Equipment Data Development Case Study – Bayesian Weibull Analysis

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Summary

This paper describes a statistical study done on a set of equipment failure data from the South Texas Project site. The main assumption in the existing methodology is that the time between failures is distributed as exponential random variable (i.e. constant failure rate) with random parameter that follows Lognormal prior distribution. In addition, the current data collection gathers only the number of failures in a given time period which is sufficient for the estimation procedure due to the exponential failure time assumption.

The current study proposes to substitute the constant failure rate with time varying one by modeling the time between failures as Weibull random variable. This requires that we have a different set of failure observations – the actual time between failures rather than the number of failures only. The previous categorization defines unique groups based on their TPNS number and failure mode code. We created three sets of data based on three different grouping rules: functional, TPNS codes, TPNS codes and failure modes (the last one is the currently used grouping rule). Due to the detailed nature of the last category, the data set consists of 142 different groups, 135 of which have less than 8 data points. We present our analysis for all three data sets but should point out that more data are needed to reach statistically sound conclusions for the third grouping.

Main accomplishments:

- Setup database of time between failures using plant specific observations only (in SAS)
- Performed goodness-of-fit and graphical data analysis to test the Weibull distribution assumption (in SAS)
- Analyzed a set of prior distributions for the Weibull parameters (in SAS)
- Construct an algorithm to compute the posterior distributions and wrote an Excel add-in to implement it.

Conclusions:

- The Weibull assumption is statistically justified for the first data set where the grouping leads to more than 30 data points per group
- For the second data set we need more data to reach a final conclusion. The participation of the rest of the power plants to a common database of failure data is crucial for this task.
- The new prior distributions on both parameters allow for higher modeling flexibility and better forecast of the failure rates.

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I. Data preparation and description

1. Initial data sets: The following Excel files were provided:

- U1 equipment failure before 1103 (with 187 records)
- U2 equipment failure before 1103 (with 116 records)
- 12-03 equipment loss (with 17 records)
- 1-04 equipment loss (with 31 records)
- 2-04 equipment loss (with 48 records)

All files have similar structure. Table 1 gives the names of the columns for the first two files (**U1 equipment failure before 1103** and **U2 equipment failure before 1103**) and one representative record. Table 2 contains the column definitions and one record for file **12-03 equipment loss**. Table 3 contains the column definitions and one record for files **1-04 equipment loss** and **2-04 equipment loss**.

We combined the above files using the *TPNS* variable as a primary key. The first data set (Excel file data1.xls) contains the columns *TPNS* and *Created TS*.

2. Data Preparation

Bellow is a list of steps that we took in preparation of the data set called data2.xls:

- Sort the data using TPNS as a key.
- Transfer the *Created TS* to a new variable that represents the interval time between two failure times for the specific component. We want to measure the days between two failure times. In SAS, which is a statistical software package, each observation of *Created TS* will transfer into a number for the days to a system specific date. (In SAS, the default specific date is 1/1/1960). Since we want the interval days, the actual default specific date is not important. We created a new variable called *date*. It stands for the number of days between *Created TS* and the specific date.
- We exported the data to a second file, data2.xls.
- Count the number of observations per TPNS: we found that we have less than 6 data points for each group, not enough to perform analysis.

3. Creating groups of data

In what follows, we describe two procedures for grouping of the data.

3.1 Groups based on functional commonalities

We followed simple rules to produce the data file called data3.xls.

- If the first character of TPNS is number, like 7S13**1**TFW0190 stands for U1, 7S13**2**TFW0190 stands for U2, we treated them as the same component.
- If the TPNSs only differ at the last several characters, such as **N1FWFV**7109, **N1FWFV**7151, **N1FWFV**7152 and **N1FWFV**7153, we treated them at the same group.
- If the TPNSs begin with letter, the second is number, for example, one is N**1**FWFV7178, the other is N**2**FWFV7178, and we treated them as the same component.
- Based on above, we got the file data3.xls. Table 4 gives an example of a group.
- We extracted the groups with more than 8 data points to perform the statistical analysis also described in data3.xls.

The exact data that belong to each separate group are in Appendix, part II, Tables 1 - 11. There are total of 11 different groups.

3.2 Groups based on code assignment and failure modes

This is the currently used grouping model, by different codes and failure modes. To be consistent with it we created a data set following these rules. The resulting file is data6.xls. Since there are large number of code and failure modes combinations many groups contained less than 5 data points. One example from data5 is shown in Table 6. There are 6 groups with more than 8 data points, listed in the Appendix, part III, Tables 1 - 6.

II. Descriptive data analysis

For each group of data we performed the following set of statistical procedures:

- Descriptive statistics – number of data points, mean, standard deviation, skewness, and kurtosis.
- Relative frequency histogram – to assess the shape of the distribution
- Weibull probability plot – graphical assessment of the Weibull assumption
- Kolmogorov-Smirnov test – goodness-of-fit test for the Weibull distribution :

The Kolmogorov-Smirnov (K-S) test is based on the empirical distribution function constructed from the observed failure data. Given *N ordered* data points $Y_1, Y_2, ..., Y_N$, the ECDF is defined as

$$E_N = n(i)/N$$

where $n(i)$ is the number of points less than Y_i, and Y_i are ordered from the smallest to the largest value. It is a step function that increases by $1/N$.

Bellow if the definition of the null and research hypotheses for the Kolmogorov-Smirnov test:

H_0: The observed data come from a Weibull distribution

H_a: The observed data do not come from the Weibull distribution

Test Statistic: The Kolmogorov-Smirnov test statistic is defined as

$$D = \max_{1 \le i \le N} \left| F(Y_i) - \frac{i}{N} \right|$$

where F is the Weibull distribution function.

The descriptive analysis is done using the SAS statistical package.

1. Results for functional grouping

The table bellow shows the descriptive statistics for the 11 groups:

Group	***# data Points***	***Mean***	***St.Deviation***	***Skewness***	***Kurtosis***
1.	18	19.667	32.711	2.747	8.404
2.	21	12.714	17.407	2.765	9.280
3.	9	41.222	55.816	2.196	5.285
4.	24	150.375	189.614	1.512	1.282
5.	38	117.632	124.584	2.764	9.906
6.	7	49.857	22.579	-.687	-.568
7.	37	10.027	10.797	2.843	10.462
8.	14	287.786	603.457	3.468	12.494
9.	18	18.278	17.364	2.066	5.07
10	18	58.944	61.681	.242	-2.167
11	26	19	26.127	1.86	2.4

If we assume that the data come from Weibull distribution with parameters α and β then the Kolmogorov-Smirnov test should yield high p-values (usually greater than 0.5). The table bellow shows the output from the test for all 11 groups and the maximum likelihood estimators for α and β.

Group	***P-Value***	α	β
1	.685	14.04	.66
2	.5108	11.39	.8332
3	.9987	34.65	.7536
4	.1458	128.0	.7677
5	.3867	121.0	1.069
6	.8173	55.98	2.63
7	.5864	10.44	1.099
8	.3443	148.4	.4987
9	.539	19.68	1.222
10	.0587	46.27	.6787
11	.4345	16.03	.7726

The Weibull assumption is statistically justified for Groups 1, 2, 3, 6, 7, 9, and 11. For all 11 groups we built the relative frequency histograms and Weibull probability plots. The resulting graphs are in the Appendix, part IV, figure 1 – 11, part V, figure 1-11. We can safely conclude that for the grouping based on functional commonalities, the Weibull distribution is a good fit.

2. Results for grouping based on code and failure mode

Out of the 142 groups that resulted from this rule we chose 6 (since they have more than 8 data points) for the analysis. They are defined in this table:

GROUP	*CODE*	*# DATA POINTS*
AOV-LE-C	451	8
TKP-LE-C	455	18
XVM-LE-W	92	6
CAV-LE-W	95	11
CAV-LE-W	96	9
MDP-LE-C	127	10

As with the previous grouping rule, the results from the descriptive analysis and goodness-of-fit test for the Weibull distribution are given in the following two tables:

Groups	**Code**	**No. of data points**	**Mean**	**Standard Deviation**	**Skewness**	**kurtosis**
AOV-LE-C	451	8	350.491	528.964	2.497	6.567
TKP-LE-C	455	18	183.410	190.698	1.192	.982
XVM-LE-W	92	6	35.583	37.504	1.317	1.545
CAV-LE-W	95	11	17.525	40.177	3.234	10.57
CAV-LE-W	96	9	25.141	54.803	2.672	7.288
MDP-LE-C	127	10	34.332	42.095	1.985	4.187

Groups	**P-Value**	α	β
1	.7015	26.21	.9368
2	.4967	13.64	.6061
3	.4547	24.65	.9364
4	.5923	168.9	.7905
5	.9534	53.33	2.359
6	.6277	503.2	.8392

III. Bayesian analysis

The main difference between classical and Bayesian estimation is the assumption about the parameters of the proposed sampling distribution. The classical approach assumes that the parameters are unknown but constant, whereas the Bayesian regards them as random variables (with specified prior distributions).
We will assume that the sampling distribution is Weibull with parameters λ and β. Its density function equals to

$$f(t;\lambda,\beta) = \lambda\beta t^{\beta-1}\exp(-\lambda t^{\beta}), t \geq 0, \lambda, \beta > 0$$

If we have n items, s of which have failed at ordered times $T_1, T_2, ..., T_s$, and $(n-s)$ have operated without failing. If there are no withdrawals then we denote as $\omega = nT_s^{\beta}$ - it is a sufficient statistic for estimating λ (also known as the rescaled total time on test).

Case 1: β is fixed, λ has gamma prior distribution with hyper-parameters α_0, β_0 and density function

$$g(\lambda;\alpha_{0,}\beta_0) = \frac{1}{\Gamma(\alpha_0)\beta_0^{\alpha_0}}\lambda^{\alpha_0-1}e^{-\lambda/\beta_0}$$

Then the posterior mean of λ given the observed failure data is

$$E(\lambda \mid w; s, \alpha_{0,}\beta_0) = \frac{\beta_0(\alpha_0+s)}{\beta_0 w+1}.$$

Case 2: Inverted gamma prior distribution on $\theta = 1/\lambda$; uniform prior distribution on β

Assume that θ has an inverted gamma prior distribution with hyper-parameters ν_0, μ_0, and β has uniform prior distribution with hyper-parameters α_0, β_0. Denote by z the observed failure information. Then the Bayesian point estimation for θ is given by $E(\theta \mid z) = J_2/[(s+\nu_0-1)J_1]$, where

$$J_2 = \int_{\alpha_0}^{\beta_0}[\frac{\beta^s\nu^{\beta}}{w_1^{s+\nu_0-1}}]d\beta \ ,$$

$$J_1 = \int_{\alpha_0}^{\beta_0}[\frac{\beta^s\nu^{\beta}}{w_1^{s+\nu_0}}]d\beta \ ,$$

$$\nu = \prod_{i=1}^{s} T_i$$

$$\omega_1 = nT_s + \mu_0$$

The Bayesian point estimator for β becomes

$$E(\beta \mid z) = J_3/J_1, where J_3 = \int_{\alpha_0}^{\beta_0}[\frac{\beta^{s+1}\nu^{\beta}}{w_1^{s+\nu_0}}]d\beta$$

The integrals do not have closed form solution and thus the Bayesian estimates must be computed by numerical integration techniques. Bellow are the results for the code and failure mode grouping using both updating procedures.

Groups	**Bayesian update estimate λ ***	**Bayesian update estimate $\theta = 1/\lambda$ ** (days)**	**Bayesian update estimate λ ** (/hour)**	**Bayesian update estimate β ****
AOV-LE-C	2.49E-05	2.40E+03	1.74E-05	8.73E-01
TKP-LE-C	1.11E-05	4222.038	9.87E-06	8.88E-01
XVM-LE-W	3.756E-07	132436.8	3.15E-07	8.64E-01
CAV-LE-W	6.803E-07	67319.79	6.19E-07	8.71E-01
CAV-LE-W	5.584E-07	83805.64	4.97E-07	8.64E-01
MDP-LE-C	6.193E-05	800.451	5.21E-05	8.72E-01

Note: *: λ is the Bayesian update estimate of failure rate; the prior distribution is Gamma;
**: Θ, λ and β are the Bayesian update estimates of mean failure time, failure rate and shape; the prior for Θ is Inverted Gamma and β is Uniform (0.2, 0.9).

The choice of the hyper-parameters values is not random. We used the values given in the DOE database for the values of the inverted gamma parameters, and empirically assessed the parameters of the uniform distribution.

