THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

RELIABILITY AND FAILURE ANALYSIS LABORATORY
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Reliability Centered Maintenance Applied to Achieve Best Life Cycle Costs

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Reliability & Failure Analysis Laboratory
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Research Institute

Dr Bill Wessels PE CRE

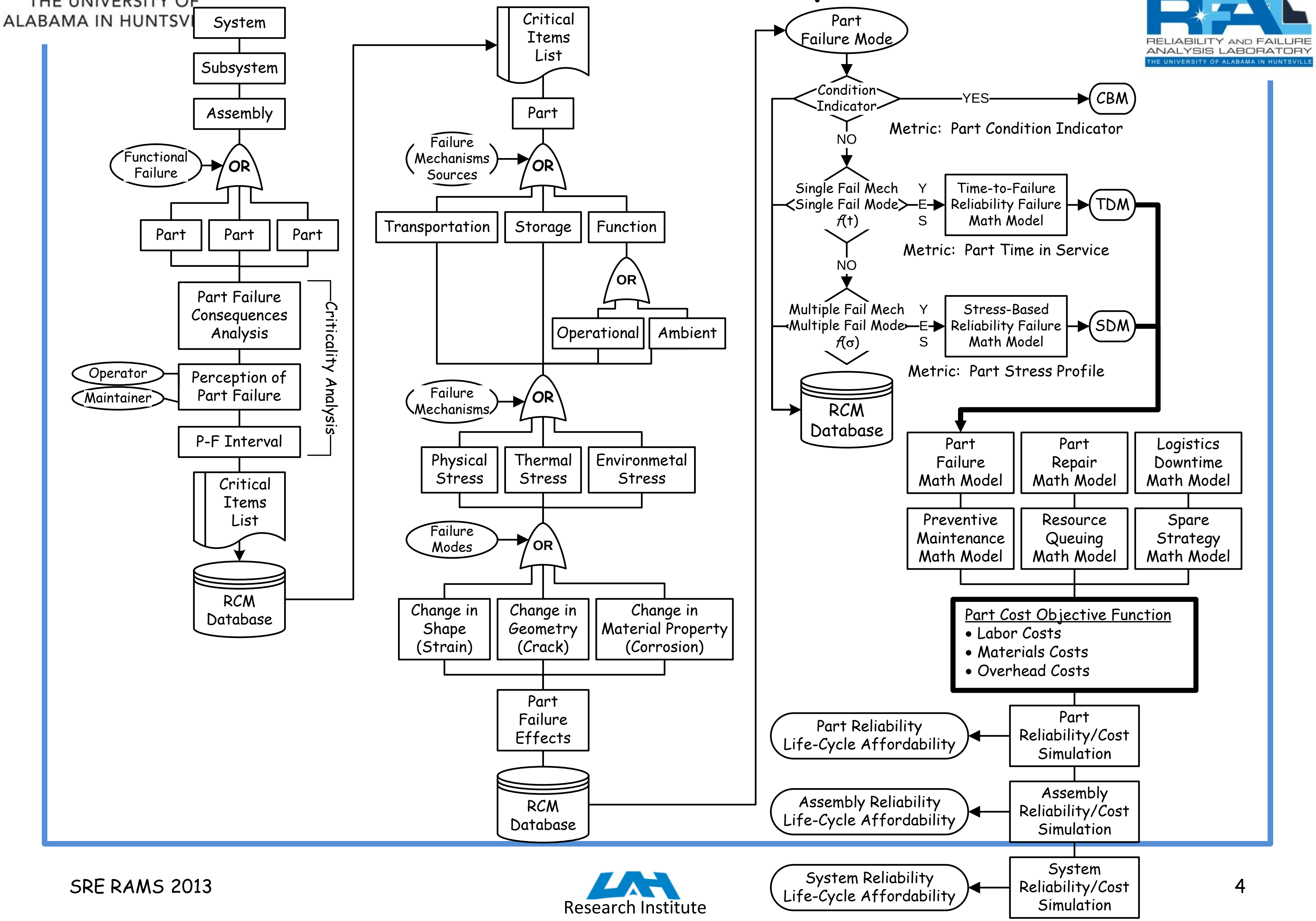
- Experience:
  - 1975 – 1989 Tramp Engineer, mining mobile machinery & process equipment life-cycle sustainability
  - 1989 – 2005 Contractor [Biomedical Devices, DoD and NASA] design-for-reliability, RCM
  - 2005 – Research in design-for-reliability & life-cycle sustainability for mechanical and structural components

