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Using multi-variate regression and simulation to identify a generic formula for throughput of flow manufacturing lines with identical stations

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ABSTRACT

Estimating throughput of a manufacturing line is important for planning. This paper use simulation and multivariate regression to estimate a generic equation to determine the throughput. Minitab was used to create random data that follow normal distributions: station speed, mean time between failure, mean time to repair, buffer capacity and line length. one thousand different random manufacturing lines were developed and modelled using plantsim. The outputs were used to run a multi-variate regression analysis to find an equation that best fits the data. A regression equation with R^2 equal 92% was found. Station speed has the largest impact on throughput.

KEYWORDS: Simulation, Regression, PlantSim, Manufacturing throughput

INTRODUCTION

Setting up a manufacturing line requires significant planning to ensure its success. The manufacturing line should be capable of yielding the minimum required throughput. An efficiently planned manufacturing line can save a company a significant amount of money in the long run. The initial step of setting up a manufacturing line is to determine the best layout. The best layout should 1) minimize labor cost, 2) minimize product damage, 3) maximize the throughput speed, 4) easily incorporate new processes, and 5) maximize safety and morale. The throughput of a manufacturing line is the number of jobs that a manufacturing line can complete in a certain amount of time. The throughput is measured in the number of products completed per hour. This is important because a manufacturing line should be capable to satisfy the anticipated demand for that product in order not to lose sales and customer satisfaction. However, this is very difficult to calculate because many factors affect the throughput of a manufacturing line.

To simplify the problem of calculating the throughput of a manufacturing line, Alden (2002) developed a general two-station line. Each of the stations has three variables with a buffer in the middle. The variables are 1) the speed of a station, S (jobs per hour), 2) the failure rate of a station, λ (failures per m), 3) the repair rate of station, μ (repairs per hour), and 4) buffer size, B (number of jobs).

The station speed measures how many jobs per hour that a station completes. The failure rate of a station measures how often a machine breaks down per hour. The repair rate of station measures how long it takes to repair the machine. It is measured in hours. The buffer size measures how many jobs can be stored in the buffer.

The buffer is used to store products processed by station 1 before moving to station 2. Alden calculates the throughput of the model based on the buffer. The buffer can be in the following states: 1) full or blocked (station 1 is blocked if the buffer is full because it has no place to store its processed parts), and 2) empty or starved (station 2 is starved because it has no parts coming from station 1 to process).

Alden's model is based on the following assumptions: 1) The buffer does not fail, and jobs flow through it with zero transit time; 2) A station does not fail if it is blocked or starved; 3) Operating times between failures at a station are exponentially distributed with mean ($\frac{1}{\lambda}$); 4) Repair times at a station are exponentially distributed with mean ($\frac{1}{\mu}$); 5) The first station is never starved and the second station is never blocked.

The two stations can be in the following states: 1) U (up): Both stations are running; 2) F (filling): Station 2 is down while station 1 is running; 3) E (emptying): station 1 is down while station 2 is running; 4) FB (fail blocked): station 1 is blocked because station 2 has failed and the buffer is full; 5) FS (fail starved): station 2 is starved because station 1 has failed; 6) SB (speed blocked) : station 1 is blocked because station 2 has slower speed; and 7) SS (speed starved): station 2 is starved because station 1 has a slower speed.

By applying the renewal theory, Alden [1] finds the expected renewal period $E(T^c)$. The renewal period is the total amount of time the system is running by finding the fraction of time spent in each state.

$$E(T^c) = E(T^U) + E(T^F) + E(T^E) + E(T^{FB}) + E(T^{FS}) + E(T^{SB}) + E(T^{SS}) \tag{1}$$

The fraction of time that the system is Up and Empty found as these are the times when the system is still producing:

$$P(U) = \frac{E(T^U)}{E(T^C)} \tag{2}$$

$$P(E) = \frac{E(T^E)}{E(T^C)} \tag{3}$$

The throughput can then be calculated by:

$$\rho = S_2 P(U) + \hat{S_2} P(E) \tag{4}$$

S_2 is the station speed of station 2 and $\hat{S_2} = \frac{S_2 \mu_2}{\lambda_2 + \mu_2}$. We use the $\hat{S_2}$ to account for its stand-alone availability.

Finding the throughput of the two-station manufacturing line is complex because of the many situations that have to be considered. Increasing the number of stations would add many more situations and factors that have to be modelled in order to accurately estimate throughput. To simplify this problem, the stations in this paper are considered to be similar; that is, they have the same set of parameter (S, λ, μ and B). This implies that it will be possible to find one equation which will be able to determine the throughput of a manufacturing line with multiple identical stations. Data collected from a simulation software will be input into a multiple regression analysis to determine an equation that models the throughput most accurately. This equation can then be easily used to find the effects of the independent variable without setting up multiple simulations.

A simplified general equation for a manufacturing line with identical station is useful. It will provide a simple equation to accurately estimate the throughput. Furthermore, the equation can be used to study the effects of changing the factors on the throughput. The regression model also tests how accurate the equation is compared to the given data. Having an equation is much easier and faster to manipulate and analyze than to set up and run a simulation. The equation can also show us which factor(s) have the greatest impact on the throughput.

The remainder of the paper is organized as follows. The section on literature review discusses incubators and AHP. The section on research methodology and results describes the methods in details and presents the findings of this paper. Finally, the section on conclusion draws some conclusions.

LITERATURE REVIEW

To the best of the authors' knowledge, there is few studies using statistical methods to estimate throughput of a manufacturing line. However, many research studies have been conducted on different optimization techniques of assembly lines. According to Rekiek et al. (2002), the design of a production system comprises of sub problems: 1) selection of pieces of equipment from a set of candidate solutions for each manufacturing operation, 2) balancing and dimensioning of workstations (assignment of operations to workstations), 3) dimensioning storage areas, i.e. buffers, 4) dimensioning transportation systems, and 5) layout. The main objective of setting up a manufacturing/production system is to increase the efficiency of the line by maximizing the ratio between throughput and required costs. This makes it important to find the optimal values for different variables that affect throughput.