IV. Appendix

I. Data tables:

A. Basic tables:

Ct	192
Computed	1
CR/WO	03-11068
Date	7/19/2003
Activity No	432385
Wan Seq No	256316
Description	WHILE ATTEMPTING TO OPEN 1D FWIV, THE MOTOR DRIVEN PUMPS WOULD NOT RUN. DURING THE OPEN ATTEMPT, THE AIR DRIVEN PUMPS RAN, BUT THE MOTOR DRIVEN PUMPS DID NOT. THE ONLY NON-COMMON ITEM IN THE PUMP RUN CIRCUITS IS A CONTACT WHICH SHOULD CLOSE ON LOW PRESSUR
Wmsy System	FW
TPNS	7S131MPA011
Failure Mode	Fails to run
Event Code	3A5- FAILED TO OPEN/FAILED IN CLOSED POSITION
Created TS	7/19/2003 5:17:57 PM
Tpns Unit	1
Actl Start Date	7/20/2003
Actl Finish Date	7/20/2003
Failure_Mode	MDP-FR-C

Table 1

Ct	1.
Computed	1.
CR/WO	03-18222 N-D-M 12/11/03
Activity No	
Wan Seq No	
Description	NOTICED A SLOW DRIP AND SMALL PUDDLE IN THE TURBINE GENERATOR BUILDING WHILE CLEANING FOR PRIDE DAY. THE DRIP WAS COMING FROM 1FW0193 - 7S131TF0193 - LOW POWER FEEDWATER VALVE FROM A 1 1/4" PIPE CAP.
Wmsy System	FW
TPNS	7S131TFW0193
Failure Mode	XVM-LE-W
Event Code	4M- TOOL POUCH MAINTENANCE
Created TS	12/11/03 10:33 AM
Tpns Unit	1

Table 2

Ct	1.
Computed	1.
CR/WO	04-194 N-D-M 01/06/04
Activity No	
Wan Seq No	
Description	STEAM GENERATOR 2C LO POWER FEED REG VALVE OUTLET ISOLATION, 7S132TFW0190, HAS A PACKING LEAK. WATER AND STEAM ARE BUBBLING UP AROUND THE STEM AFTER CLOSING THE VALVE.
Wmsy System	FW
TPNS	7S132TFW0190
Failure mode	XVM-LE-W
Event Code	3C1W- WATER LEAK
Created TS	01/06/04 04:28 AM
Tpns Unit	2
Actl Start Date	
Actl Finish Date	

Table 3

TPNS	CreatedTS	date	time	time3
7T081MPA001A	4/5/2003	15800	21	1
7T081MPA1803	4/26/2003	15821	59	2
7T082MPA1803	4/26/2003	15821	59	9
7T082MPA001B	6/24/2003	15880	30	12
7T081MPA001A	7/24/2003	15910	2	21
7T081MPA001A	7/26/2003	15912	12	30
7T082MPA1803	8/7/2003	15924	1	59
7T081MPA001A	8/8/2003	15925	9	59
7T082MPA1803	8/17/2003	15934	178	178
7T081MPA001A	2/11/2004	16112		
7T081MPA001A	2/11/2004	16112		

Table 4

TPNS	TS	code	date	time
7S131MPA011	4/14/2003	127	15809	2
7S131MPA011	4/14/2003	127	15809	2
7S131MPA008	4/16/2003	127	15811	30
7S131MPA010	5/16/2003	127	15841	64
7S131MPA011	7/19/2003	127	15905	8
7S131MPA008	7/27/2003	127	15913	1
7S131MPA011	7/27/2003	127	15913	1
7S131MPA010	7/28/2003	127	15914	1
7S131MPA008	7/29/2003	127	15915	1
7S131MPA008	7/30/2003	127	15916	1
7S131MPA011	8/13/2003	127	15930	14
7S131MPA008	8/16/2003	127	15933	3
7S131MPA010	8/16/2003	127	15933	31
7S131MPA010	9/16/2003	127	15964	22
7S131MPA011	10/8/2003	127	15986	138
7S131MPA008	2/23/2004	127	16124	

Table 5

TPNS	CreatedTS	FailureModes	Code
7S131MPA008	4/16/2003 14:12	MDP-LE-C	127
7S131MPA008	7/29/2003 3:24	MDP-LE-C	127
7S131MPA008	8/16/2003 22:41	MDP-LE-C	127
7S131MPA010	5/16/2003 13:42	MDP-LE-C	127
7S131MPA010	7/28/2003 10:18	MDP-LE-C	127
7S131MPA010	8/16/2003 22:44	MDP-LE-C	127
7S131MPA010	9/16/2003 9:53	MDP-LE-C	127
7S131MPA011	10/8/2003 12:47	MDP-LE-C	127
7S131MPA011	8/13/2003 5:42	MDP-LE-C	127
7S131MPA011	7/27/2003 3:46	MDP-LE-C	127
7S131MPA008	02/23/04 10:00 PM	MDP-LE-C	127
7S131MPA008	7/27/2003 3:38	MDP-NS-C	127
7S131MPA008	7/30/2003 1:58	MDP-NS-C	127
7S131MPA011	4/14/2003 18:30	MDP-NS-C	127
7S131MPA011	4/14/2003 18:30	MDP-NS-C	127

Table 6

II. Data tables for Functional grouping

TPNS	CreatedTS	date	time	Group 1 (Sorted time)
7S132MPA009	4/9/03	15804	5	1
7S131MPA011	4/14/03	15809	2	1
7S131MPA011	4/14/03	15809	2	1
7S131MPA008	4/16/03	15811	30	1
7S131MPA010	5/16/03	15841	64	2
7S131MPA011	7/19/03	15905	8	2
7S131MPA008	7/27/03	15913	1	2
7S131MPA011	7/27/03	15913	1	3
7S131MPA010	7/28/03	15914	1	4
7S131MPA008	7/29/03	15915	1	5
7S131MPA008	7/30/03	15916	14	8
7S131MPA011	8/13/03	15930	3	14
7S131MPA008	8/16/03	15933	31	22
7S131MPA010	8/16/03	15933	31	30
7S131MPA010	9/16/03	15964	22	31
7S131MPA011	10/8/03	15986	132	31
7S132MPA009	2/17/04	16118	4	64
7S132MPA009	2/21/04	16122	2	132
7S131MPA008	2/23/04	16124		

Table1

TPNS	CreatedTS	date	time	Group2
7S132TFW0519	5/14/2003	15839	15	1
7S132TFW0519	5/14/2003	15839	15	1
7S132TFW0003	5/29/2003	15854	30	1
7S132TFW0239	6/28/2003	15884	29	2
7S131TFW0057	7/27/2003	15913	5	2
7S131TFW0516	7/27/2003	15913	5	2
7S131TFW0068	8/1/2003	15918	1	2
7S131TFW0109	8/1/2003	15918	1	2
7S131TFW0476	8/1/2003	15918	1	5
7S131TFW0042	8/2/2003	15919	2	5
7S131TFW0093	8/2/2003	15919	2	5
7S131TFW0109	8/2/2003	15919	2	8
7S131TFW0194	8/2/2003	15919	2	8
7S131TFW0272	8/2/2003	15919	2	15
7S131TFW0190	8/4/2003	15921	5	15
7S131TFW0061	8/9/2003	15926	77	16
7S131TFW0054	10/25/2003	16003	16	18
7S131TFW0200	11/10/2003	16019	8	23
7S131TFW0107	11/18/2003	16027	23	29
7S131TFW0193	12/11/2003	16050	18	30
7S132TFW0065	12/29/2003	16068	8	77
7S132TFW0190	1/6/2004	16076		

Table2

TPNS	CreatedTS	date	time	Group3
7T081MPA001A	4/5/2003	15800	21	1
7T081MPA1803	4/26/2003	15821	59	2
7T082MPA1803	4/26/2003	15821	59	9
7T082MPA001B	6/24/2003	15880	30	12
7T081MPA001A	7/24/2003	15910	2	21
7T081MPA001A	7/26/2003	15912	12	30
7T082MPA1803	8/7/2003	15924	1	59
7T081MPA001A	8/8/2003	15925	9	59
7T082MPA1803	8/17/2003	15934	178	178
7T081MPA001A	2/11/2004	16112		
7T081MPA001A	2/11/2004	16112		

Table3

TPNS	CreatedTS	date	time	Group 4
7T082MRC003A	1/23/1995	12806	91	2
7T081MRC004B	4/24/1995	12897	331	3
7T081MRC003B	3/20/1996	13228	48	3
7T081MRC004B	3/20/1996	13228	48	27
7T081MRC005B	3/20/1996	13228	48	37
7T081MRC005A	5/7/1996	13276	37	41
7T081MRC003A	6/13/1996	13313	63	41
7T082MRC003A	8/15/1996	13376	41	47
7T082MRC004B	9/25/1996	13417	499	48
7T082MRC005B	9/25/1996	13417	499	48
7T081MRC005B	2/6/1998	13916	332	48
7T082MRC005B	1/4/1999	14248	47	49
7T082MRC003B	2/20/1999	14295	319	50
7T082MRC004B	1/5/2000	14614	27	50
7T082MRC003B	2/1/2000	14641	50	57
7T082MRC004B	3/22/2000	14691	50	63
7T081MRC004B	5/11/2000	14741	255	91
7T081MRC004B	1/21/2001	14996	669	255
7T082MRC004B	11/21/2002	15665	2	319
7T082MRC005B	11/23/2002	15667	57	331
7T082MRC003B	1/19/2003	15724	3	332
7T082MRC005B	1/19/2003	15724	3	499
7T082MRC005B	1/22/2003	15727	49	499
7T082MRC005B	3/12/2003	15776	41	669
7T081MRC004B	4/22/2003	15817		
7T081MRC004B	4/22/2003	15817		

Table4

TPNS	CreatedTS	date	time	Group5
7T082XEH0006	3/2/1995	12844	396	4
7T081XEH0169	4/1/1996	13240	71	8
7T081XEH0002	6/11/1996	13311	8	10
7T082XEH0099	6/19/1996	13319	72	12
7T082XEH0156	6/19/1996	13319	72	19
7T082XEH0164	6/19/1996	13319	72	20
7T081XEH0011	8/30/1996	13391	26	26
7T082XEH0164	9/25/1996	13417	12	29
7T082XEH0007	10/7/1996	13429	181	39
7T082XEH0011	10/7/1996	13429	181	39
7T081XEH0095	4/6/1997	13610	84	41
7T081XEH0161	4/6/1997	13610	84	71
7T081XEH0154	6/29/1997	13694	667	72
7T081XEH0162	4/27/1999	14361	139	72
7T081XEH0167	9/13/1999	14500	29	72
7T082XEH0001	10/12/1999	14529	211	84
7T081XEH0154	5/10/2000	14740	308	84
7T081XEH0004	3/14/2001	15048	19	88
7T082XEH0006	4/2/2001	15067	10	92
7T082XEH0011	4/12/2001	15077	88	92
7T081XEH0003	7/9/2001	15165	92	92
7T081XEH0003	7/9/2001	15165	92	92
7T081XEH0007	7/9/2001	15165	92	92
7T081XEH0007	7/9/2001	15165	92	92
7T081XEH0011	7/9/2001	15165	92	94
7T081XEH0011	7/9/2001	15165	92	106
7T082XEH0099	10/9/2001	15257	128	106
7T081XEH0011	2/14/2002	15385	4	128
7T081XEH0009	2/18/2002	15389	41	139
7T081XEH0011	3/31/2002	15430	235	181
7T082XEH0154	11/21/2002	15665	20	181
7T082XEH0002	12/11/2002	15685	39	188
7T082XEH0010	12/11/2002	15685	39	188
7T082XEH0154	1/19/2003	15724	94	211
7T082XEH0011	4/23/2003	15818	188	235
7T082XEH0011	4/23/2003	15818	188	308
7T082XEH0011	10/28/2003	16006	106	396
7T082XEH0011	10/28/2003	16006	106	667
7T081XEH0020	2/11/2004	16112		
7T081XEH0020	2/11/2004	16112		

Table5

TPNS	CreatedTS	date	time	Group6
8S102MTU0133	04/11/2003	15806	12	12
8S101MTU0133	04/23/2003	15818	36	36
8S101MTU0233	04/23/2003	15818	36	36
8S102MTU0333	05/29/2003	15854	75	57
8S101MTU0133	08/12/2003	15929	57	65
8S101MTU0133	10/08/2003	15986	68	68
8S101MTU0233	12/15/2003	16054	65	75
8S102MTU0233	02/18/2004	16119		
8S102MTU0333	02/18/2004	16119		

