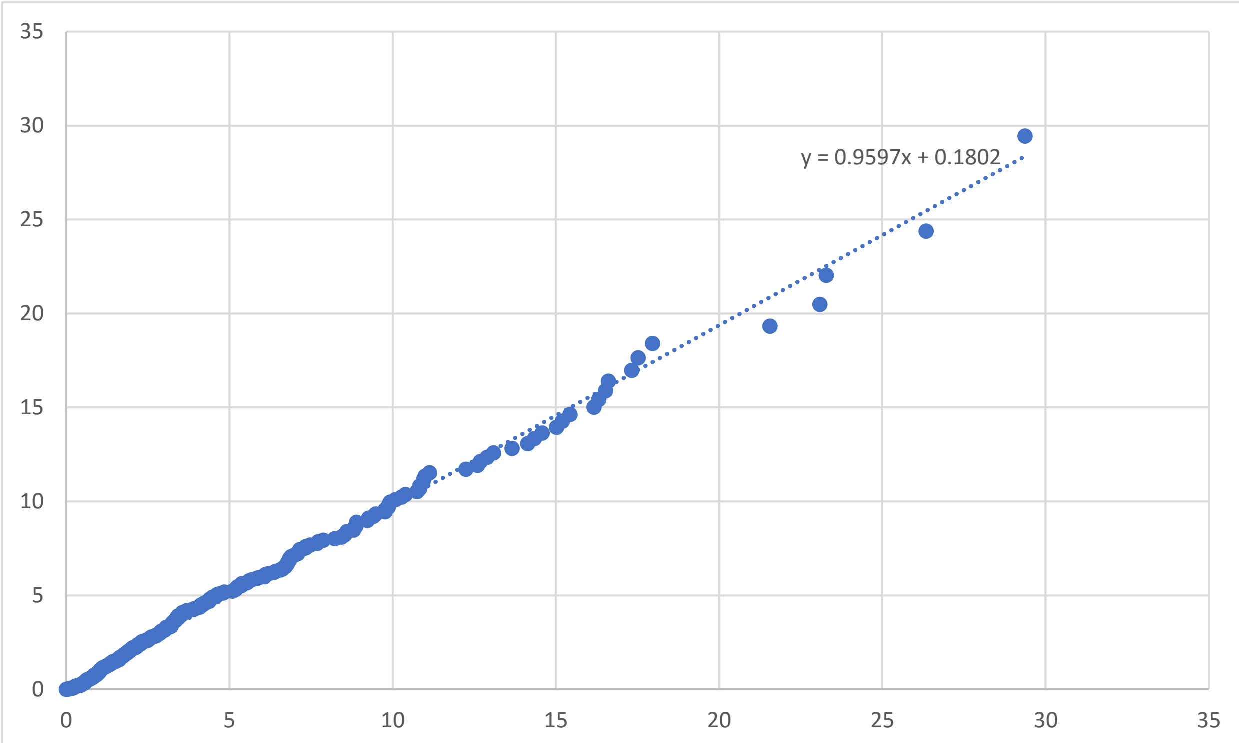
4.4 W1 Assembly Time

Given that the data represents service times and is a continuous variable, it likely follows an exponential distribution. As there are 300 data points, $\lceil\sqrt{300}\,\rceil = 18$ bins will be used to produce the histogram below:



Based on the shape of this plot, the sample data does seem to fit an exponential distribution, but quantile-quantile plot and chi-squared test must be used before we can say with certainty that this is the distribution that fits.

Using $\lambda = \frac{1}{\bar{X}}$ as the parameter estimation and the quantile function $F^{-1}(x) = \frac{-ln(1-x)}{\lambda} = -\bar{X}ln(1-x)$ yields the following quantile-quantile plot:



The linearity of this plot further confirms that an exponential distribution for W1 assembly time is a good fit, and the parameter estimation is accurate since the slope of the plot is almost exactly one.