Blumenfeld & Li (2005) took an analytical approach to identify a general equation for throughput of a similar station manufacturing line. Their equation was based on Alden's model. This equation was used to produce and analyze many different manufacturing lines. Askin & Standridge (1993) took a similar approach to identify a general equation for manufacturing lines with stations that have variable operation times. Equations such as these are used to increase throughput by easily analyzing the effects of each variable on the throughput. However, a statistical analysis is advantageous because it has the ability to produce a single linear equation. The coefficients of each variable can be easily compared to determine which factors have a greater effect on throughput. Fechet & Nedelcu (2012) used multiple regression to find the relationship between incomes, number of employees, product price and total revenue. Chatterjee & Hadi (2012) stated that to successfully implement a regression analysis requires a balance of theoretical results, empirical rules, and subjective judgment.

RESEARCH METHODOLOGY

Manufacturing throughput is an important factor that a company needs to know before starting manufacturing. The information on throughput is needed so that the company can estimate its production capacity. This capacity is then compared to the sales demand to determine if any changes are needed before beginning manufacturing. There are four independent factors that affect the throughput of a manufacturing line: 1) the speed of a station, S (jobs per hour), 2) mean Time Between Failure (MTBF), $\frac{1}{\lambda}$, 3) Mean Time to Repair (MTTR), $\frac{1}{\mu}$, and 4) buffer size, B (number of jobs).

A multi-variate regression analysis can be used to find the relationship between several independent variables and a dependent variable. In this case, multi-variate regression is used to find the relationship between throughput, ρ (jobs per hour) and the four independent variables. Manufacturing lines have many different stations with different throughputs. Finding exact throughput for such a line is complex. To simplify the problem, it is assumed that all the stations are identical. This assumption makes it possible to identify a general formula to estimate throughputs of a manufacturing line with M identical stations.

Data Description

PlantSim is a simulation software produced by Siemens. PlantSim can be used to model any type of manufacturing line. A simulation can be run in PlantSim to determine throughout and bottleneck of the whole system or other statistics of independent stations. Minitab Random function was used to generate random data with a normal distribution. Table 1 shows the variables and the lower and upper limits.

Table 1: Key system parameters of a manufacturing line

Independent Variable	Station Speed	MTBF	MTTR	Buffer size	Line length	Simulated Throughput
Units	Jobs/Hour	Min	Min	Jobs/Hour	Number	Jobs/Hour
Range	10-60	20-200	2-20	0-40	2-20	

The distribution of the random data was analyzed. The graphs of the distributions curve which best fit the random data for each variable are presented in Figures 1-5. They all follow the Johnson transformation and they have very high P value and low AD values. The data matches this distribution very closely.