Table6

TPNS	CreatedTS	date	time	Group7
8S131MPA02	04/15/2003	15810	6	1
8S131MPA028	04/21/2003	15816	5	2
8S132MPA02	04/26/2003	15821	2	2
8S131MPA06	04/28/2003	15823	3	2
8S131MPA01	05/01/2003	15826	2	2
8S132MPA02	05/03/2003	15828	1	2
8S132MPA028	05/04/2003	15829	6	2
8S131MPA01	05/10/2003	15835	22	2
8S131MPA11	06/01/2003	15857	15	2
8S131MPA007	06/16/2003	15872	12	3
8S131MPA007	06/28/2003	15884	27	3
8S131MPA028	07/25/2003	15911	10	3
8S132MPA007	07/25/2003	15911	10	5
8S131MPA007	08/04/2003	15921	2	5
8S131MPA05	08/04/2003	15921	2	6
8S131MPA05	08/06/2003	15923	2	6
8S131MPA05	08/06/2003	15923	2	8
8S131MPA12	08/06/2003	15923	2	8
8S131MPA02	08/08/2003	15925	2	8
8S131MPA02	08/10/2003	15927	16	8
8S131MPA11	08/26/2003	15943	3	8
8S131MPA11	08/29/2003	15946	8	8
8S131MPA11	09/06/2003	15954	5	8
8S131MPA11	09/11/2003	15959	8	10
8S131MPA03	09/19/2003	15967	11	10
8S131MPA02	09/30/2003	15978	58	11
8S131MPA05	11/27/2003	16036	11	11
8S131MPA01	12/08/2003	16047	15	12
8S131MPA02	12/08/2003	16047	15	13
8S131MPA03	12/23/2003	16062	3	15
8S132MPA13	12/26/2003	16065	32	15
8S131MPA04	01/27/2004	16097	8	15
8S132MPA04	02/04/2004	16105	8	16
8S132MPA04	02/04/2004	16105	8	22
8S132MPA05	02/04/2004	16105	8	27
8S132MPA05	02/04/2004	16105	8	32
8S132MPA03	02/12/2004	16113	13	58
8S131MPA01	02/25/2004	16126		

Table 7

TPNS	CreatedTS	date	time	Group8
9S131ZLP609	10/13/1994	12704	385	1
9S131ZLP609	10/13/1994	12704	385	1
9S132ZLP609	11/02/1995	13089	2338	1
9S131ZLP609	03/28/2002	15427	82	1
9S131ZLP609	03/28/2002	15427	82	82
9S132ZLP609	06/18/2002	15509	166	82
9S132ZLP609	12/01/2002	15675	161	94
9S132ZLP145	05/11/2003	15836	94	161
9S131ZLP609	08/13/2003	15930	166	166
9S131ZLP609	08/13/2003	15930	166	166
9S131ZLP609	01/26/2004	16096	1	166
9S131ZLP609	01/26/2004	16096	1	385
9S131ZLP609A	01/26/2004	16096	1	385
9S131ZLP609A	01/26/2004	16096	1	2338
9S131ZLP609	01/27/2004	16097		
9S132ZLP609	01/27/2004	16097		

Table 8

TPNS	CreatedTS	date	time	Group9
A1FWFV7143	04/22/2003	15817	40	3
A1FWFV7141	06/01/2003	15857	9	5
A2FWFV7142	06/10/2003	15866	13	7
A2FWFV7141	06/23/2003	15879	26	7
A2FWFV7143	06/23/2003	15879	26	7
A1FWFV7142	07/19/2003	15905	3	7
A1FWFV7141	07/22/2003	15908	7	8
A2FWFV7141	07/22/2003	15908	7	8
A2FWFV7142	07/22/2003	15908	7	9
A2FWFV7143	07/22/2003	15908	7	13
A1FWFV7141	07/29/2003	15915	5	15
A1FWFV7142	08/03/2003	15920	8	15
A1FWFV7147A	08/03/2003	15920	8	26
A1FWFV7141	08/11/2003	15928	73	26
A2FWFV7147A	10/23/2003	16001	30	30
A2FWFV7147A	10/23/2003	16001	30	30
A1FWFV7141	11/22/2003	16031	15	40
A1FWFV7143	11/22/2003	16031	15	73
A1FWFV7143	12/07/2003	16046		

Table 9

TPNS	CreatedTS	date	time	Group10
N2FWFCV0554	04/02/2003	15797	2	2
N1FWFCV0551	04/04/2003	15799	4	4
N1FWFCV0552	04/04/2003	15799	4	4
N2FWFCV0551	04/04/2003	15799	4	4
N2FWFCV0552	04/04/2003	15799	4	4
N2FWFCV0553	04/04/2003	15799	4	4
N2FWFCV0553	04/08/2003	15803	5	4
N2FWFCV0551	04/13/2003	15808	20	4
N2FWFCV0552	05/03/2003	15828	138	5
N1FWFCV0551	09/18/2003	15966	4	20
N1FWFCV0554	09/18/2003	15966	4	124
N1FWFCV0551	09/22/2003	15970	124	124
N1FWFCV0552	09/22/2003	15970	124	124
N1FWFCV0553	09/22/2003	15970	124	124
N2FWFCV0551	09/22/2003	15970	124	124
N2FWFCV0552	09/22/2003	15970	124	124
N2FWFCV0553	09/22/2003	15970	124	124
N2FWFCV0554	09/22/2003	15970	124	138
N1FWFCV0552	01/24/2004	16094		

Table 10

TPNS	CreatedTS	date	time	Group11
N1FWFV7109	04/03/2003	15798	1	1
N1FWFV7151	04/04/2003	15799	3	1
N1FWFV7152	04/04/2003	15799	3	1
N1FWFV7153	04/04/2003	15799	3	2
N2FWFV7151	04/04/2003	15799	3	3
N2FWFV7152	04/04/2003	15799	3	3
N2FWFV7154	04/04/2003	15799	3	3
N1FWFV7154	04/07/2003	15802	2	3
N1FWFV7153	04/09/2003	15804	6	3
N1FWFV7151	04/15/2003	15810	1	3
N1FWFV7177	04/15/2003	15810	1	6
N1FWFV7104	04/16/2003	15811	6	6
N1FWFV7114	04/16/2003	15811	6	6
N1FWFV7114	04/16/2003	15811	6	6
N1FWFV7178	04/22/2003	15817	8	8
N2FWFV7109	04/30/2003	15825	82	13
N2FWFV7114	04/30/2003	15825	82	16
N2FWFV7104	07/21/2003	15907	16	16
N2FWFV7109	07/21/2003	15907	16	16
N2FWFV7114	07/21/2003	15907	16	24
N1FWFV7114	08/06/2003	15923	35	24
N1FWFV7177	09/10/2003	15958	13	35
N2FWFV7153	09/23/2003	15971	45	45
N1FWFV7154	11/07/2003	16016	86	82
N2FWFV7176	02/01/2004	16102	24	82
N2FWFV7178	02/01/2004	16102	24	86
N1FWFV7109	02/25/2004	16126		

III. Data tables for code assignment and failure modes

TPNS	Created TS	Failure_Mode	code	date	Group1
7T081XEH0011	8/30/1996 4:50	AOV-LE-C	451	35307	39
7T082XEH0007	10/7/1996	AOV-LE-C	451	35346	1619
7T081XEH0004	3/14/2001 10:11	AOV-LE-C	451	36964	29
7T082XEH0011	4/12/2001	AOV-LE-C	451	36993	308
7T081XEH0011	2/14/2002 4:32	AOV-LE-C	451	37301	45
7T081XEH0011	3/31/2002 8:40	AOV-LE-C	451	37346	388
7T082XEH0011	4/23/2003	AOV-LE-C	451	37735	188
7T082XEH0011	4/23/2003	AOV-LE-C	451	37735	188
7T082XEH0011	10/28/2003	AOV-LE-C	451	37922	
7T082XEH0011	10/28/2003	AOV-LE-C	451	37922	

Table1

TPNS	Created TS	Failure_Mode	code	date	Group2
7T081MRC004B	4/24/1995 8:04	TKP-LE-C	455	34813	331
7T081MRC003B	3/20/1996 8:13	TKP-LE-C	455	35144	189
7T081MRC004B	3/20/1996 8:13	TKP-LE-C	455	35144	189
7T081MRC005B	3/20/1996 8:13	TKP-LE-C	455	35144	189
7T082MRC005B	9/25/1996	TKP-LE-C	455	35333	499
7T081MRC005B	2/6/1998 10:37	TKP-LE-C	455	35832	333
7T082MRC005B	1/4/1999	TKP-LE-C	455	36165	46
7T082MRC003B	2/20/1999	TKP-LE-C	455	36211	347
7T082MRC003B	2/1/2000	TKP-LE-C	455	36558	50
7T082MRC004B	3/22/2000	TKP-LE-C	455	36608	50
7T081MRC004B	5/11/2000 10:11	TKP-LE-C	455	36657	255
7T081MRC004B	1/21/2001 11:18	TKP-LE-C	455	36912	669
7T082MRC004B	11/21/2002	TKP-LE-C	455	37582	2
7T082MRC005B	11/23/2002	TKP-LE-C	455	37583	57
7T082MRC005B	1/19/2003	TKP-LE-C	455	37640	3
7T082MRC003B	1/19/2003	TKP-LE-C	455	37640	3
7T082MRC005B	1/22/2003	TKP-LE-C	455	37644	49
7T082MRC005B	3/12/2003	TKP-LE-C	455	37692	41
7T081MRC004B	4/22/2003 17:25	TKP-LE-C	455	37734	
7T081MRC004B	4/22/2003 17:25	TKP-LE-C	455	37734	

Table 2

TPNS	Created TS	Failure_Mode	code	date	Group3
A1FWFV7143	4/22/2003 14:47	XVM-LE-W	92	37734	40
A1FWFV7141	6/1/2003 13:25	XVM-LE-W	92	37774	48
A1FWFV7142	7/19/2003 16:38	XVM-LE-W	92	37822	3
A1FWFV7141	7/22/2003 21:28	XVM-LE-W	92	37825	7
A1FWFV7141	7/29/2003 23:47	XVM-LE-W	92	37832	13
A1FWFV7141	8/11/2003 14:56	XVM-LE-W	92	37845	102
A1FWFV7141	11/22/2003 1:21	XVM-LE-W	92	37947	213
A1FWFV7143	11/22/2003 1:25	XVM-LE-W	92	37947	1358202565

Table3

TPNS	Created TS	Failure_Mode	code	date	Group4
N2FWFCV0554	4/2/2003	CAV-LE-W	95	37713	3
N1FWFCV0551	4/4/2003 15:45	CAV-LE-W	95	37716	4
N1FWFCV0552	4/4/2003 15:45	CAV-LE-W	95	37716	4
N2FWFCV0551	4/4/2003	CAV-LE-W	95	37716	4
N2FWFCV0552	4/4/2003	CAV-LE-W	95	37716	4
N2FWFCV0553	4/4/2003	CAV-LE-W	95	37716	4
N2FWFCV0553	4/8/2003	CAV-LE-W	95	37720	4
N2FWFCV0551	4/13/2003	CAV-LE-W	95	37724	20
N2FWFCV0552	5/3/2003	CAV-LE-W	95	37744	138
N1FWFCV0554	9/18/2003 4:03	CAV-LE-W	95	37882	4
N1FWFCV0551	9/18/2003 4:05	CAV-LE-W	95	37882	4
N1FWFCV0551	9/22/2003 10:14	CAV-LE-W	95	37886	
N1FWFCV0552	9/22/2003 10:14	CAV-LE-W	95	37886	
N1FWFCV0553	9/22/2003 10:14	CAV-LE-W	95	37886	
N2FWFCV0552	9/22/2003	CAV-LE-W	95	37886	
N2FWFCV0553	9/22/2003	CAV-LE-W	95	37886	
N2FWFCV0554	9/22/2003	CAV-LE-W	95	37886	

Table4

TPNS	Created TS	Failure_Mode	code	date	Group5
N1FWFV7151	4/4/2003 15:45	CAV-LE-W	96	37716	2
N1FWFV7152	4/4/2003 15:45	CAV-LE-W	96	37716	2
N1FWFV7153	4/4/2003 15:45	CAV-LE-W	96	37716	2
N2FWFV7151	4/4/2003	CAV-LE-W	96	37716	2
N2FWFV7152	4/4/2003	CAV-LE-W	96	37716	2
N2FWFV7154	4/4/2003	CAV-LE-W	96	37716	2
N1FWFV7154	4/7/2003 9:02	CAV-LE-W	96	37718	3
N1FWFV7153	4/9/2003 20:23	CAV-LE-W	96	37721	166
N2FWFV7153	9/23/2003	CAV-LE-W	96	37887	45
N1FWFV7154	11/7/2003 2:56	CAV-LE-W	96	37932	

Table5

Created TS	Failure_Mode	code	date	Group6
4/16/2003 14:12	MDP-LE-C	127	37728	30
5/16/2003 13:42	MDP-LE-C	127	37758	72
7/27/2003 3:46	MDP-LE-C	127	37829	1
7/28/2003 10:18	MDP-LE-C	127	37830	1
7/29/2003 3:24	MDP-LE-C	127	37831	15
8/13/2003 5:42	MDP-LE-C	127	37846	4
8/16/2003 22:41	MDP-LE-C	127	37850	30
8/16/2003 22:44	MDP-LE-C	127	37850	30
9/16/2003 9:53	MDP-LE-C	127	37880	22
10/8/2003 12:47	MDP-LE-C	127	37903	138
02/23/04 10:00 PM	MDP-LE-C	127	38041	