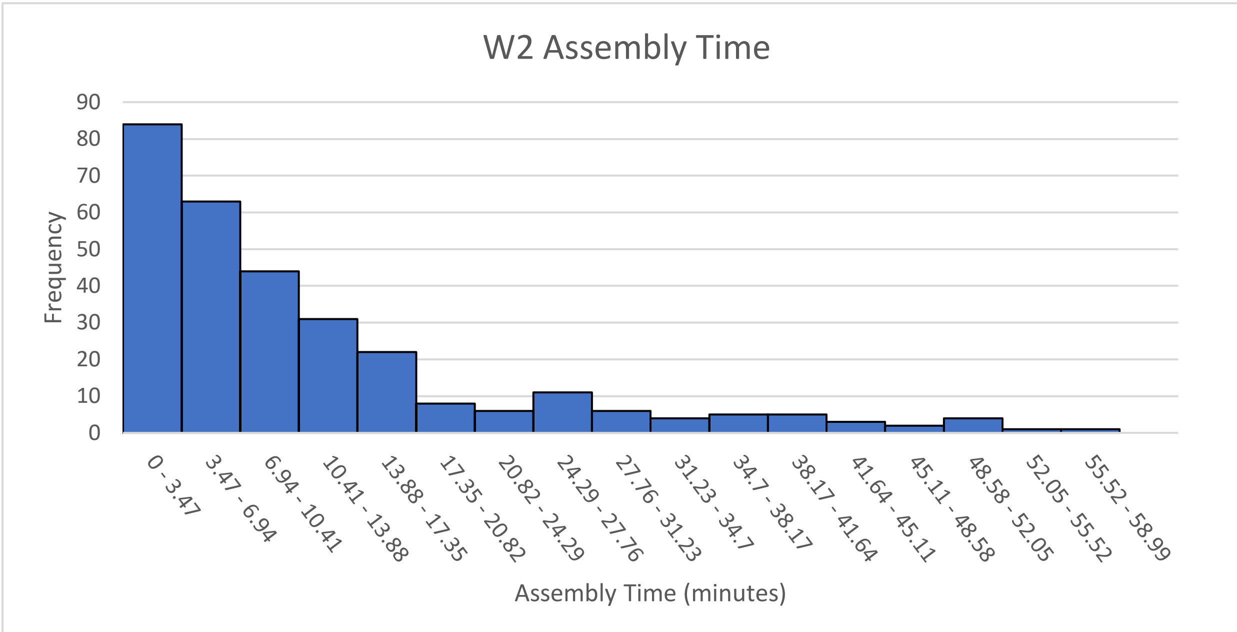
To finalize this choice of distribution, a chi-squared test must be performed. This is an appropriate test to use in these circumstances since there are a large number of data points and there are estimated parameters.

H_0 = the assembly time for W1 follows an exponential distribution with $\lambda = \frac{1}{\bar{X}}$ =0.217183

With 18 bins and one variable estimated, the assumed chi-square distribution has $18 - 1 - 1 = 16$ degrees of freedom. Using a significance level of 0.05, the threshold value obtained from tables is $z_o{}^2_{0.05,\,16} = 26.3$. By calculating expected frequencies from the hypothesized exponential distribution (see Appendix 1.4), $z_o{}^2 = 13.52932$. Since this is below the threshold value, the hypothesis can be confidently accepted, and we can say with certainty that the assembly time for W1 components follows an exponential distribution with $\lambda =$ 0.217183.