- Credentials
  - BS USMA, West Point '70
  - PhD Reliability Systems Engineering, UAHuntsville '96
  - PE MechE, Pennsylvania, '82
  - CRE, ASQ, '96
- **Author** – Practical Reliability engineering and Analysis for System Design and Life-Cycle Sustainment, CRC Press, 2010

Introduction

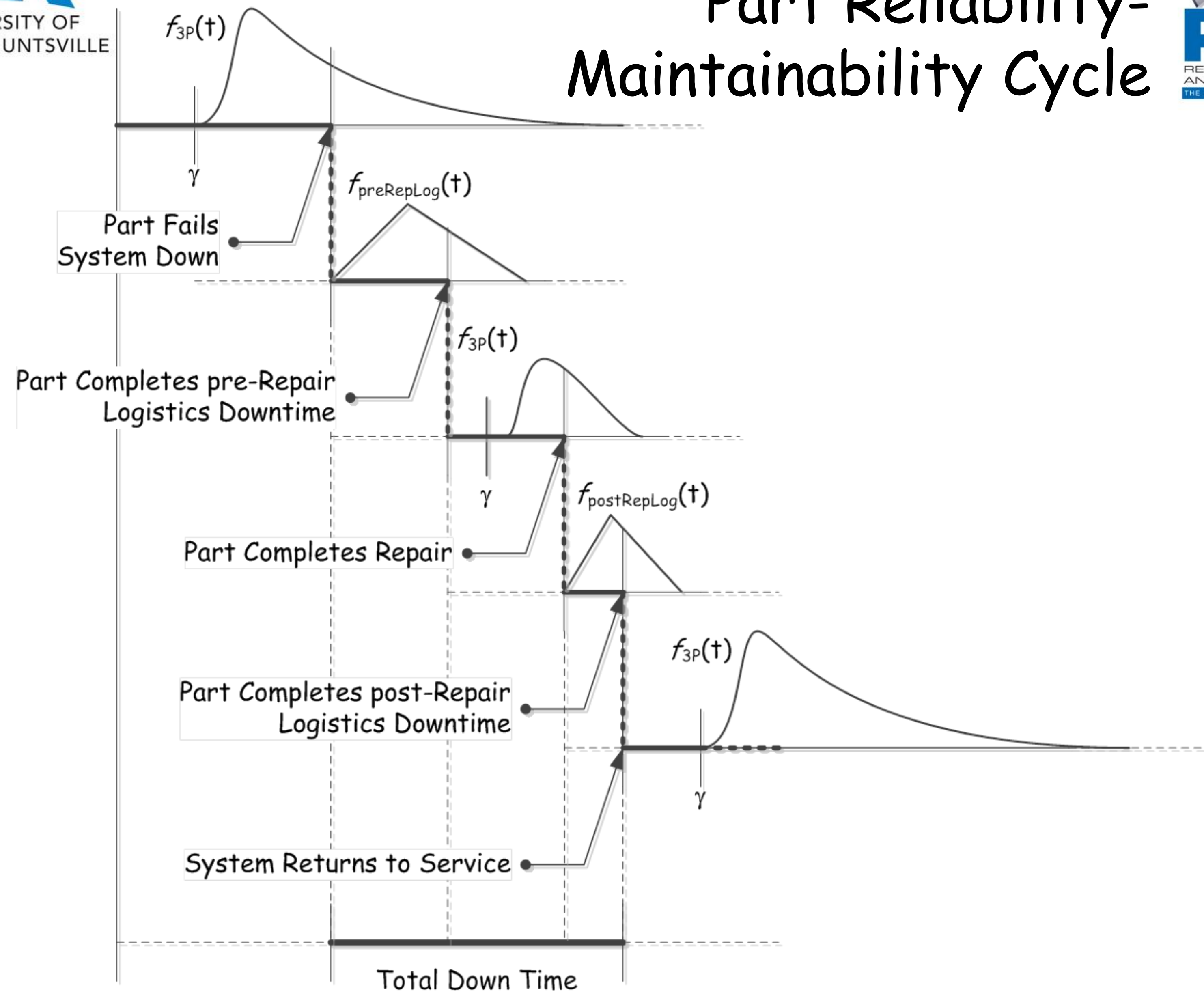
- Reliability-centered maintenance serves to preserve system functionality by performing scheduled maintenance actions that prevent unscheduled system downing events during scheduled operations
- RCM achieves its objective by developing an understanding of critical part failure
- Understanding part failure is manifested by the ability to measure the consumed life of a critical part
- Scheduled maintenance is defined by application of a risk threshold to the consumed life