Table6

IV. Histograms for Functional Grouping

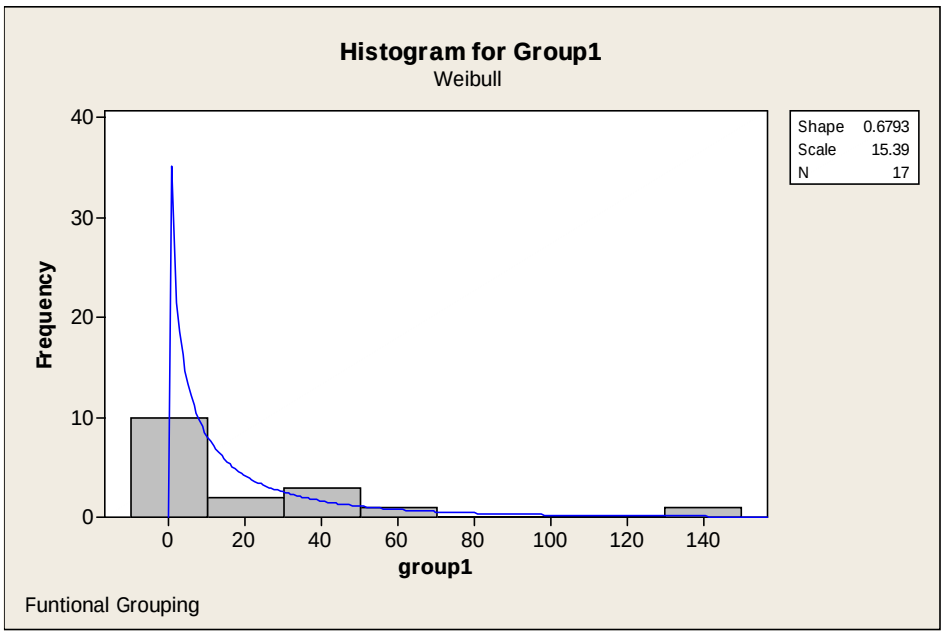


Figure1

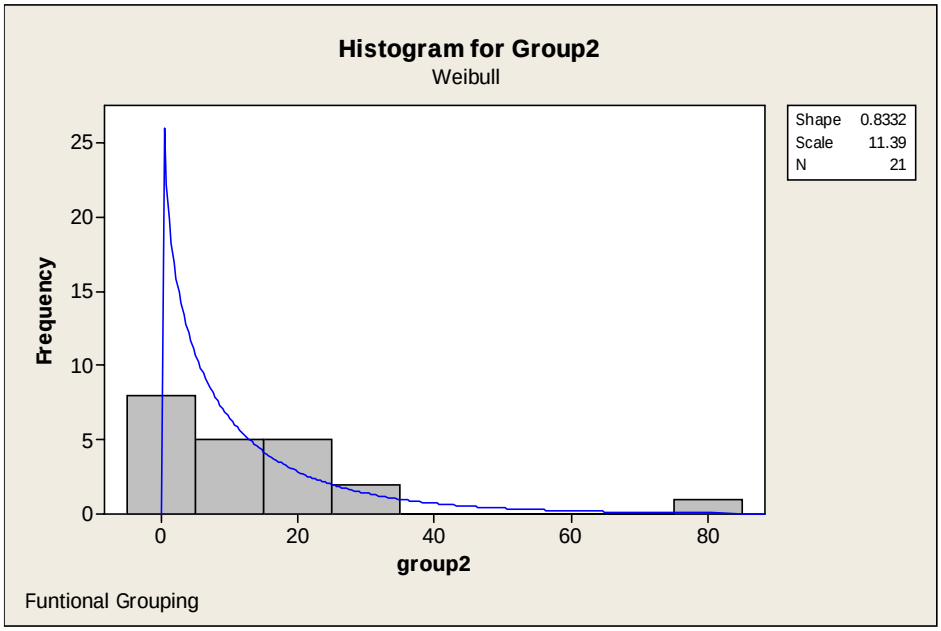


Figure2

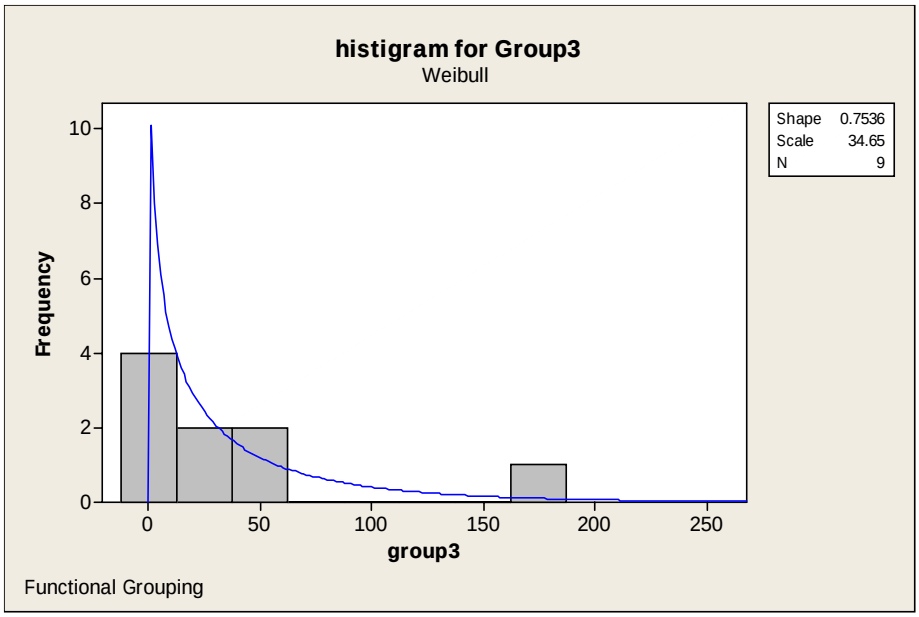


Figure 3

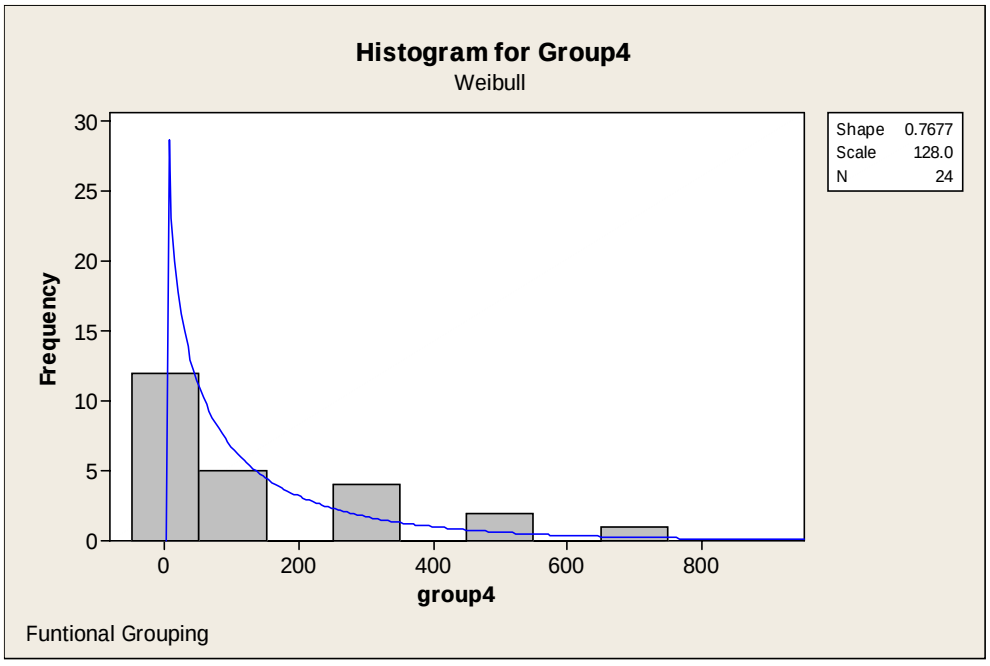


Figure4

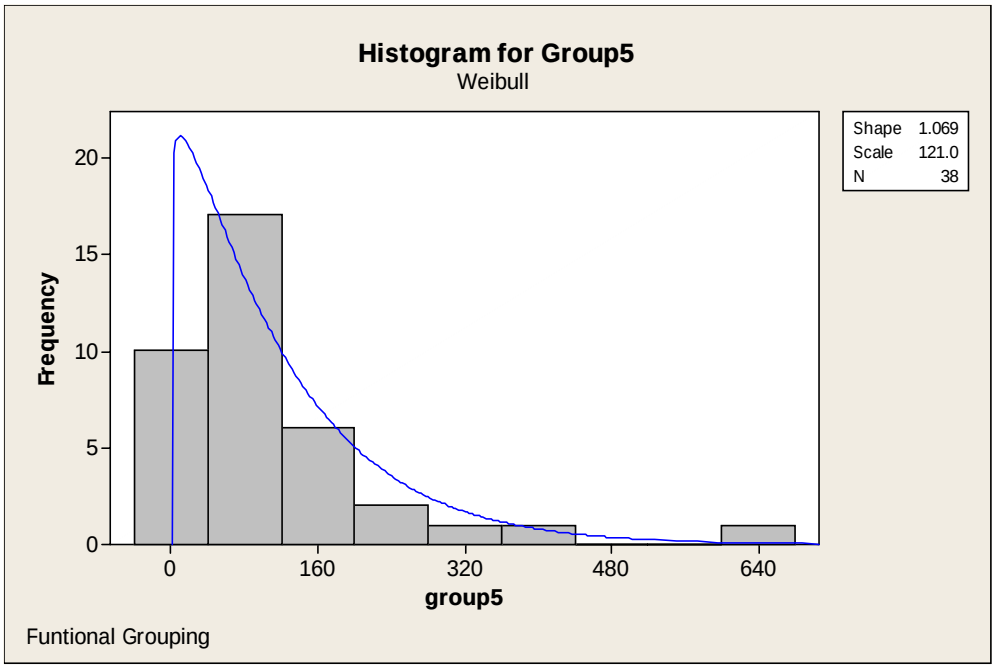


Figure5

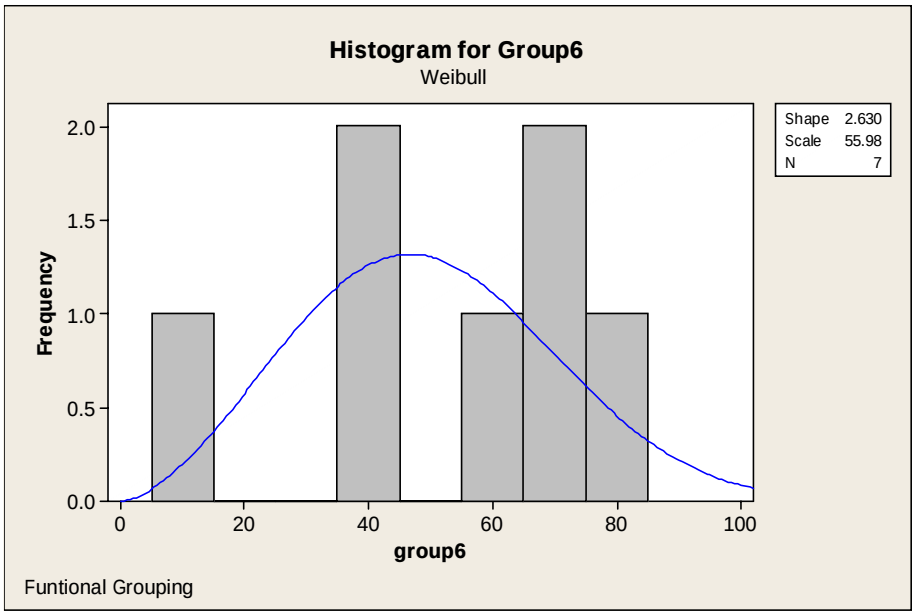


Figure 6