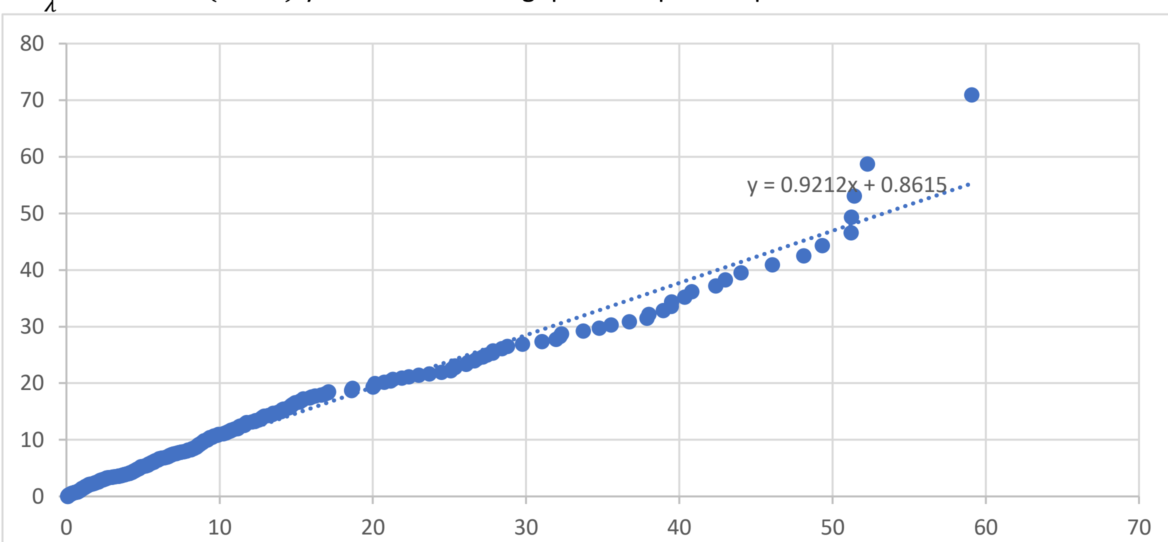
4.5 W2 Assembly Time

Given that the data represents service times and is a continuous variable, it likely follows an exponential distribution. As there are 300 data points, $\lceil\sqrt{300}\,\rceil = 18$ bins would be the standard; however, to reduce the number of empty bins, 17 bins will be used in the graph below:



Based on the shape of this plot, the sample data does seem to fit an exponential distribution, but quantile-quantile plot and chi-squared test must be used before we can say with certainty that this is the distribution that fits.

Using $\lambda = \frac{1}{\bar{X}}$ as the parameter estimation and the quantile function $F^{-1}(x) = \frac{-ln(1-x)}{\lambda} = -\bar{X}ln(1-x)$ yields the following quantile-quantile plot:



The linearity of this plot further confirms that an exponential distribution for W2 assembly time is a good fit, and the parameter estimation is accurate since the slope of the plot is almost exactly one. A few of the largest values do not adhere to this linear trend as strongly, but this is fairly typical of the extrema in q-q plot.

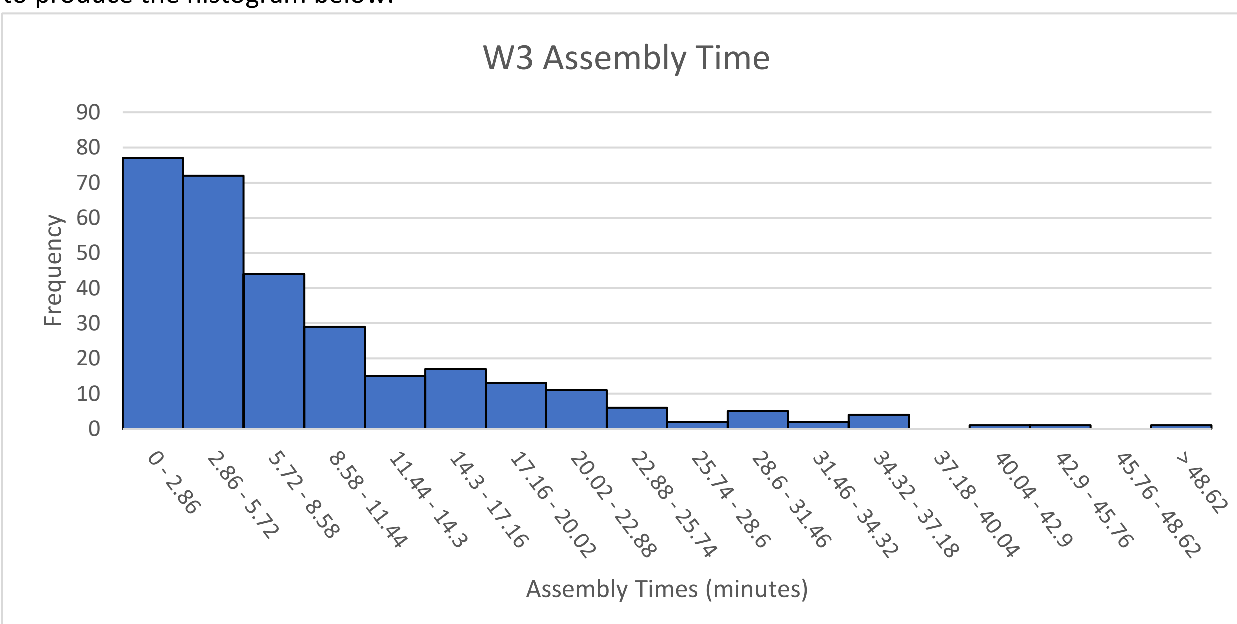
To finalize this choice of distribution, a chi-squared test must be performed. This is an appropriate test to use in these circumstances since there are a large number of data points and there are estimated parameters.