RCM Roadmap

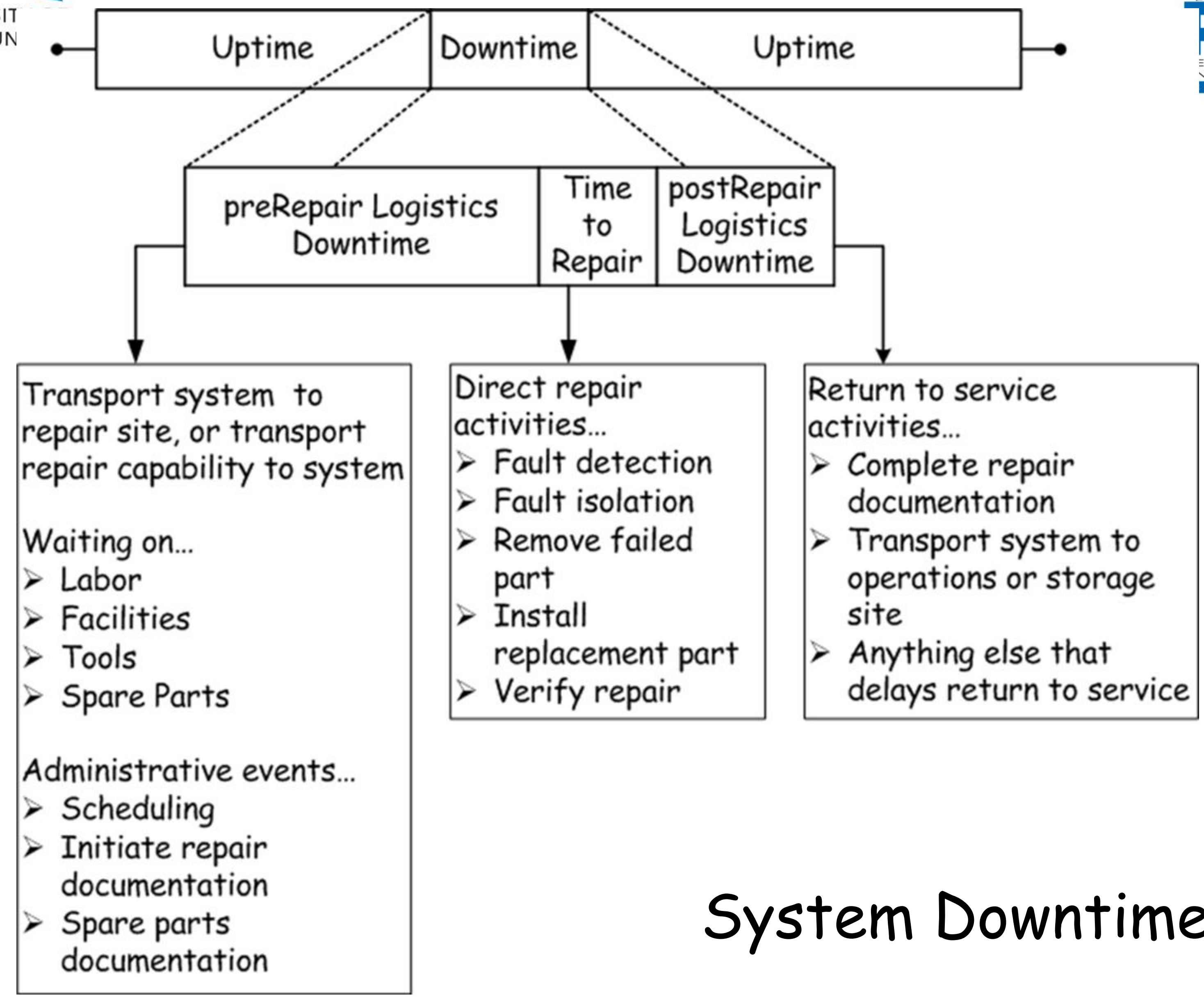


System
Subsystem
Assembly
Functional Failure
OR
Part
Part
Part
Part Failure Consequences Analysis
Operator
Maintainer
Perception of Part Failure
P-F Interval
Criticality Analysis
Critical Items List
RCM Database
Critical Items List
Part
Failure Mechanisms Sources
OR
Transportation
Storage
Function
OR
Operational
Ambient
Failure Mechanisms
OR
Physical Stress
Thermal Stress
Environmetal Stress
Failure Modes
OR
Change in Shape (Strain)
Change in Geometry (Crack)
Change in Material Property (Corrosion)
Part Failure Effects
RCM Database
Part Failure Mode
Condition Indicator
YES
CBM
Metric: Part Condition Indicator
NO
Single Fail Mech
Single Fail Mode
f(t)
YES
Time-to-Failure Reliability Failure Math Model
TDM
Metric: Part Time in Service
NO
Multiple Fail Mech
Multiple Fail Mode
f(σ)
YES
Stress-Based Reliability Failure Math Model
SDM
Metric: Part Stress Profile
RCM Database
Part Failure Math Model
Part Repair Math Model
Logistics Downtime Math Model
Preventive Maintenance Math Model
Resource Queuing Math Model
Spare Strategy Math Model
Part Cost Objective Function
• Labor Costs
• Materials Costs
• Overhead Costs
Part Reliability Life-Cycle Affordability
Part Reliability/Cost Simulation
Assembly Reliability Life-Cycle Affordability
Assembly Reliability/Cost Simulation
System Reliability Life-Cycle Affordability
System Reliability/Cost Simulation