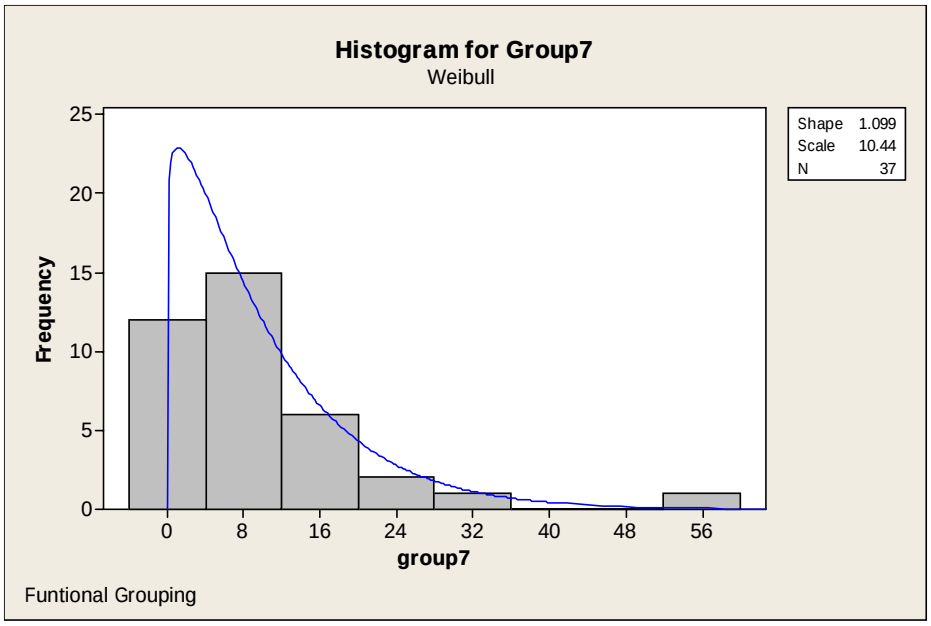


Figure7

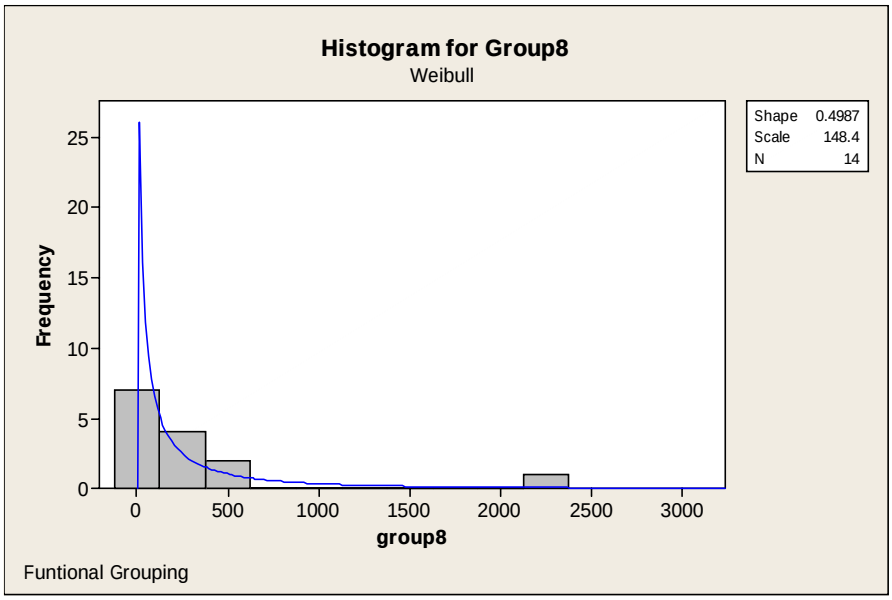


Figure8

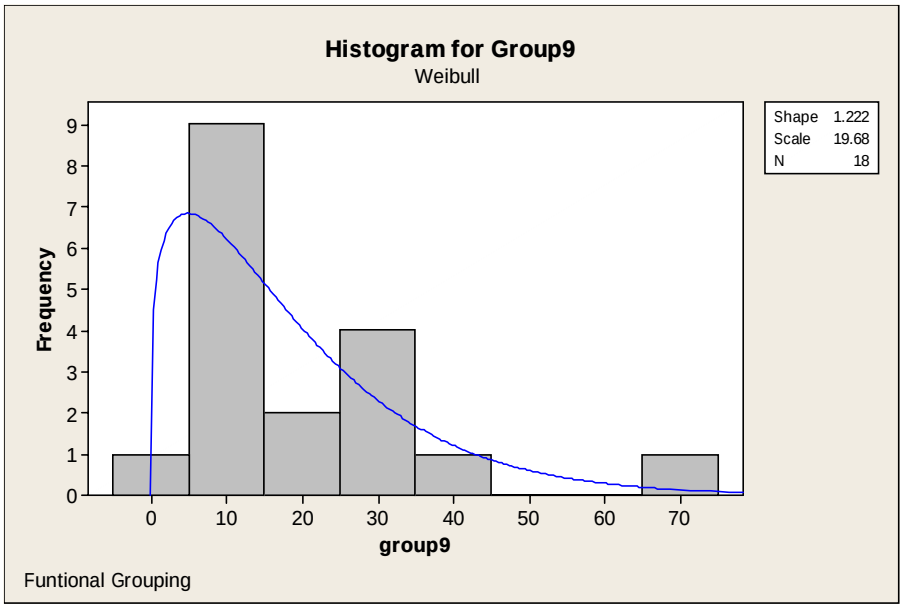


Figure 9

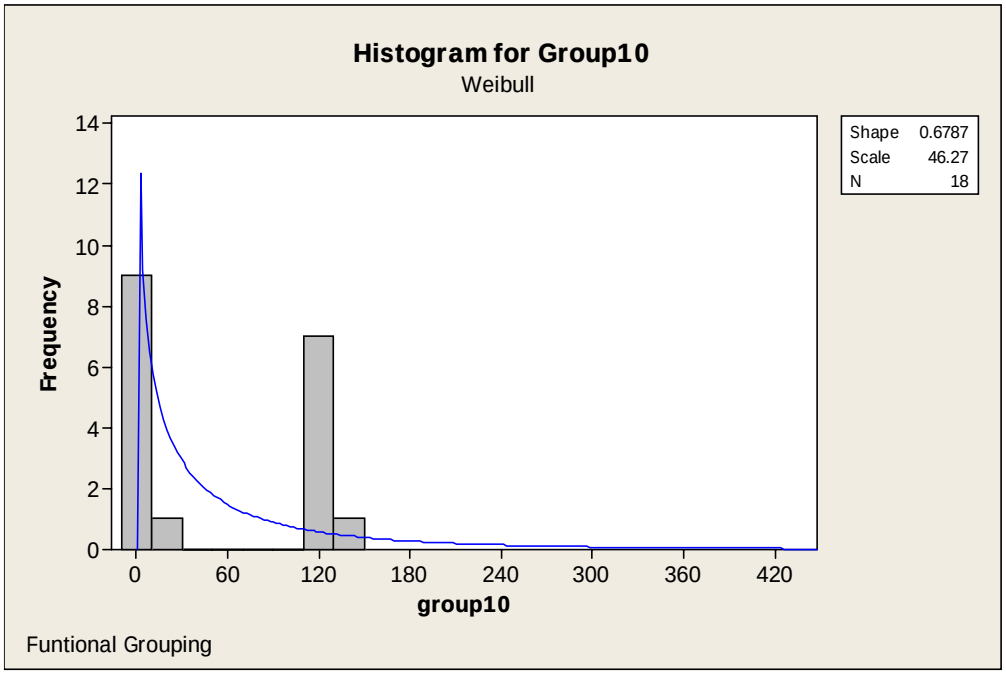


Figure 10

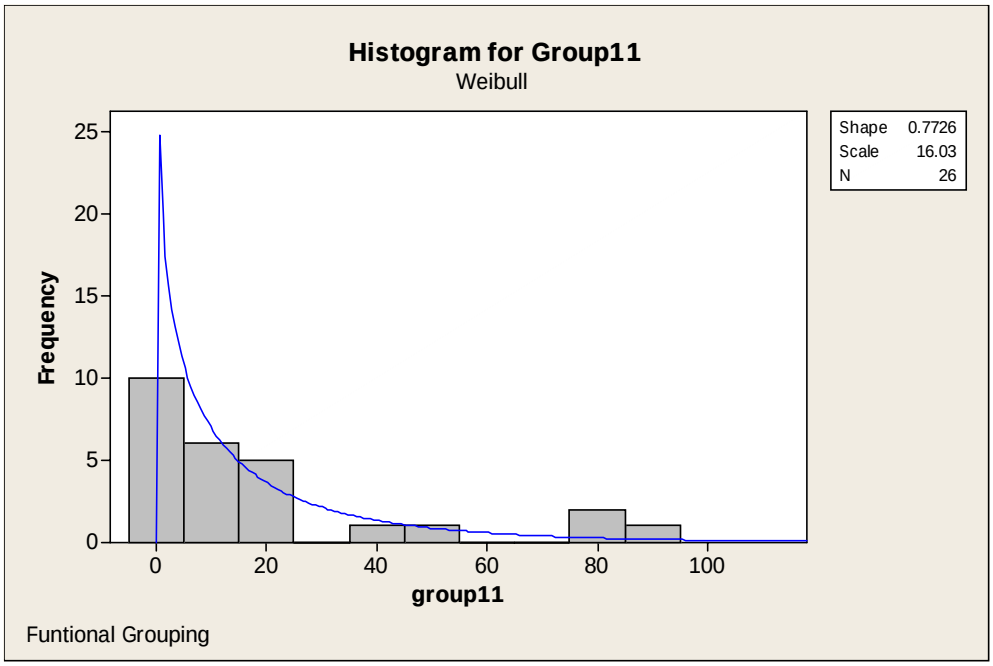

Histogram for Group11
Weibull
Shape 0.7726
Scale 16.03
N 26
Frequency
25
20
15
10
5
0
0
20
40
60
80
100
group11
Funtional Grouping