Figure 1 Generated data for station speed

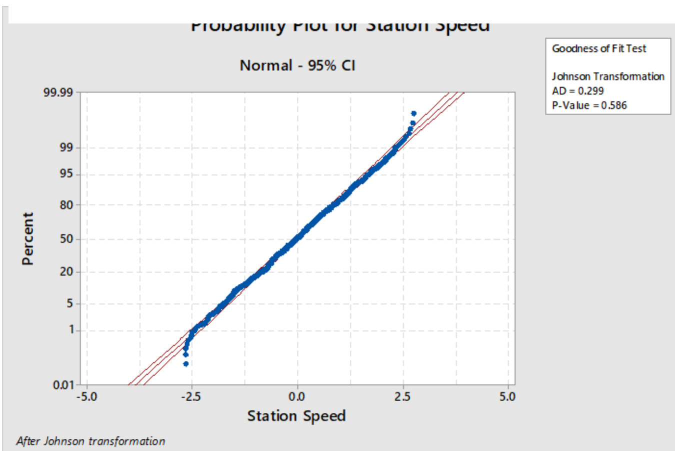


Figure 2 Generated data for MTBF

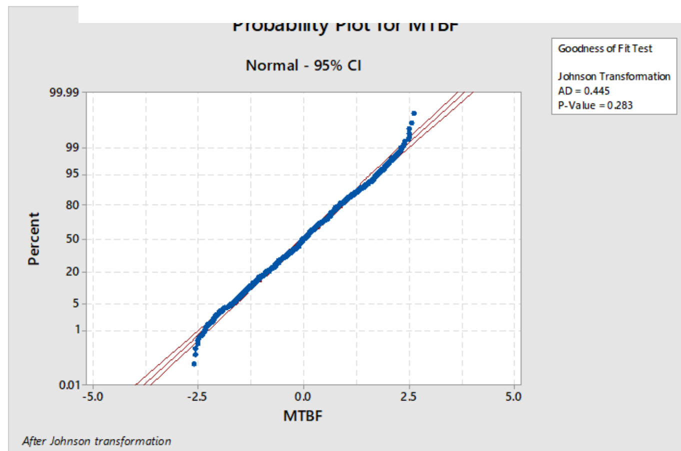


Figure 3 Generated data for MTTR

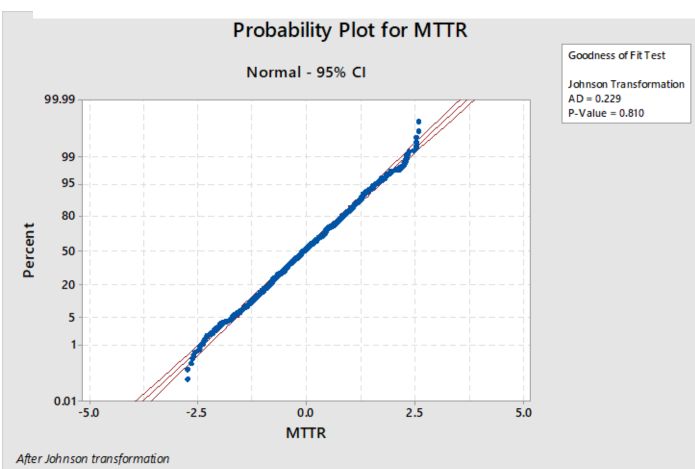


Figure 4 Generated data for buffer size

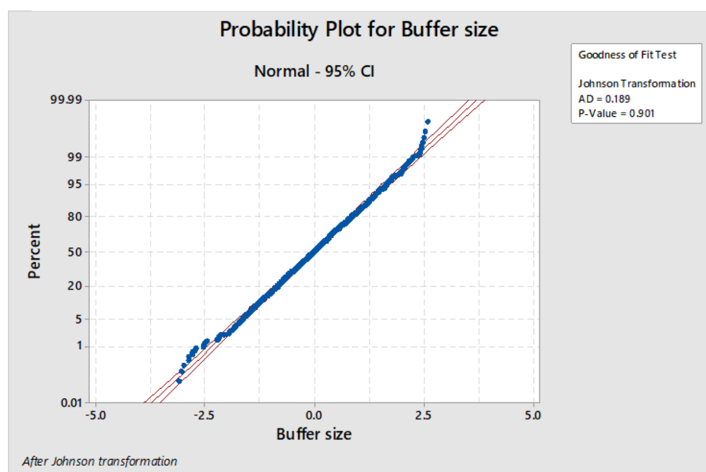
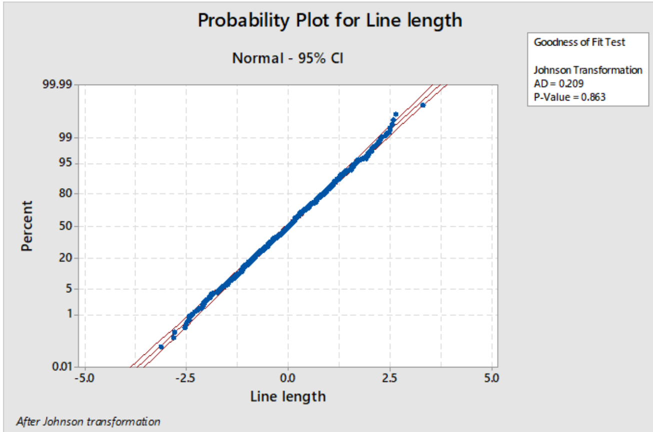


Figure 5 Generated data for line length



The MTBF and MTTR are given in minutes for the following reasons. The MTBF is converted to percentage of time that the station is available in PlantSim. Therefore, by using both values in minutes will not affect this percentage. The MTTR is input in minutes into the simulation software; however, the system automatically converts its units into hours while running the simulation. Therefore, the unit of the simulation throughput is still be in jobs per hour. A variety of manufacturing lines were examined in this study to find the most realistic limits for production lines. The two special cases are buffer size and line length. The buffer size includes 0 for some manufacturing lines that do not use buffer zones and line length starts at 2 because there must be at least 2 stations to make a manufacturing line.

Using this method, a total of 1000 random manufacturing lines were created in PlantSim. The randomly generated manufacturing lines were then sorted in ascending order of line length. This made it easier to run the model for each situation before adding a station to run the next set of models. PlantSim was then used to find the throughput of each situation. Table A.1 in the Appendix shows the variables used and the simulation throughput.

RESULTS

A multi-variate regression model was run using throughput as the dependent variable and the four independent variables as the predicators. The output from Minitab is shown in Table 1 and Figure 5-8.

Table 1: Outputs of the Multi-Variate Regression Analysis

Analysis of Variance					
Source	DF	j SS	Adj MS	F-Value	P-Value
Regression	5	4448	26890	2317.09	0.000
Station Speed (S)	1	3800	11380 0	9806.18	0.000
MTBF	1	42	7642	658.48	0.000
MTTR	1	361	12861	1108.20	0.000
Buffer size (B)	1	27	3227	278.04	0.000
Line length (M)	1	5	475	40.95	0.000
Error	995	535	12		
Total	1000	145983			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
3.40659	92.10%	92.06%	91.98%

Coefficients					
Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	1.229	0.525	2.34	0.020	
Station Speed (S)	0.74561	0.00753	99.03	0.000	1.00
MTBF	0.05368	0.00209	25.66	0.000	1.01
MTTR	-0.6679	0.0201	-33.29	0.000	1.01
Buffer size (B)	0.15411	0.00924	16.67	0.000	1.00
Line length (M)	-0.1312	0.0205	-6.4	0.000	1.01

Regression Equation

Throughput = 1.229 + 0.74561 S + 0.05368 MTBF - 0.6679 MTTR + 0.15411 B - 0.1312 M

Table A.2 shows the values of unusual outliers of the data and their fit.

Figure 6: Residential plot (throughput versus fits) of the multi-variate regression analysis

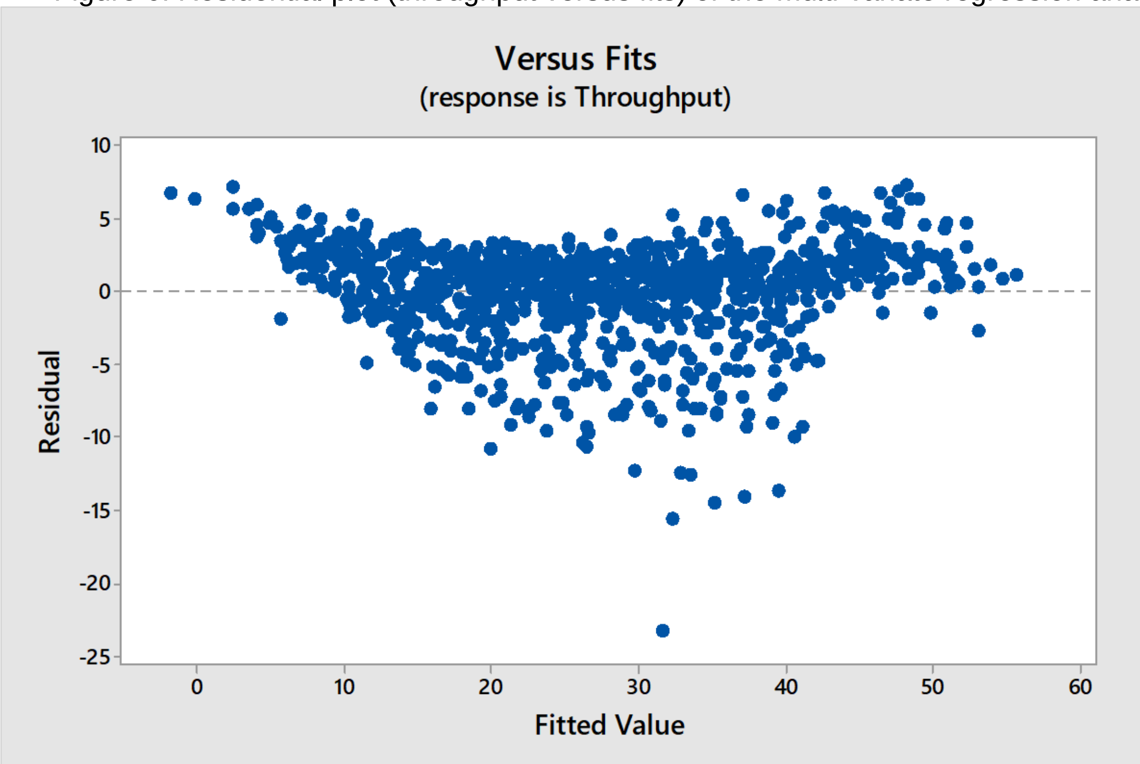


Figure 6: Residential plot (throughput versus order) of the multi-variate regression analysis