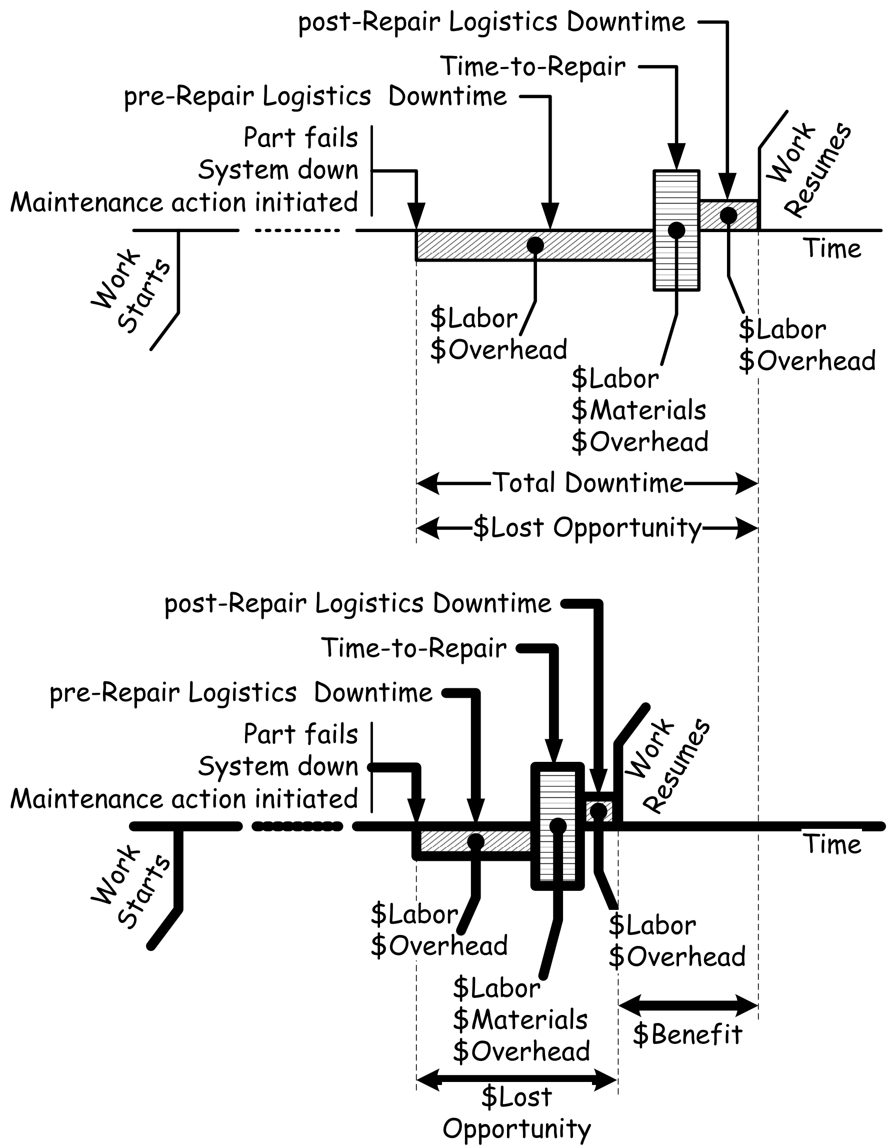
Part Reliability-Maintainability Cycle



System Downtime



Source of RCM Cost Benefit



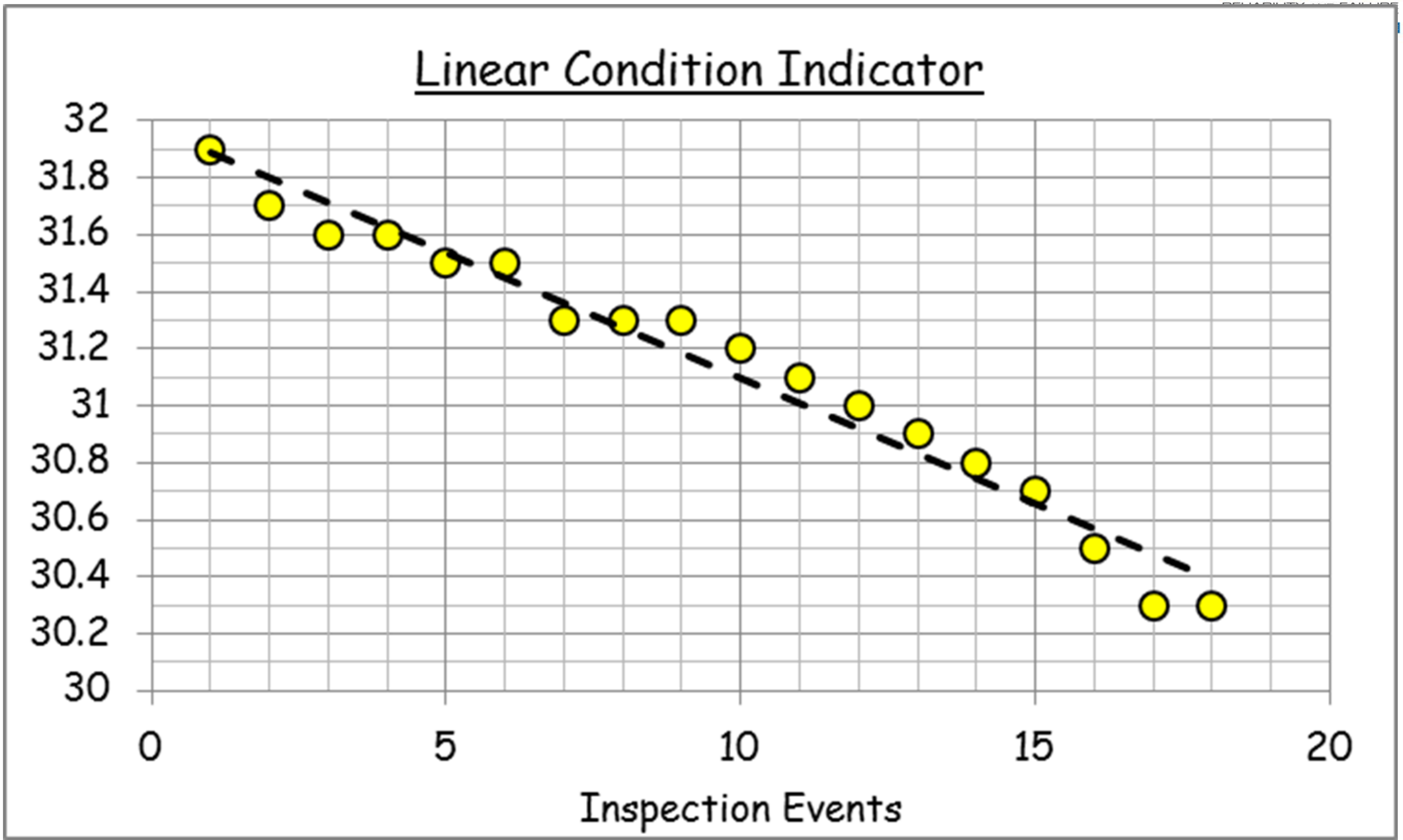
Top Level RCM Path

- Develop a rank ordered critical items list – CIL
- Perform reliability failure analysis to identify:
  - Sources of failure mechanisms (Conditions of use)
  - Failure mechanisms action on the critical part (Cause of part failure)
  - Failure modes (Damage to part)
  - Failure effects – part (Symptoms of the damage)
  - Failure effects – assembly (Consequences of part failure)
- Select appropriate RCM Path
  - CBM
  - TDM
  - SDM