Figure 11

V. Histograms for Code and Failure Mode Grouping

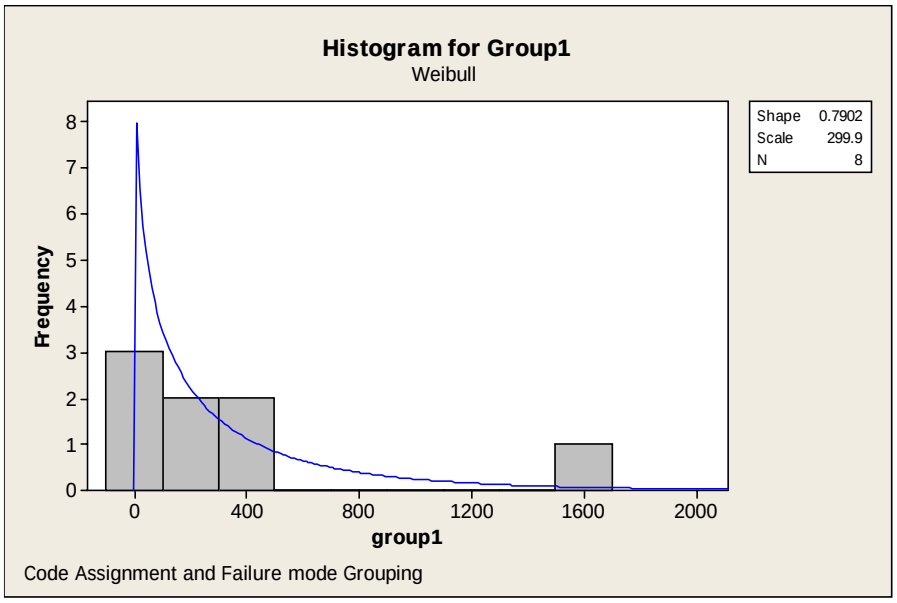


Figure 1

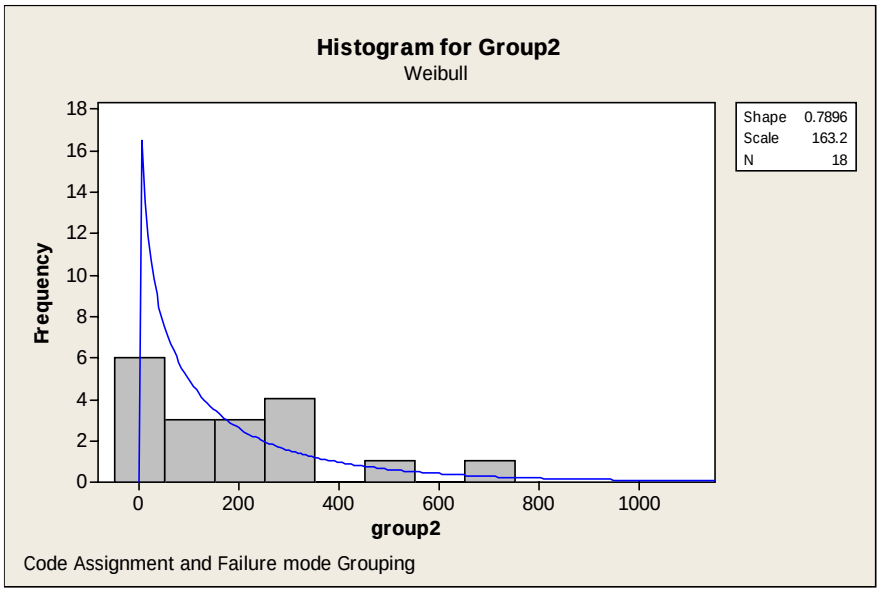


Figure 2

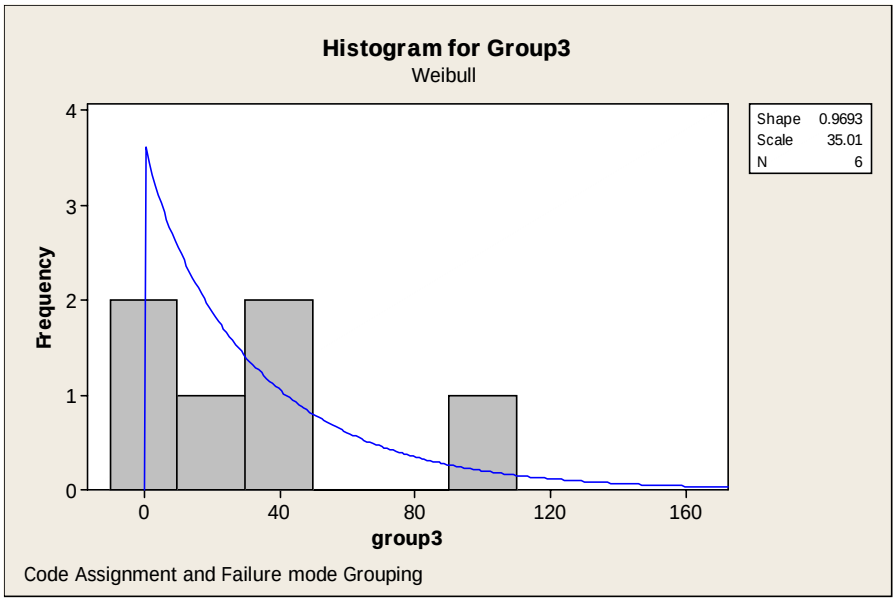


Figure 3

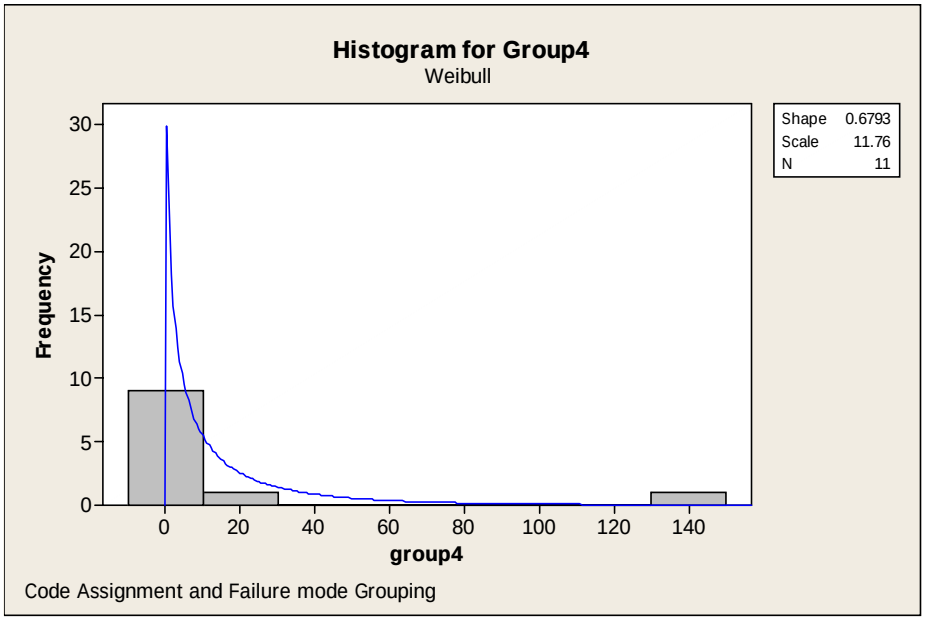


Figure 4

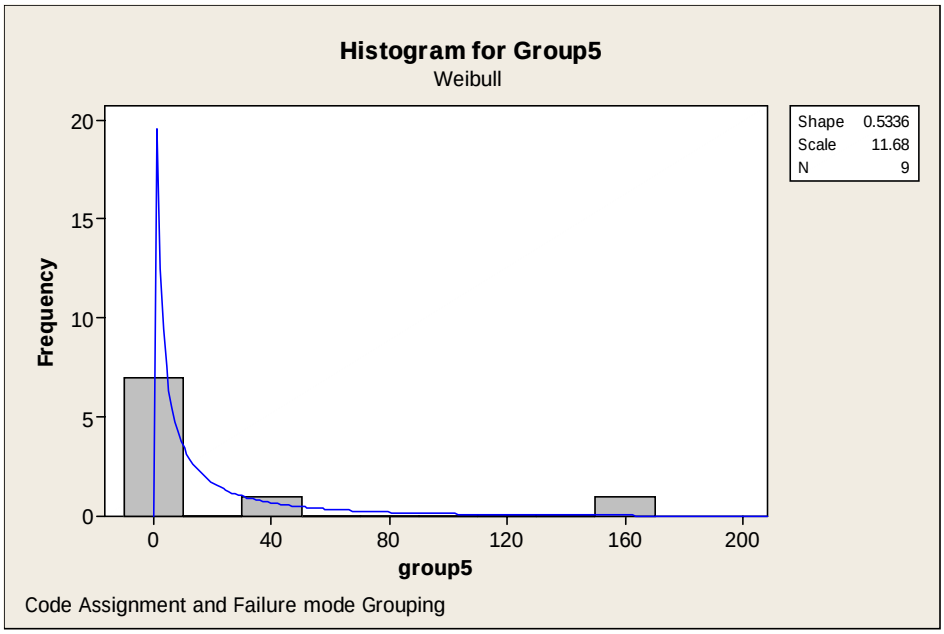


Figure 5

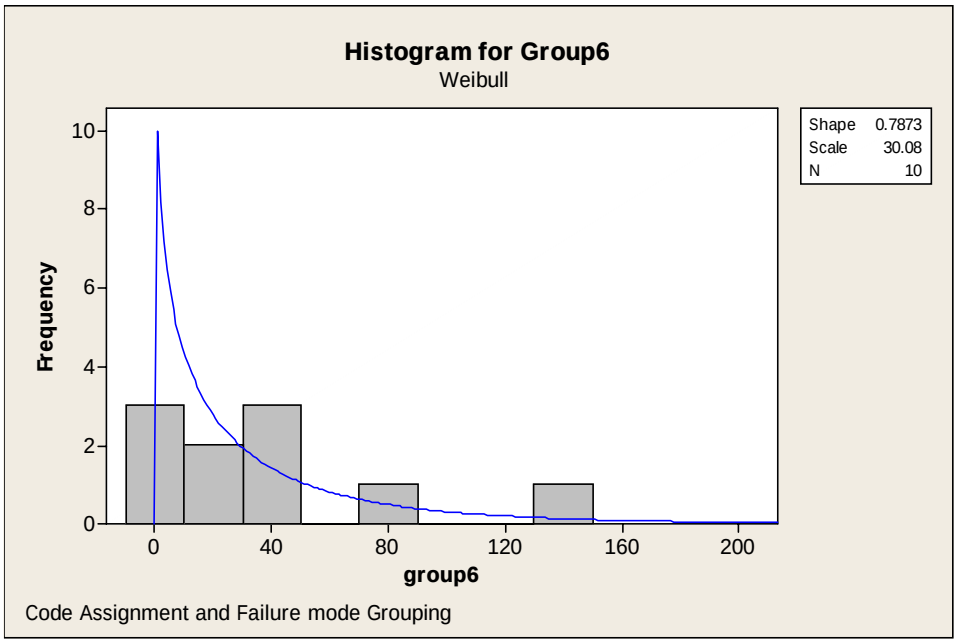


Figure 6

VI. Probability Plots for Functional Grouping

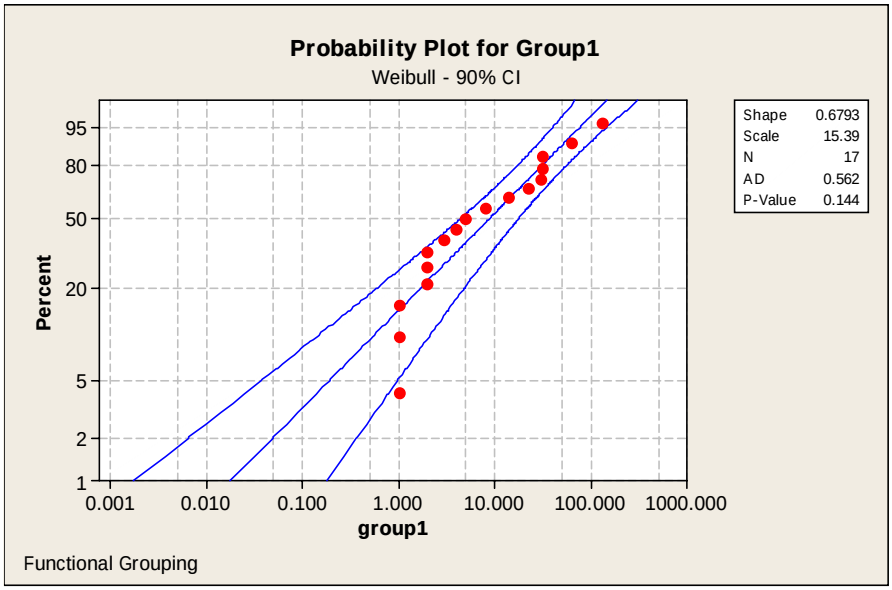


Figure 1

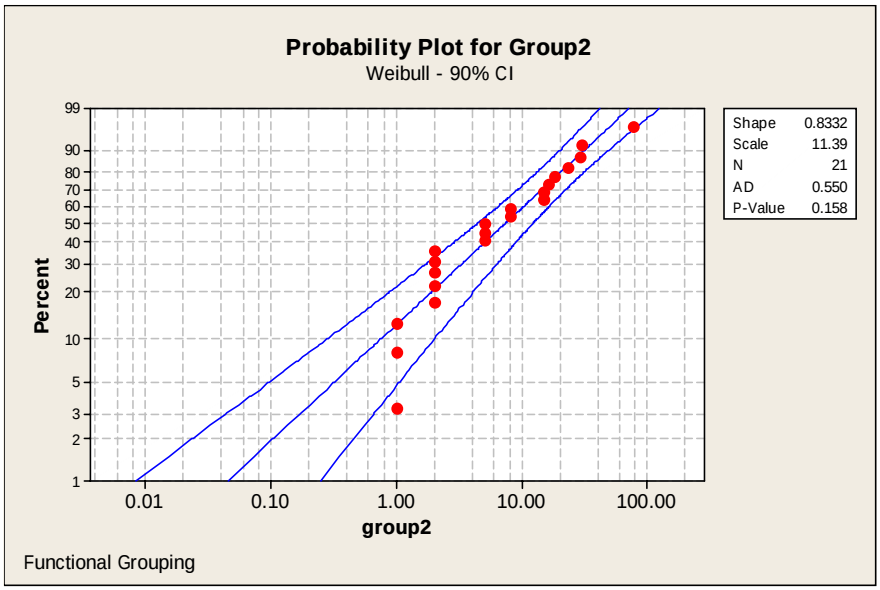


Figure2

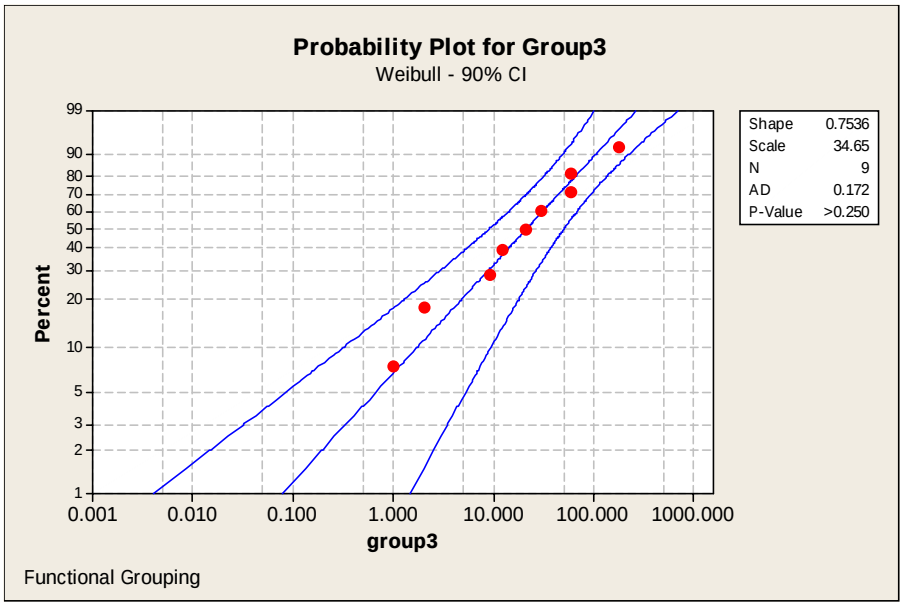