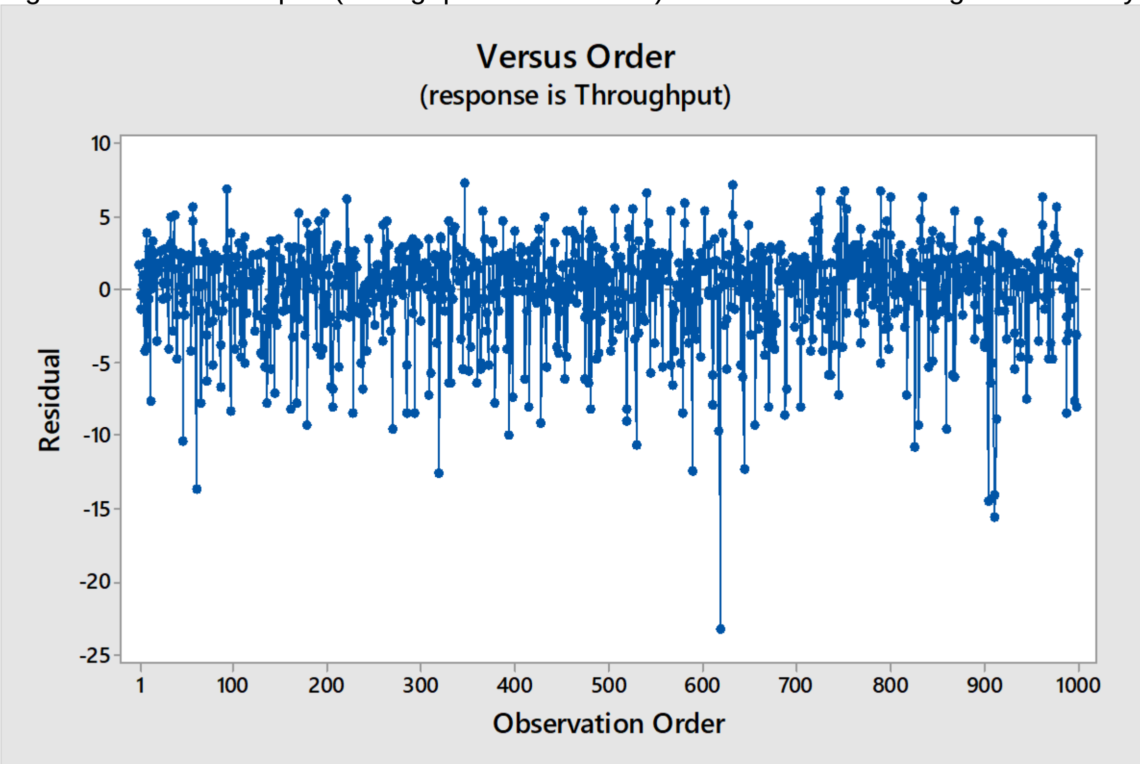


Figure 7: Normal probability plot of the multi-variate regression analysis

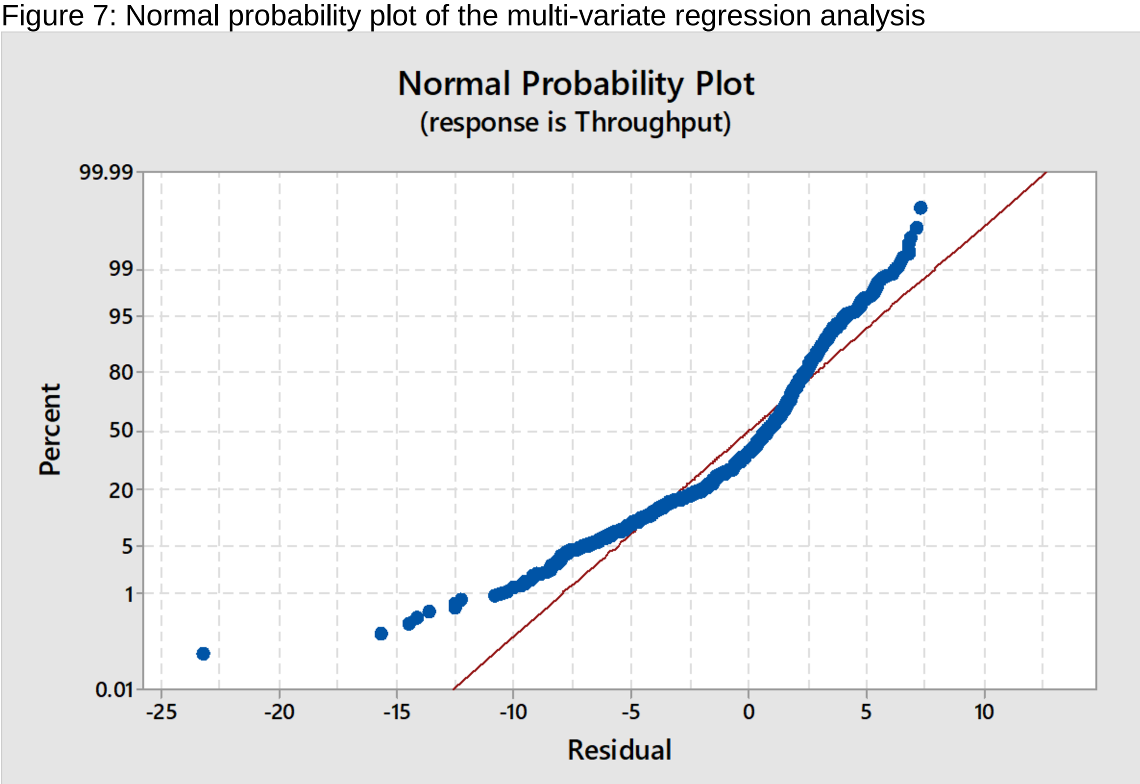
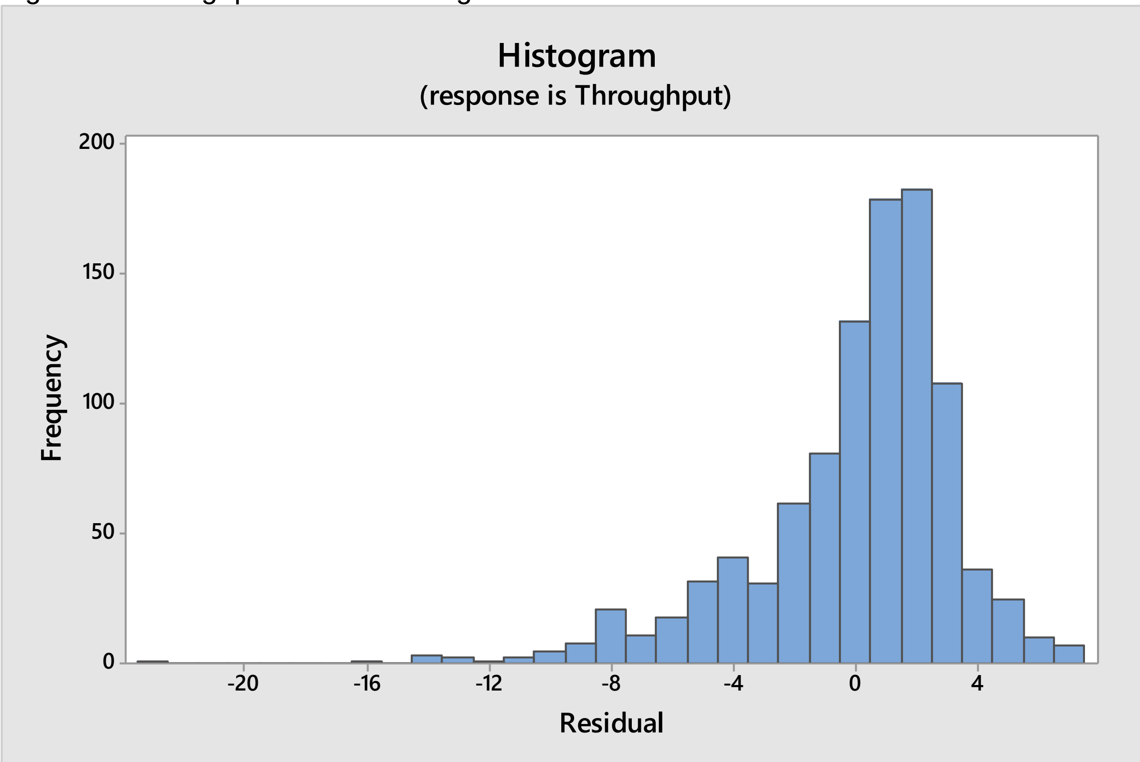