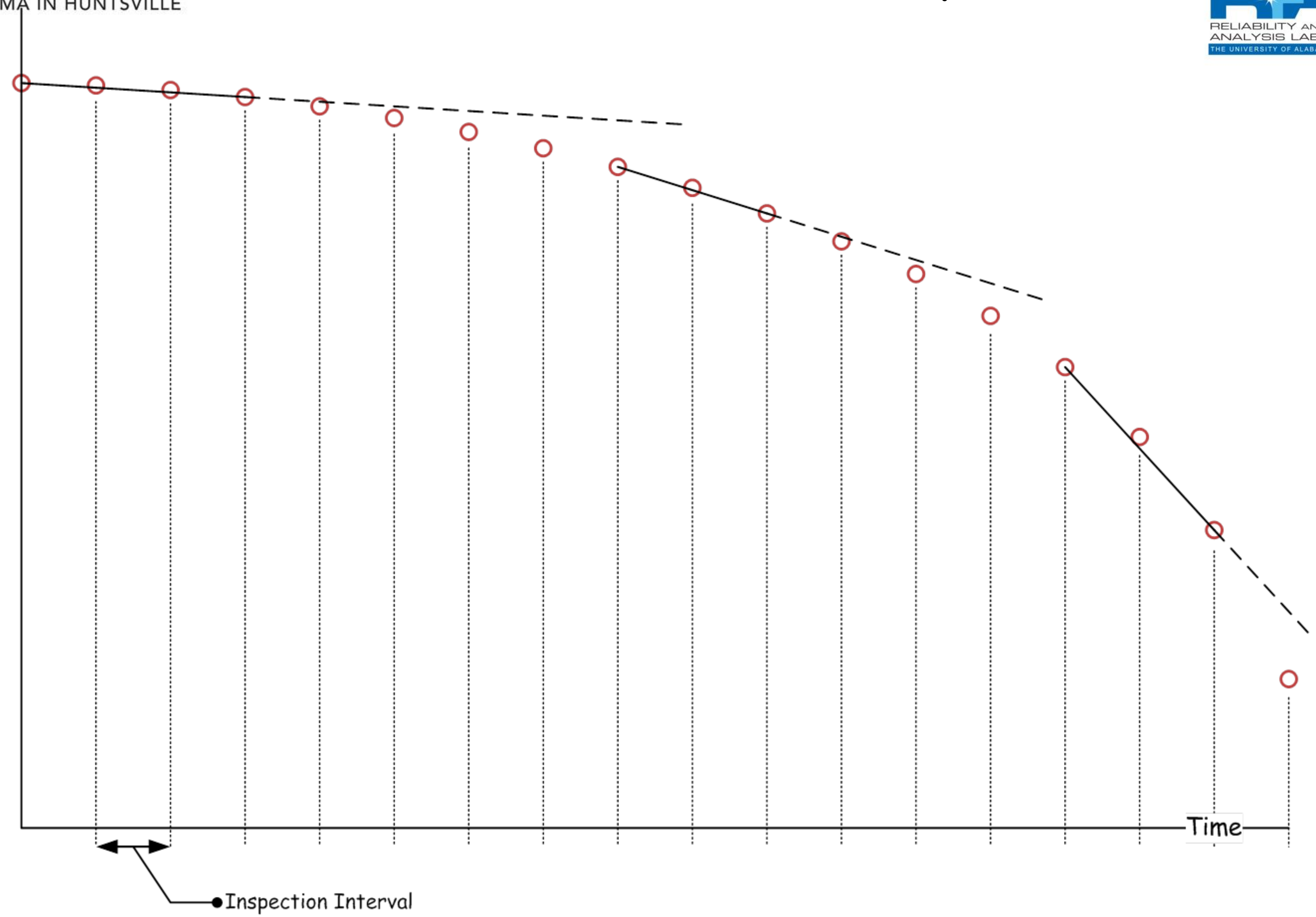
Condition-Based Maintenance CBM

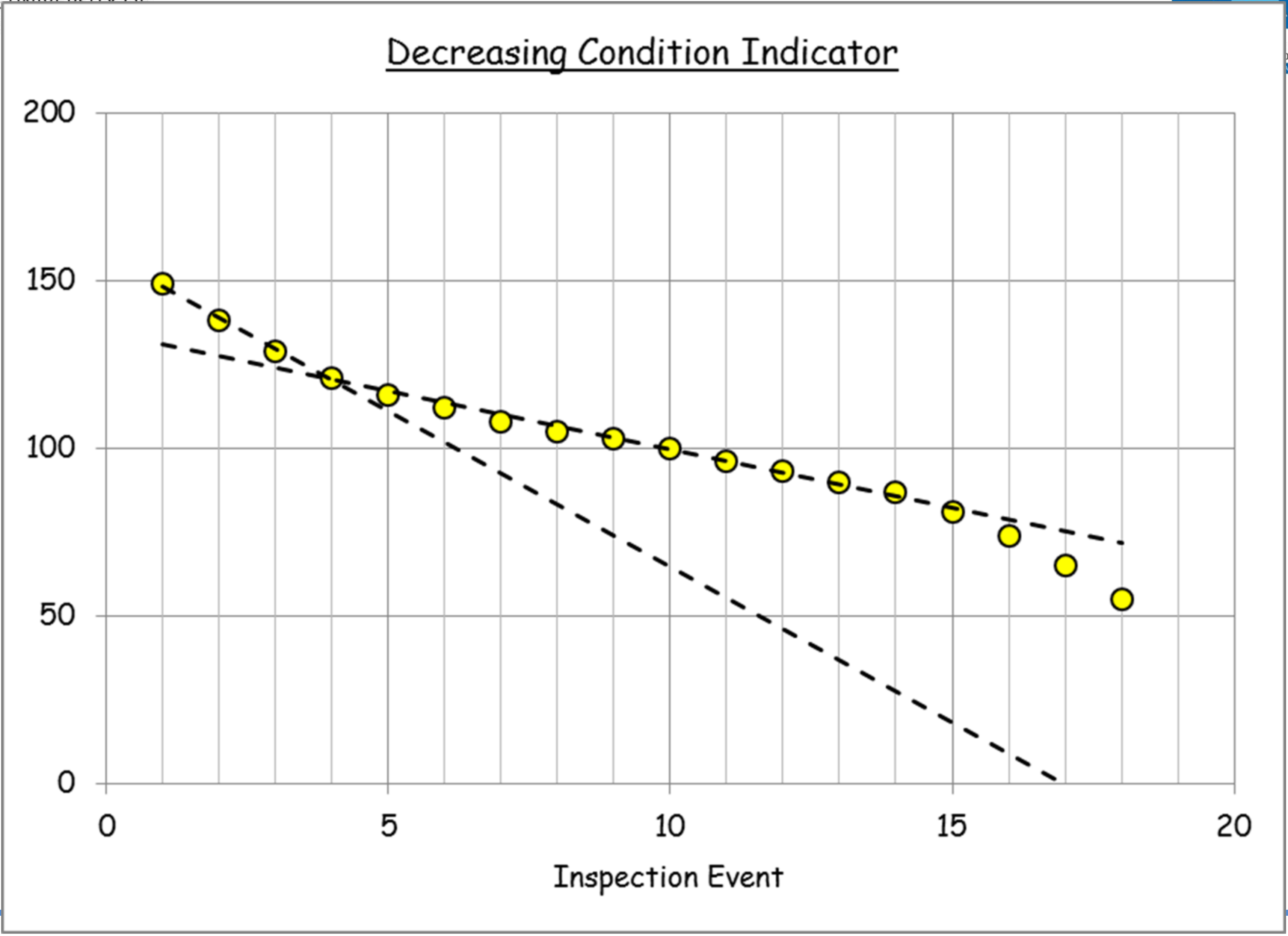
- Consumed life characterized by a condition that defines the failure mode/damage
  - Change in shape
  - Change in geometry
  - Change in material properties
- Method for investigating the damage, NDI
  - Visual inspection of condition indicator
  - Manual measurement of condition indicator
  - Sensor measurement of condition indicator
- Metrics that characterize the damage
- Risk Threshold