H_0 = the assembly time for W2 follows an exponential distribution with $\lambda = \frac{1}{\bar{X}}$ =0.0902

With 17 bins and one variable estimated, the assumed chi-square distribution has $17 - 1 - 1 = 15$ degrees of freedom. Using a significance level of 0.05, the threshold value obtained from tables is $z_o{}^2{}_{0.05,\,15} = 25$. By calculating expected frequencies from the hypothesized exponential distribution (see Appendix 1.5), $z_o{}^2 = 13.64$. Since this is below the threshold value, the hypothesis can be confidently accepted, and we can say with certainty that the assembly time for W2 components follows an exponential distribution with $\lambda = 0.0902$.

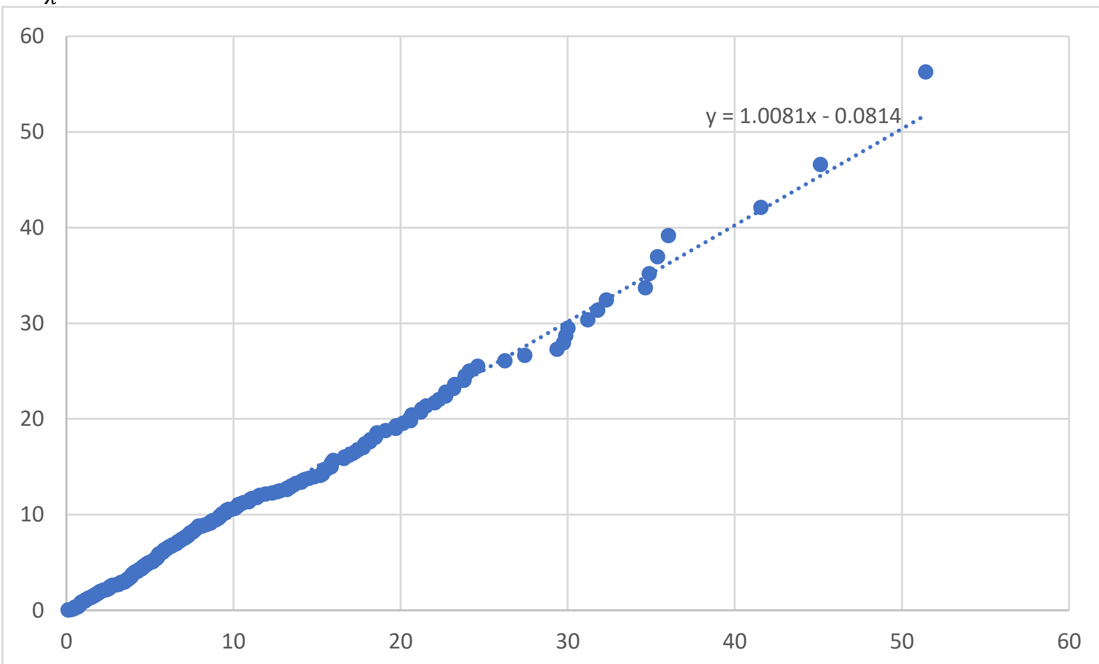
4.6 W2 Assembly Time

Given that the data represents service times and is a continuous variable, it likely follows an exponential distribution. As there are 300 data points, $\lceil \sqrt{300} \rceil = 18$ bins will be used to produce the histogram below:



Based on the shape of this plot, the sample data does seem to fit an exponential distribution, but quantile-quantile plot and chi-squared test must be used before we can say with certainty that this is the distribution that fits.

Using $\lambda = \frac{1}{\bar{X}}$ as the parameter estimation and the quantile function $F^{-1}(x) = \frac{-ln(1-x)}{\lambda} = -\bar{X}ln(1-x)$ yields the following quantile-quantile plot:



The linearity of this plot further confirms that an exponential distribution for W3 assembly time is a good fit, and the parameter estimation is accurate since the slope of the plot is almost exactly one.

To finalize this choice of distribution, a chi-squared test must be performed. This is an appropriate test to use in these circumstances since there are a large number of data points and there are estimated parameters.