Figure 8: Throughput residual histogram



DISCUSSION

The results of the regression analysis from Minitab are discussed in three aspects: 1) the statistical significance of the relation between the dependent variable and each independent variable, 2) the fit between the model and the data; 3) the assumptions of the model.
To determine the statistical significance of the relation between the dependent variable, the p-values needs to be compared to the significance level. The null hypothesis is that the coefficient of the independent variable is equal to 0, which implies that there is no relation between the dependent variable and the four independent variables. In the case, we use the significance value (α) of 0.05, The p-values for all our independent variable are less than our significance level. This implies that we can reject the null hypothesis Since a continuous predicator was used in this analysis, we can conclude that the coefficients of the independent variables are not equal to 0.
In order to determine how well the model fits the data, we analyze the S and R values from the regression analysis. The S value is measured in the unit of the dependent variable and represents the standard deviation of how far the data values fall from the fitted values. The S value for the regression analysis is 3.4 which indicates that the models results are +/- 7% of actual throughput. There are three different R values: 1) R_sq = 92.1%, shows the variation in the response compared in the model; 2) R_sq (adj) = 92.06%, adj stands for adjusted which mean this r-square is adjusted for the number of independent variables used to run the regression analysis; and 3) R_sq (pred) = 91.98%, pred stands for predicted which means this value shows how accurately the model can predict responses for new observations.

The R-squared values are all above 91%, which implies that the model fits the data well. However, the residual plots still need to be analyzed to determine if the analysis meets the assumption.
The regression analysis has outputted four different residual plots (Figures 5-8). Figure 5 shows the residual versus fit plot and evaluate whether the residuals are randomly distributed with a constant variance. The points in Figure 5 seem to randomly lie on either side of the x-axis. Figure 6 shows the residual versus order plot and determines whether the residuals are independent from one another. The points are randomly scattered around the x-axis until observation number 750. After this point, the points are skewed more towards the upper part of the graph. There is no clear pattern in Figure 6 so it suggests that the residuals are independent of each other. Figure 7 shows the normal probability plot and determines whether the residuals are normally distributed or not. Figure 7 shows that most of the points lie around the straight line with several outliers. Figure 8 show the throughput residual histogram and suggests that the residues are normally distributed.

CONCLUSION

Multi-variate regression analysis is used to find a general formula, which provide an accurate estimation of the throughput of a manufacturing line with identical stations. This formula is easier and much faster to provide an estimation of manufacturing throughput than simulation. This formula also makes it easy to change any of the variables and analyze the effects on throughput immediately. The equation that was found using regression analysis is:
Throughput = 1.229 + 0.74561 S + 0.05368 MTBF - 0.6679 MTTR + 0.15411 B - 0.1312 M
We can also rank the five independent variables in terms of how much they affect the throughput. We can see that increasing station speed has the most effect on throughput. Also, having a lower mean time to repair a broken machine affects the throughput significantly. It should also be noted that having a shorter line length increases the throughput. The effect of the buffer would be negligible once it surpasses the total number of jobs each station produces in a third of an hour. This is because the maximum time considered for mean time to repair is twenty minutes, which implies that a machine will be fixed within twenty minutes after it fails. Therefore, a buffer supply of twenty minutes is sufficient to feed the station down the line to continue production process.
This equation can also be used for non-identical stations if a suitable relationship between factors of the manufacturing line and factors in the equation can be found. This will make this equation much more practical and applicable to many different situations.