Figure3

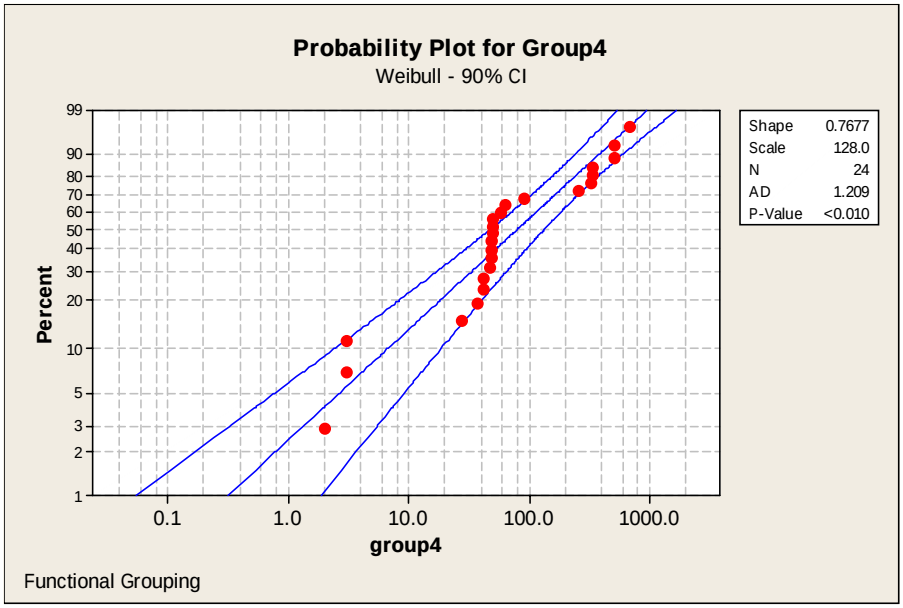
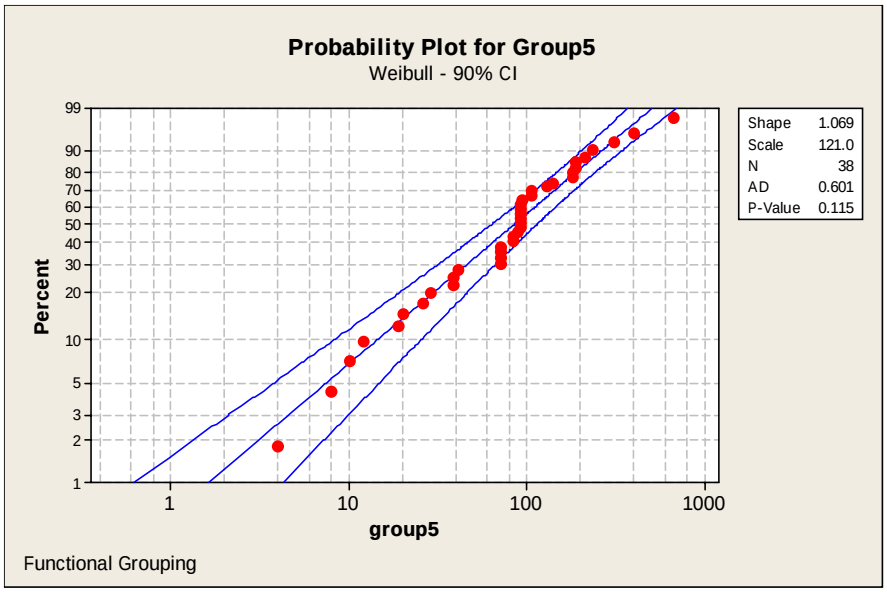


Figure 4



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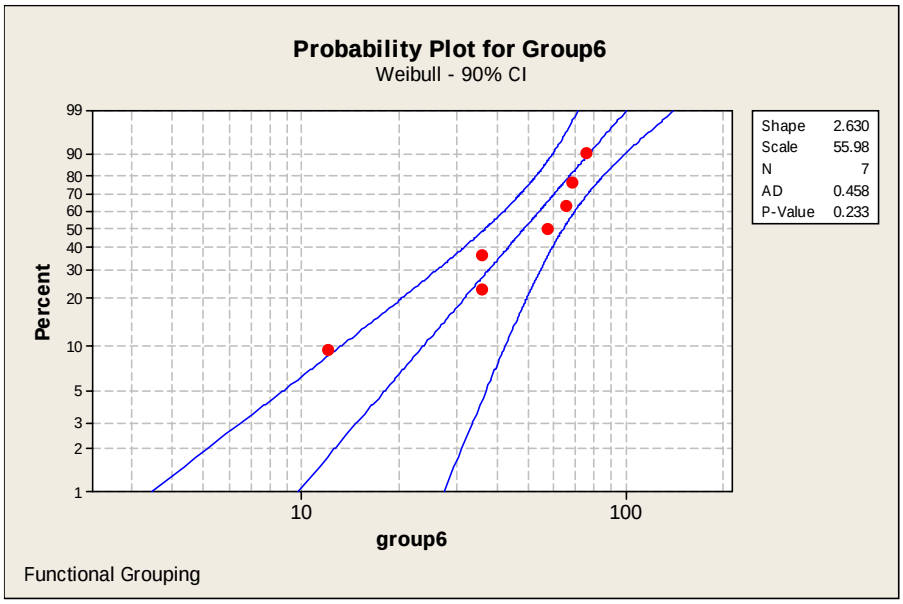

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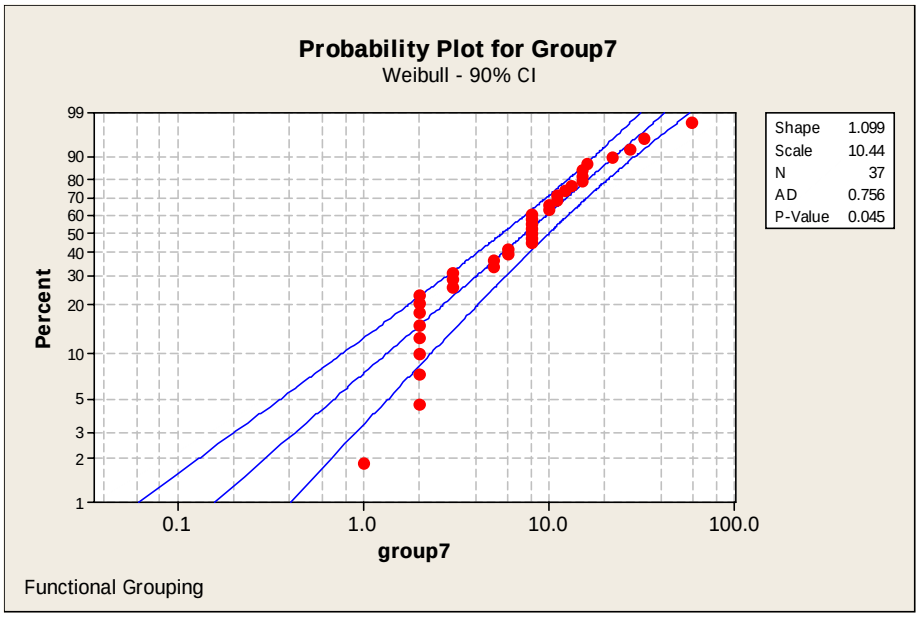

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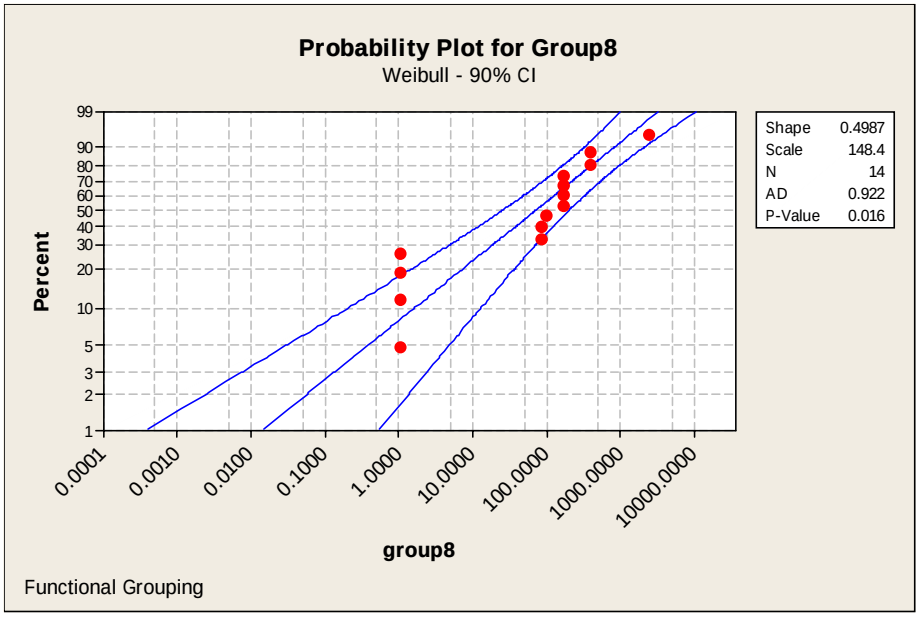

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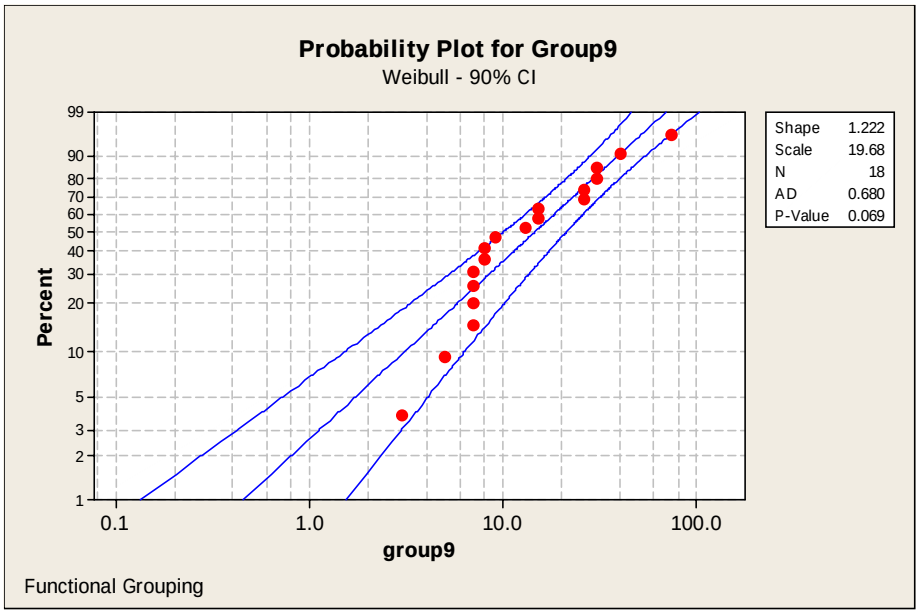

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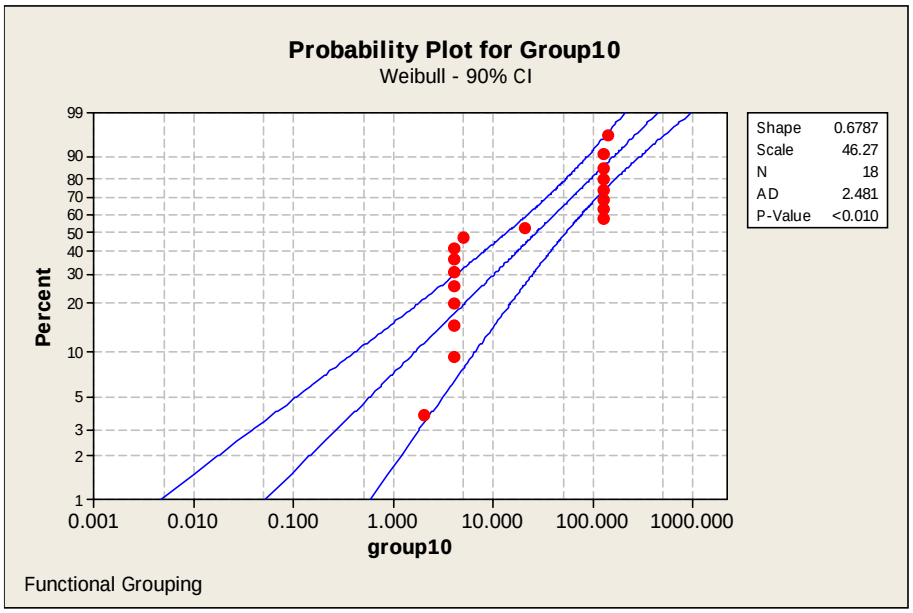