H_0 = the assembly time for W3 follows an exponential distribution with $\lambda = \frac{1}{\bar{X}}$ =0.113693

With 18 bins and one variable estimated, the assumed chi-square distribution has $18 - 1 - 1 = 16$ degrees of freedom. Using a significance level of 0.05, the threshold value obtained from tables is $z_o^2{}_{0.05,\,16}$ = 26.3. By calculating expected frequencies from the hypothesized exponential distribution (see Appendix 1.6), z_o^2 = 13.68477. Since this is below the threshold value, the hypothesis can be confidently accepted, and we can say with certainty that the assembly time for W3 components follows an exponential distribution with $\lambda = 0.113693$.

Appendix

Appendix 1.1: Spreadsheet Data for C1 Inspection Time

number of points	300
number of bins	18
max value	76.284
min value	0.087
data range	76.197
bin width	4.233167
sample mean	10.08446
sample variance	92.5225

bin	bin lower range	bin upper range	range	observed frequency O_i	expected frequency E_i	X_0^2 $\frac{(O_i - E_i)^2}{E_i}$
1	0	4.24	0 - 4.24	86	101	2.227723
2	4.24	8.48	4.24 - 8.48	77	67	1.492537
3	8.48	12.72	8.48 - 12.72	48	45	0.2
4	12.72	16.96	12.72 - 16.96	35	30	0.833333
5	16.96	21.2	16.96 - 21.2	18	20	0.2
6	21.2	25.44	21.2 - 25.44	17	14	0.642857
7	25.44	29.68	25.44 - 29.68	7	9	0.444444
8	29.68	33.92	29.68 - 33.92	4	6	0.666667
9	33.92	38.16	33.92 - 38.16	4	4	0
10	38.16	42.4	38.16 - 42.4	1	3	1.333333
11	42.4	46.64	42.4 - 46.64	0	2	2
12	46.64	50.88	46.64 - 50.88	0	2	2
13	50.88	55.12	50.88 - 55.12	1	1	0
14	55.12	59.36	55.12 - 59.36	1	1	0
15	59.36	63.6	59.36 - 63.6	0	1	1
16	63.6	67.84	63.6 - 67.84	0	1	1
17	67.84	72.08	67.84 - 72.08	0	1	1
18	72.08	76.284	> 72.08	1	1	0
				300		15.0409