Appendix

Table A.1: Randomly generated independent variables in ascending order of line length
Note that the columns below represent the following

Observation # (1)	Station Speed (2)	MTBF (3)	MTTR (4)	Buffer size (5)	Line length (6)	Simulation Throughput (7)
Jobs/Hour	Min	Min	Jobs/Hour	Number	Jobs/Hour	Jobs/Hour

1	2	3	4	5	6	7
1	39	28	13	16	2	24
2	19	191	11	11	2	18
3	55	178	6	22	2	53
4	17	138	15	8	2	14
5	37	100	8	13	2	33
6	60	109	7	26	2	55
7	54	118	2	9	2	53
8	22	135	18	26	2	19
9	40	115	2	11	2	39
10	44	100	4	17	2	42
11	41	90	13	21	2	34

12	25	22	5	28	2	20
13	15	56	18	34	2	11
14	20	108	9	20	2	18
15	54	42	14	24	2	36
16	11	124	3	2	2	11
17	13	124	20	26	2	11
18	24	55	14	16	2	18
19	20	63	15	8	2	15
20	41	107	14	36	2	35
21	14	37	8	20	2	11
22	31	135	6	4	2	28
23	32	51	12	16	3	24
24	29	115	8	8	3	26
25	38	170	18	26	3	33
26	36	153	10	10	3	32
27	25	182	2	14	3	25
28	43	139	18	39	3	36
29	28	70	10	9	3	22
30	15	43	14	19	3	11
31	31	106	17	26	3	25
32	26	42	19	30	3	17
33	37	164	8	21	3	35
34	53	160	10	9	3	47
35	43	115	17	27	3	35
36	51	194	3	37	3	50
37	32	186	4	5	3	31
38	37	100	4	20	3	35
39	23	165	9	10	3	21
40	50	184	11	35	3	46
41	35	136	19	26	3	28
42	24	119	14	32	3	20
43	44	24	12	5	3	21
44	10	129	16	14	3	9
45	49	89	2	23	3	47
46	49	192	18	35	3	42
47	43	96	10	28	3	37
48	32	147	2	37	3	31
49	35	118	9	33	3	32
50	30	90	9	35	3	27
51	58	182	10	39	3	53
52	35	45	2	34	3	33
53	14	28	13	16	3	9
54	57	74	3	7	3	53
55	52	102	18	8	3	37
56	46	180	15	30	3	40
57	56	180	18	37	3	48
58	46	44	18	28	3	28
59	30	56	8	9	3	24
60	21	53	20	15	3	13
61	11	151	19	37	3	10
62	46	110	18	14	3	35
63	11	36	3	37	3	10
64	12	104	10	15	3	11
65	46	122	10	3	3	38
66	24	113	15	23	3	20
67	39	32	4	31	3	34
68	30	68	9	27	3	25
69	12	156	18	33	3	10
70	42	147	12	15	3	36
71	58	144	10	8	3	50
72	34	100	16	33	3	28
73	46	156	19	17	3	36
74	30	187	11	39	3	28
75	43	121	12	34	4	38
76	43	157	12	35	4	39
77	47	154	8	34	4	43
78	37	59	18	14	4	23
79	29	41	6	21	4	25
80	38	144	5	14	4	36
81	33	190	3	37	4	32
82	33	35	18	11	4	17
83	35	71	19	37	4	25
84	54	50	17	16	4	32
85	50	192	4	29	4	49
86	50	189	4	2	4	47
87	54	162	14	12	4	44
88	20	40	6	35	4	17
89	33	186	5	36	4	32
90	57	117	2	3	4	55
91	56	34	18	8	4	24
92	55	153	13	9	4	45
93	57	67	18	12	4	35
94	42	104	11	26	4	36
95	42	69	19	23	4	28
96	44	25	4	18	4	35
97	33	161	13	16	4	29
98	39	37	4	19	4	35
99	56	172	4	24	4	54
100	44	46	12	37	4	32
101	34	33	5	28	4	28
102	32	98	16	36	4	26
103	23	26	8	0	4	11
104	34	99	19	15	4	24
105	14	66	6	7	4	12
106	47	176	14	37	4	42
107	59	196	9	10	4	53
108	41	46	2	14	4	39
109	58	161	13	33	4	51
110	49	71	14	9	4	33
111	51	47	8	3	4	34
112	25	101	15	14	4	20
113	48	198	19	39	4	41
114	39	147	14	36	4	34
115	51	144	5	6	4	47
116	24	124	7	28	4	22
117	34	179	14	24	4	30
118	57	128	18	17	4	43
119	38	104	9	4	4	31
120	15	171	8	40	4	14
121	13	126	17	35	4	11
122	18	44	11	37	4	14
123	30	163	16	35	4	26
124	35	187	5	40	4	34
125	20	111	15	38	4	17
126	50	100	4	31	4	47
127	23	60	4	13	4	21
128	12	80	11	22	5	11
129	21	45	19	17	5	12
130	12	104	7	29	5	11
131	20	163	9	4	5	18
132	45	69	6	19	5	39
133	46	64	16	27	5	32
134	42	154	7	6	5	38

135	47	156	19	16	5	36
136	50	126	11	10	5	41
137	40	44	4	24	5	36
138	26	98	4	29	5	25
139	29	126	14	18	5	24
140	16	64	11	10	5	13
141	32	34	10	27	5	23
142	17	118	15	25	5	14
143	35	147	15	14	5	29
144	31	129	2	15	5	30
145	25	142	8	0	5	20
146	38	169	19	13	5	30
147	59	30	14	3	5	23
148	13	153	15	35	5	12
149	39	41	19	7	5	18
150	23	144	12	12	5	20
151	33	147	10	3	5	27
152	59	27	16	34	5	31
153	35	159	13	7	5	29
154	42	30	17	37	5	23
155	35	145	11	26	5	32
156	30	90	15	13	5	23
157	16	139	16	31	5	14
158	17	64	12	17	5	14
159	32	106	5	19	5	30
160	54	92	6	29	5	49
161	37	76	18	35	5	27
162	38	60	9	9	5	29
163	12	71	12	23	5	10
164	24	99	4	10	5	23
165	13	150	5	5	5	13
166	38	128	9	7	5	32
167	25	101	3	37	5	24
168	34	132	4	31	5	33
169	55	42	2	3	5	48
170	23	99	16	25	5	18
171	31	135	11	15	5	27
172	59	181	12	1	5	45
173	33	38	8	12	5	25
174	50	49	13	29	5	35
175	24	147	14	30	5	21