Figure 10

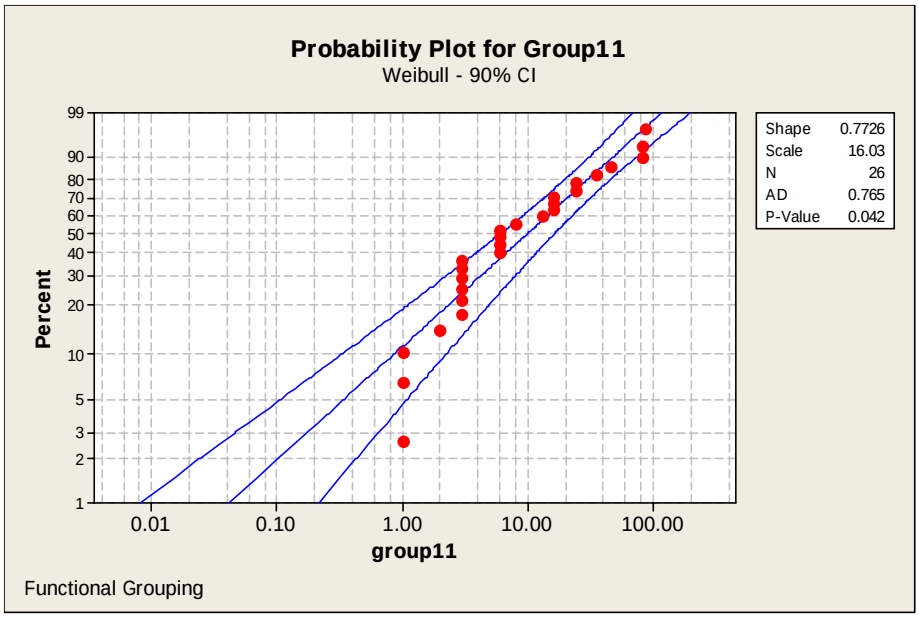
Probability Plot for Group11
Weibull - 90% CI
Percent
99
90
80
70
60
50
40
30
20
10
5
3
2
1
0.01
0.10
1.00
10.00
100.00
group11
Shape 0.7726
Scale 16.03
N 26
AD 0.765
P-Value 0.042
Functional Grouping

Figure 11

VII. Probability Plots for Code Assignment and Failure Mode Grouping

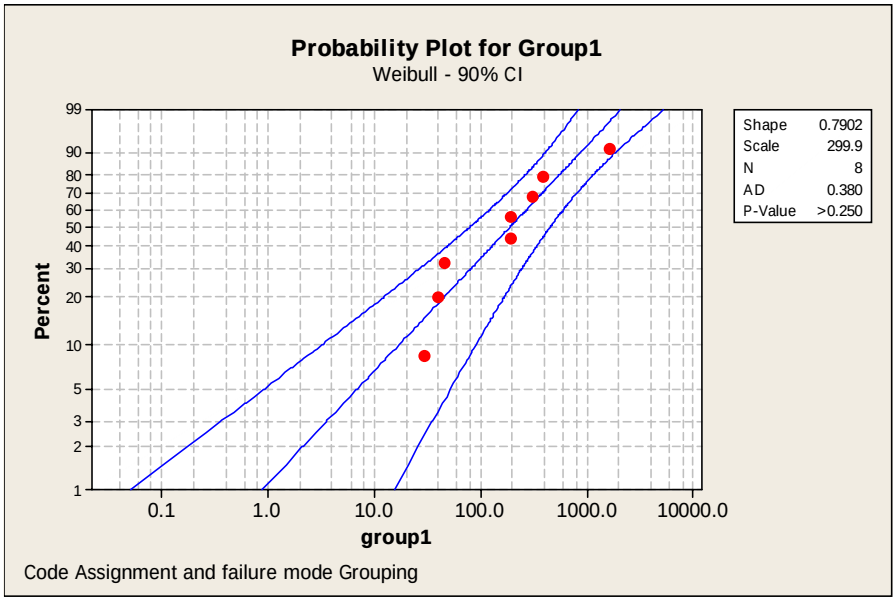

Figure 1

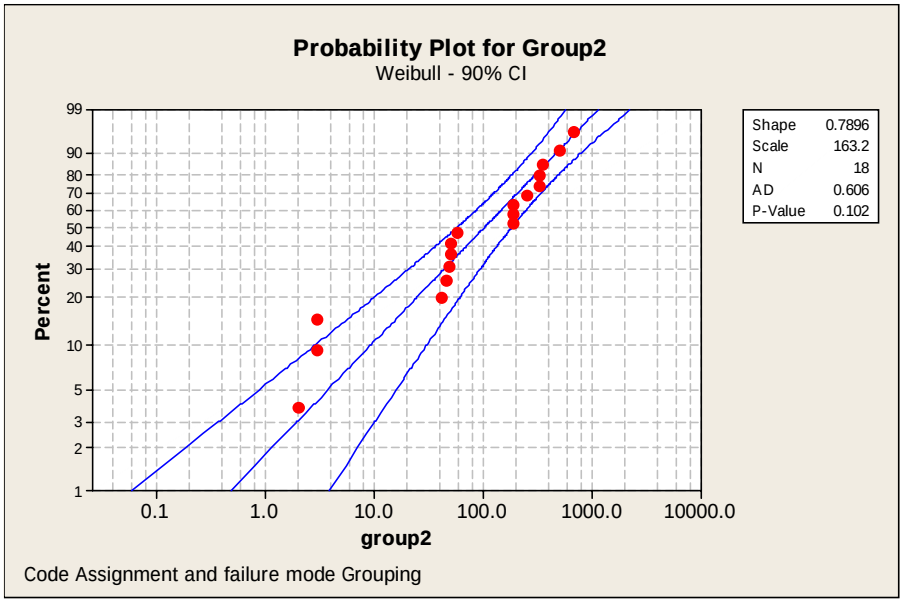

Figure 2

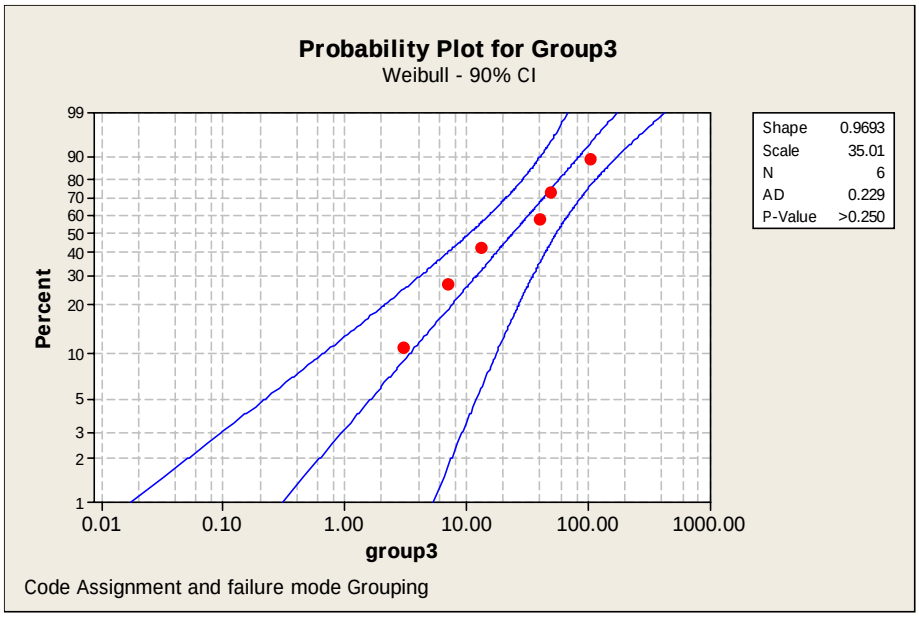

Figure 3

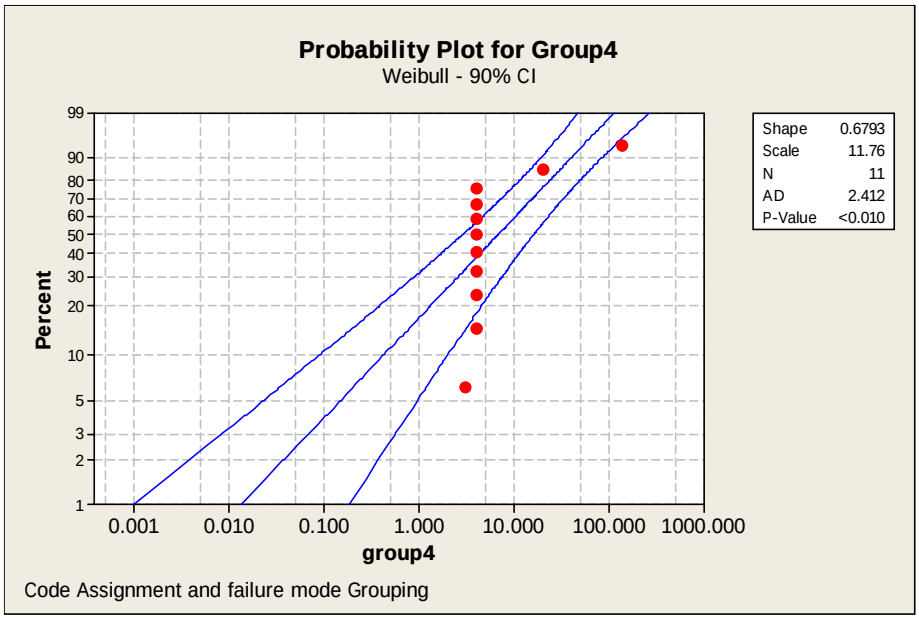

Figure 4

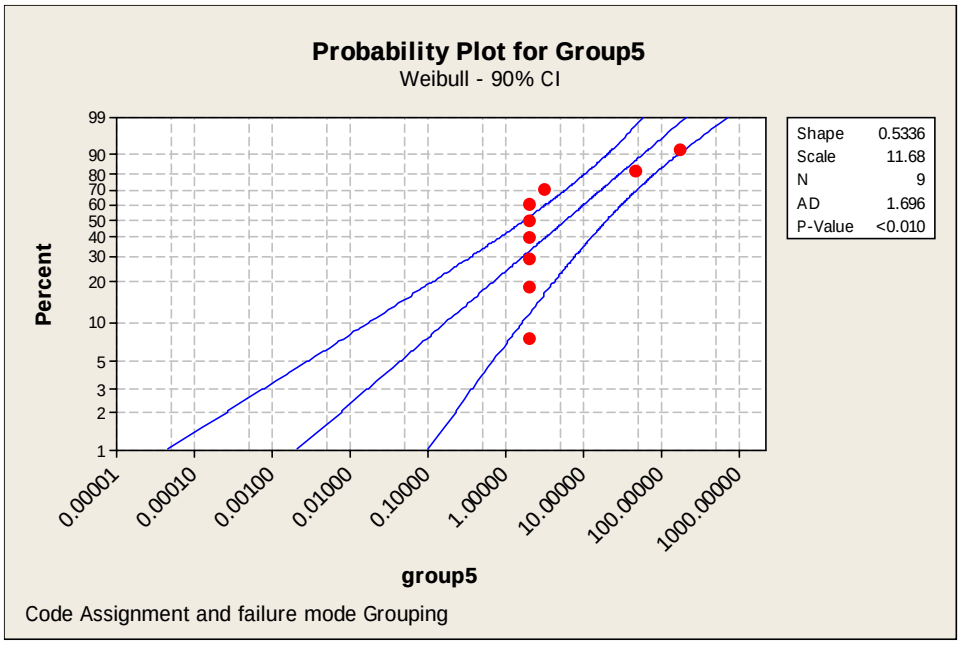

Figure 5

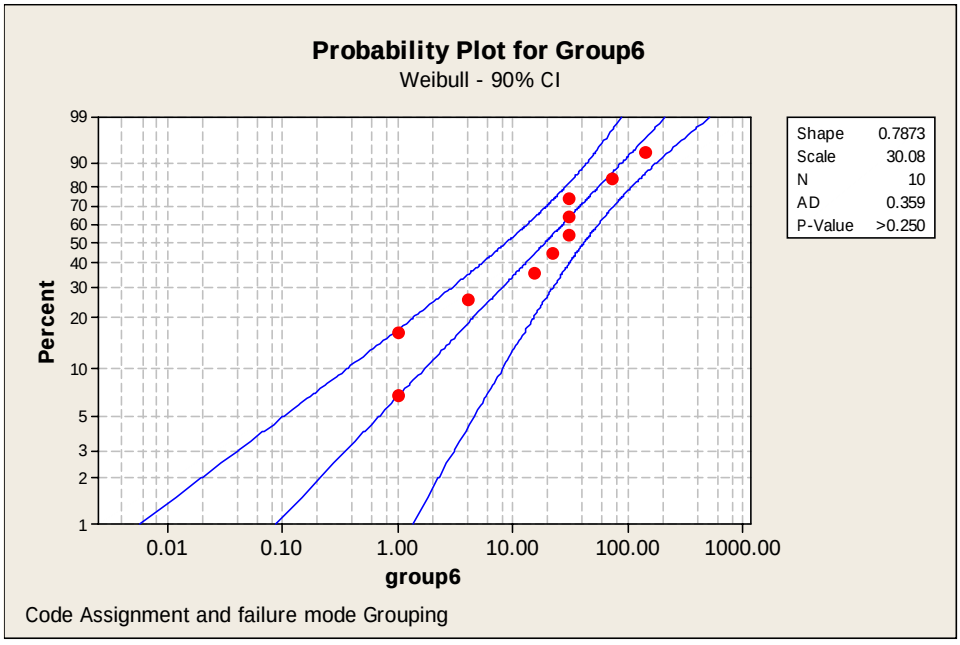

Figure6