Appendix 1.2: Spreadsheet Data for C2 Inspection Time

number of points	300
number of bins	18
max value	114.426
min value	0.13
data range	114.296
bin width	6.349778
sample mean	15.5369
sample variance	215.6443

bin	bin lower range	bin upper range	range	observed frequency O_i	expected frequency E_i	X_0^2 $\frac{(O_i - E_i)^2}{E_i}$
1	0	6.35	0 - 6.35	86	101	2.227723
2	6.35	12.7	6.35 - 12.7	76	67	1.208955
3	12.7	19.05	12.7 - 19.05	49	45	0.355556
4	19.05	25.4	19.05 - 25.4	35	30	0.833333
5	25.4	31.75	25.4 - 31.75	17	20	0.45
6	31.75	38.1	31.75 - 38.1	18	14	1.142857
7	38.1	44.45	38.1 - 44.45	7	9	0.444444
8	44.45	50.8	44.45 - 50.8	4	6	0.666667
9	50.8	57.15	50.8 - 57.15	4	4	0
10	57.15	63.5	57.15 - 63.5	1	3	1.333333
11	63.5	69.85	63.5 - 69.85	0	2	2
12	69.85	76.2	69.85 - 76.2	0	2	2
13	76.2	82.55	76.2 - 82.55	1	1	0
14	82.55	88.9	82.55 - 88.9	1	1	0
15	88.9	95.25	88.9 - 95.25	0	1	1
16	95.25	101.6	95.25 - 101.6	0	1	1
17	101.6	107.95	101.6 - 107.95	0	1	1
18	107.95	114.426	> 107.95	1	1	0
				300		15.66287

Appendix 1.3: Spreadsheet Data for C3 Inspection Time

number of points	300
number of bins	18
max value	104.019
min value	0.031
data range	103.988
bin width	5.777111
sample mean	20.63276
sample variance	394.3862

bin	bin lower range	bin upper range	range	observed frequency O_i	expected frequency E_i	X_0^2 $\frac{(O_i - E_i)^2}{E_i}$
1	0	5.78	0 - 5.78	69	74	0.337838
2	5.78	11.56	5.78 - 11.56	55	56	0.017857
3	11.56	17.34	11.56 - 17.34	41	42	0.02381
4	17.34	23.12	17.34 - 23.12	37	32	0.78125
5	23.12	28.9	23.12 - 28.9	23	24	0.041667
6	28.9	34.68	28.9 - 34.68	21	19	0.210526
7	34.68	40.46	34.68 - 40.46	15	14	0.071429
8	40.46	46.24	40.46 - 46.24	7	11	1.454545
9	46.24	52.02	46.24 - 52.02	10	8	0.5
10	52.02	57.8	52.02 - 57.8	5	6	0.166667
11	57.8	63.58	57.8 - 63.58	3	5	0.8
12	63.58	69.36	63.58 - 69.36	3	4	0.25
13	69.36	75.14	69.36 - 75.14	2	3	0.333333
14	75.14	80.92	75.14 - 80.92	3	2	0.5
15	80.92	86.7	80.92 - 86.7	2	2	0
16	86.7	92.48	86.7 - 92.48	0	2	2
17	92.48	98.26	92.48 - 98.26	0	1	1
18	98.26	104.019	> 98.26	4	1	9
				300		17.48892

Appendix 1.4: Spreadsheet Data for W1 Assembly Time

number of points	300
number of bins	18
max value	29.375
min value	0.007
data range	29.368
bin width	1.631556
sample mean	4.604417
sample variance	22.62537