176	14	44	16	24	5	9
177	51	196	12	21	5	45
178	16	160	18	24	5	14
179	58	86	15	4	5	35
180	52	190	13	15	5	45
181	57	41	16	14	5	30
182	50	180	6	21	5	47
183	57	197	7	11	5	53
184	53	159	7	8	5	47
185	54	180	9	34	5	50
186	14	179	5	22	5	13
187	27	188	19	7	5	21
188	21	148	3	12	5	20
189	38	115	14	8	6	29
190	26	142	3	40	6	25
191	58	20	2	29	6	51
192	13	194	18	35	6	11
193	26	84	19	21	6	19
194	55	55	4	38	6	51
195	46	98	14	29	6	36
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736	41	26	5	32	16	32
737	57	105	9	39	16	50
738	17	104	17	23	16	14
739	36	174	17	30	16	30
740	16	20	15	33	16	9
741	40	100	4	33	16	38
742	52	24	8	20	16	33
743	37	31	16	11	16	16
744	47	68	2	5	16	44
745	39	145	9	20	16	35
746	56	144	6	36	16	52
747	14	128	16	39	16	12
748	39	186	18	35	16	33
749	59	107	12	6	16	38
750	17	193	18	40	16	15
751	39	178	14	28	16	33
752	44	175	4	11	16	43
753	14	124	11	8	16	12
754	44	70	8	34	16	37
755	20	167	6	36	16	19
756	22	97	9	27	16	19
757	57	125	18	5	16	28
758	13	99	19	21	16	10
759	24	39	10	3	16	12
760	53	84	15	24	16	37
761	14	128	3	17	16	13
762	16	92	8	31	16	15
763	50	97	3	19	16	49
764	47	83	12	27	16	36
765	31	165	14	36	16	27
766	19	179	8	2	16	16
767	12	29	6	31	16	10
768	29	22	4	13	16	23
769	36	61	19	37	16	23
770	51	98	7	29	16	45
771	49	23	16	21	16	21
772	51	72	4	10	16	46
773	54	155	4	39	16	52
774	13	31	10	15	17	9
775	37	53	13	25	17	26
776	46	109	8	15	17	40
777	46	131	2	9	17	45
778	51	57	4	9	17	44
779	24	45	17	15	17	14
780	11	41	14	39	17	8
781	39	150	12	8	17	31
782	26	133	9	22	17	23
783	53	74	16	14	17	32
784	42	111	16	7	17	25
785	29	153	20	4	17	16
786	23	134	15	5	17	16
787	10	102	11	21	17	9
788	17	188	16	6	17	14
789	14	62	9	19	17	12
790	56	135	17	11	17	36
791	37	146	14	38	17	32
792	33	99	18	20	17	23
793	14	33	18	18	17	8
794	37	82	12	9	17	26
795	57	40	8	26	17	42
796	22	112	10	21	17	19
797	14	96	3	4	17	13
798	44	157	16	17	17	34
799	48	192	19	5	17	29
800	38	136	15	32	17	32
801	28	118	3	29	17	27
802	52	26	12	26	17	29
803	54	45	16	18	17	28
804	31	23	6	26	17	23
805	25	103	5	6	17	23
806	50	46	10	26	17	36
807	21	83	7	16	17	19
808	54	76	6	21	17	47
809	50	54	15	4	17	17
810	37	130	14	21	17	30
811	47	69	11	27	17	36
812	21	58	19	15	17	13
813	39	75	7	20	17	33

814	40	23	17	30	17	19
815	38	107	18	39	17	29
816	15	62	12	0	17	4
817	39	37	6	38	17	32
818	37	197	9	26	17	34
819	45	53	14	31	17	31
820	37	33	13	1	17	9
821	36	121	12	13	17	29
822	31	186	12	3	17	23
823	23	122	5	26	17	22
824	10	68	8	24	17	9
825	30	37	6	21	17	24
826	21	154	18	3	17	12
827	58	156	10	13	17	48
828	22	169	14	26	17	20
829	28	90	7	11	17	24
830	44	119	7	28	17	40
831	10	30	6	38	17	9
832	50	38	16	18	17	25
833	57	94	12	20	18	43
834	22	101	18	30	18	17
835	11	120	16	16	18	9
836	39	39	11	39	18	27
837	34	29	5	8	18	26
838	25	43	10	15	18	18
839	14	71	5	13	18	13
840	24	78	19	38	18	17
841	27	72	3	2	18	24
842	13	40	8	7	18	10
843	56	55	10	37	18	43
844	13	186	6	23	18	12
845	23	180	18	14	18	18
846	47	32	16	16	18	22
847	44	141	12	5	18	30
848	27	77	7	34	18	24
849	17	133	15	22	18	14
850	19	165	7	7	18	17
851	39	115	16	3	18	20
852	51	188	3	20	18	50
853	18	95	14	36	18	15
854	24	144	3	14	18	24
855	30	151	10	8	18	25
856	26	28	7	26	18	19
857	13	94	10	35	18	12
858	59	67	17	24	18	35
859	56	161	4	9	18	52
860	39	114	11	27	18	34
861	29	39	3	20	18	26
862	55	65	15	24	18	35
863	15	114	7	39	18	14
864	10	192	9	38	18	10
865	36	111	5	4	18	31
866	40	186	17	14	18	30
867	29	115	3	0	18	23
868	17	89	19	24	18	13
869	31	104	11	7	18	23
870	40	47	13	30	18	28
871	39	90	16	9	18	23
872	31	175	8	22	18	29
873	52	71	6	20	18	46
874	24	80	10	35	18	20
875	37	113	10	13	18	30
876	11	166	19	15	18	9
877	39	100	20	24	18	27
878	49	191	17	35	18	41
879	38	43	9	28	18	29
880	14	189	13	25	18	13
881	20	99	19	32	18	15
882	12	24	5	14	18	10
883	21	49	8	1	18	11
884	33	150	19	5	18	19
885	53	31	20	26	18	23
886	59	36	17	9	18	21
887	29	183	12	23	18	26
888	52	31	10	36	18	35
889	18	104	18	40	18	14
890	30	163	18	21	18	24
891	24	88	5	29	18	23
892	45	46	6	35	18	38
893	43	176	17	16	18	33
894	41	107	15	32	18	33
895	23	194	16	29	18	21
896	54	198	10	36	18	49
897	53	70	5	28	18	48
898	54	111	19	31	18	38
899	19	129	11	18	18	17
900	50	138	14	29	18	40
901	44	36	18	29	18	23
902	14	83	20	15	18	10
903	32	118	16	14	18	23
904	55	92	13	28	18	42
905	49	151	3	25	18	48
906	43	36	6	11	18	32
907	52	65	10	33	18	41
908	28	99	8	23	18	25
909	10	52	9	5	19	8
910	50	75	20	14	19	26
911	41	101	5	10	19	37
912	34	171	15	5	19	23
913	43	30	10	38	19	29
914	13	127	6	19	19	12
915	14	100	11	6	19	11
916	31	121	5	9	19	28
917	53	25	15	30	19	26
918	22	155	16	18	19	19
919	23	82	16	32	19	18
920	40	121	17	1	19	14
921	43	188	17	28	19	36