bin	bin lower range	bin upper range	range	observed frequency O_i	expected frequency E_i	X_0^2 $\frac{(O_i - E_i)^2}{E_i}$
1	0	1.64	0 - 1.64	92	90	0.044444
2	1.64	3.28	1.64 - 3.28	70	63	0.777778
3	3.28	4.92	3.28 - 4.92	41	45	0.355556
4	4.92	6.56	4.92 - 6.56	22	31	2.612903
5	6.56	8.2	6.56 - 8.2	22	22	0
6	8.2	9.84	8.2 - 9.84	16	16	0
7	9.84	11.48	9.84 - 11.48	13	11	0.363636
8	11.48	13.12	11.48 - 13.12	5	8	1.125
9	13.12	14.76	13.12 - 14.76	4	6	0.666667
10	14.76	16.4	14.76 - 16.4	5	4	0.25
11	16.4	18.04	16.4 - 18.04	5	3	1.333333
12	18.04	19.68	18.04 - 19.68	0	2	2
13	19.68	21.32	19.68 - 21.32	0	2	2
14	21.32	22.96	21.32 - 22.96	1	1	0
15	22.96	24.6	22.96 - 24.6	2	1	1
16	24.6	26.24	24.6 - 26.24	0	1	1
17	26.24	27.88	26.24 - 27.88	1	1	0
18	27.88	29.375	> 27.88	1	1	0
				300		13.52932

Appendix 1.5: Spreadsheet Data for W2 Assembly Time

number of points	300
number of bins	17
max value	59.078
min value	0.091
data range	58.987
bin width	3.469824
sample mean	11.09261
sample variance	140.3376

bin	bin lower range	bin upper range	range	observed frequency O_i	expected frequency E_i	X_0^2 $\frac{(O_i - E_i)^2}{E_i}$
1	0	3.47	0 - 3.47	84	81	0.111111
2	3.47	6.94	3.47 - 6.94	63	59	0.271186
3	6.94	10.41	6.94 - 10.41	44	44	0
4	10.41	13.88	10.41 - 13.88	31	32	0.03125
5	13.88	17.35	13.88 - 17.35	22	24	0.166667
6	17.35	20.82	17.35 - 20.82	8	17	4.764706
7	20.82	24.29	20.82 - 24.29	6	13	3.769231
8	24.29	27.76	24.29 - 27.76	11	10	0.1
9	27.76	31.23	27.76 - 31.23	6	7	0.142857
10	31.23	34.7	31.23 - 34.7	4	5	0.2
11	34.7	38.17	34.7 - 38.17	5	4	0.25
12	38.17	41.64	38.17 - 41.64	5	3	1.333333
13	41.64	45.11	41.64 - 45.11	3	2	0.5
14	45.11	48.58	45.11 - 48.58	2	2	0
15	48.58	52.05	48.58 - 52.05	4	2	2
16	52.05	55.52	52.05 - 55.52	1	1	0
17	55.52	58.99	55.52 - 58.99	1	1	0
				300		13.64034

Appendix 1.6: Spreadsheet Data for W3 Assembly Time

number of points	300
number of bins	18
max value	51.418
min value	0.102
data range	51.316
bin width	2.850889
sample mean	8.79558
sample variance	74.82545

bin	bin lower range	bin upper range	range	observed frequency O_i	expected frequency E_i	X_0^2 $\frac{(O_i - E_i)^2}{E_i}$
1	0	2.86	0 - 2.86	77	84	0.583333
2	2.86	5.72	2.86 - 5.72	72	61	1.983607
3	5.72	8.58	5.72 - 8.58	44	44	0
4	8.58	11.44	8.58 - 11.44	29	32	0.28125
5	11.44	14.3	11.44 - 14.3	15	23	2.782609
6	14.3	17.16	14.3 - 17.16	17	17	0
7	17.16	20.02	17.16 - 20.02	13	12	0.083333
8	20.02	22.88	20.02 - 22.88	11	9	0.444444
9	22.88	25.74	22.88 - 25.74	6	7	0.142857
10	25.74	28.6	25.74 - 28.6	2	5	1.8
11	28.6	31.46	28.6 - 31.46	5	4	0.25
12	31.46	34.32	31.46 - 34.32	2	3	0.333333
13	34.32	37.18	34.32 - 37.18	4	2	2
14	37.18	40.04	37.18 - 40.04	0	2	2
15	40.04	42.9	40.04 - 42.9	1	1	0
16	42.9	45.76	42.9 - 45.76	1	1	0
17	45.76	48.62	45.76 - 48.62	0	1	1
18	48.62	51.418	> 48.62	1	1	0
				300		13.68477