922	17	116	4	7	19	16
923	22	134	17	26	19	18
924	52	166	17	34	19	43
925	30	57	19	3	19	10
926	12	68	16	18	19	9
927	18	47	4	31	19	16
928	28	165	6	5	19	25
929	54	149	16	10	19	36
930	25	197	20	12	19	19
931	19	56	15	34	19	14
932	44	52	12	18	19	30
933	29	186	18	3	19	17
934	22	29	20	27	19	11
935	25	21	13	33	19	14
936	26	99	10	31	19	23
937	24	25	10	19	19	15
938	46	105	18	22	19	31
939	41	23	15	38	19	21
940	52	66	16	9	19	26
941	59	31	8	4	19	26
942	54	122	5	9	19	49
943	27	143	11	4	19	20
944	26	41	13	1	19	7
945	41	176	17	19	19	32
946	15	119	13	25	19	13
947	35	168	8	4	19	29
948	13	160	5	32	19	12
949	39	78	15	10	19	24
950	38	43	8	27	19	29
951	55	86	19	2	19	17
952	55	150	19	6	19	28
953	15	40	5	17	19	13
954	58	46	10	34	19	42
955	48	139	13	8	19	34
956	55	21	14	2	19	8
957	25	140	16	15	19	20
958	34	25	7	34	19	25
959	11	157	7	2	19	9
960	47	38	6	35	19	38
961	33	114	3	32	19	31
962	12	114	15	3	19	8
963	25	71	20	20	19	16
964	45	151	11	19	19	39
965	17	76	6	23	19	16
966	11	104	6	33	19	11
967	48	105	4	14	19	45
968	23	105	18	11	19	16
969	54	157	11	7	19	41
970	40	189	19	33	20	33
971	20	87	17	4	20	11
972	17	200	2	36	20	17
973	55	170	15	6	20	36
974	40	38	6	39	20	33
975	26	137	11	11	20	22
976	34	148	8	38	20	32
977	43	70	16	11	20	24
978	49	42	18	23	20	25
979	42	89	4	16	20	39
980	37	49	13	31	20	26
981	22	40	5	24	20	19
982	14	152	13	19	20	12
983	17	51	4	9	20	15
984	30	65	19	36	20	21
985	18	115	13	28	20	15
986	59	75	19	23	20	34
987	34	93	8	19	20	29
988	46	69	11	10	20	31
989	52	78	4	33	20	49
990	49	105	7	27	20	44
991	13	199	9	32	20	12
992	39	144	6	33	20	37
993	18	190	18	18	20	16
994	44	125	12	6	20	30
995	46	117	4	30	20	44
996	60	161	17	4	20	32
997	26	43	4	34	20	23
998	59	198	18	31	20	47
999	43	158	12	10	20	34
1000	32	109	13	13	20	25

Table A.2: Fits and Diagnostics for Unusual Observations Minitab

Obs #	Simulated Throughput	Fit	Resid	Std	Resi
12	17.249	24.875	-7.626	-2.25	R
47	15.926	26.249	-10.323	-3.04	R
61	25.822	39.481	-13.659	-4.03	R
67	25.264	33.001	-7.737	-2.28	R
93	54.573	47.702	6.870	2.02	R
98	27.051	35.328	-8.277	-2.44	R
137	21.545	29.281	-7.737	-2.28	R
144	32.206	39.251	-7.045	-2.08	R
163	14.430	22.620	-8.190	-2.41	R
169	14.022	21.819	-7.797	-2.30	R
180	17.261	26.503	-9.242	-2.73	R
206	13.640	21.697	-8.058	-2.37	R
207	12.396	19.247	-6.851	-2.02	R
229	26.893	35.330	-8.437	-2.49	R
239	23.351	30.185	-6.834	-2.01	R
270	23.812	33.377	-9.564	-2.82	R
285	16.699	25.179	-8.480	-2.50	R
294	19.935	28.452	-8.518	-2.51	R
309	29.934	37.119	-7.185	-2.12	R
320	21.103	33.628	-12.524	-3.69	R
347	55.583	48.256	7.327	2.16	R
380	15.180	22.989	-7.809	-2.30	R
395	30.664	40.683	-10.019	-2.96	R
398	28.351	35.660	-7.310	-2.15	R
416	7.821	15.842	-8.022	-2.36	R
429	12.168	21.356	-9.188	-2.71	R
482	22.659	30.854	-8.196	-2.41	R
519	20.880	29.010	-8.130	-2.39	R
520	30.122	39.161	-9.039	-2.66	R
530	15.950	26.554	-10.605	-3.12	R
580	20.554	29.010	-8.456	-2.49	R
589	20.376	32.881	-12.505	-3.69	R
612	22.870	30.769	-7.899	-2.33	R
617	16.950	26.680	-9.730	-2.87	R
619	8.471	31.724	-23.253	-6.86	R
632	9.605	2.480	7.125	2.10	R
645	17.478	29.722	-12.244	-3.61	R
656	28.078	37.403	-9.324	-2.75	R
671	10.367	18.416	-8.050	-2.37	R
688	13.948	22.599	-8.651	-2.55	R
689	26.166	33.038	-6.872	-2.03	R
705	25.792	33.817	-8.024	-2.36	R
727	5.111	-1.710	6.821	2.01	R
746	13.468	20.630	-7.161	-2.11	R
752	53.253	46.439	6.813	2.01	R
790	49.530	42.705	6.825	2.01	R
818	28.286	35.567	-7.280	-2.15	R
827	9.071	19.933	-10.861	-3.20	R

831	31.889	41.151	-9.262	-2.73	R
860	14.325	23.848	-9.523	-2.81	R
904	20.749	35.238	-14.489	-4.27	R
911	23.147	37.294	-14.146	-4.17	R
912	16.751	32.388	-15.638	-4.61	R
913	22.675	31.576	-8.901	-2.62	R
945	12.635	20.193	-7.558	-2.23	R
988	29.082	37.480	-8.398	-2.47	R
997	16.905	24.543	-7.638	-2.25	R
999	26.168	34.253	-8.085	-2.38	R

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