Notional Linear CBM Concept



Notional CBM Concept



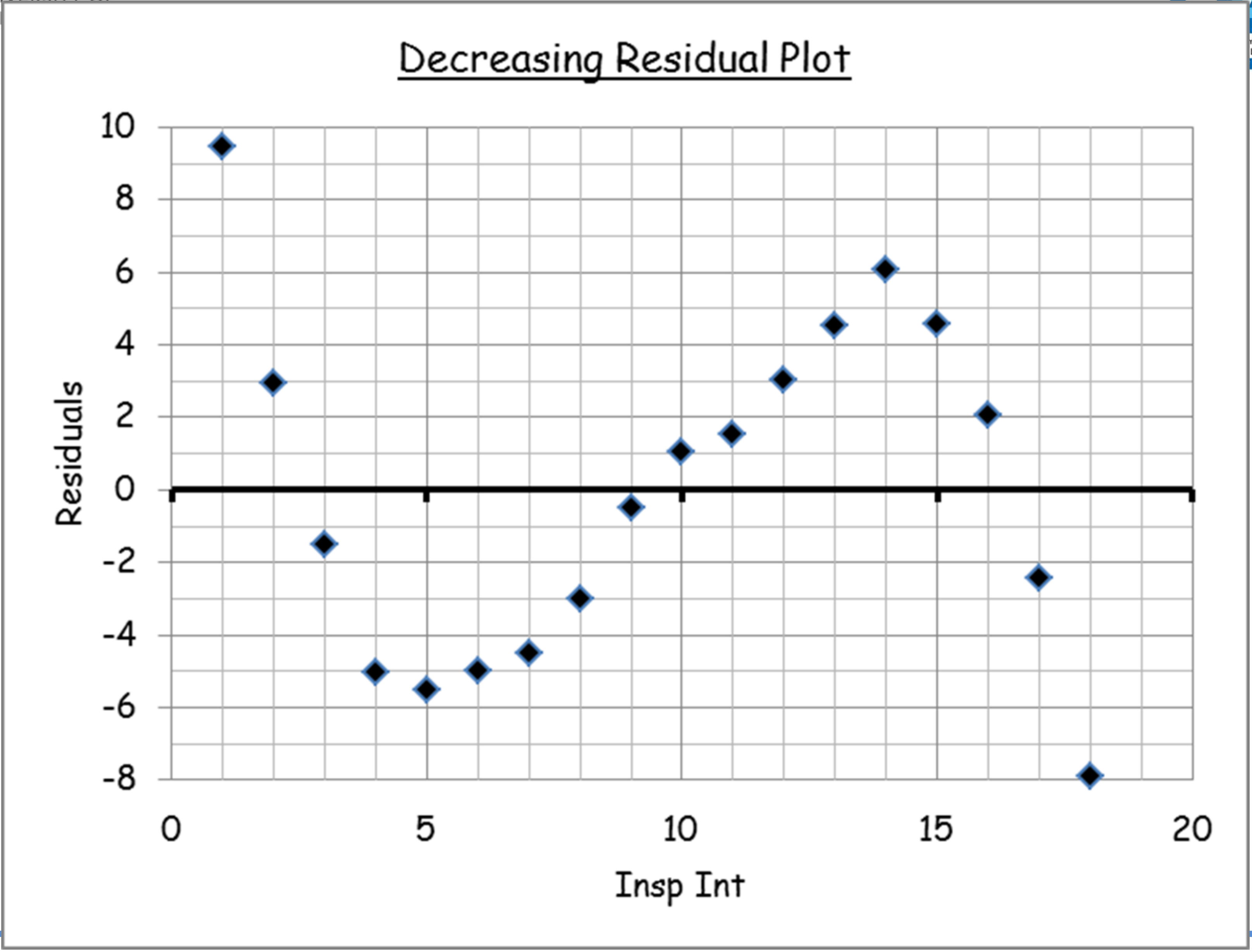

Decreasing Condition Indicator
200
150
100
50
0
0
5
10
15
20
Inspection Event

Decreasing Condition Indicator

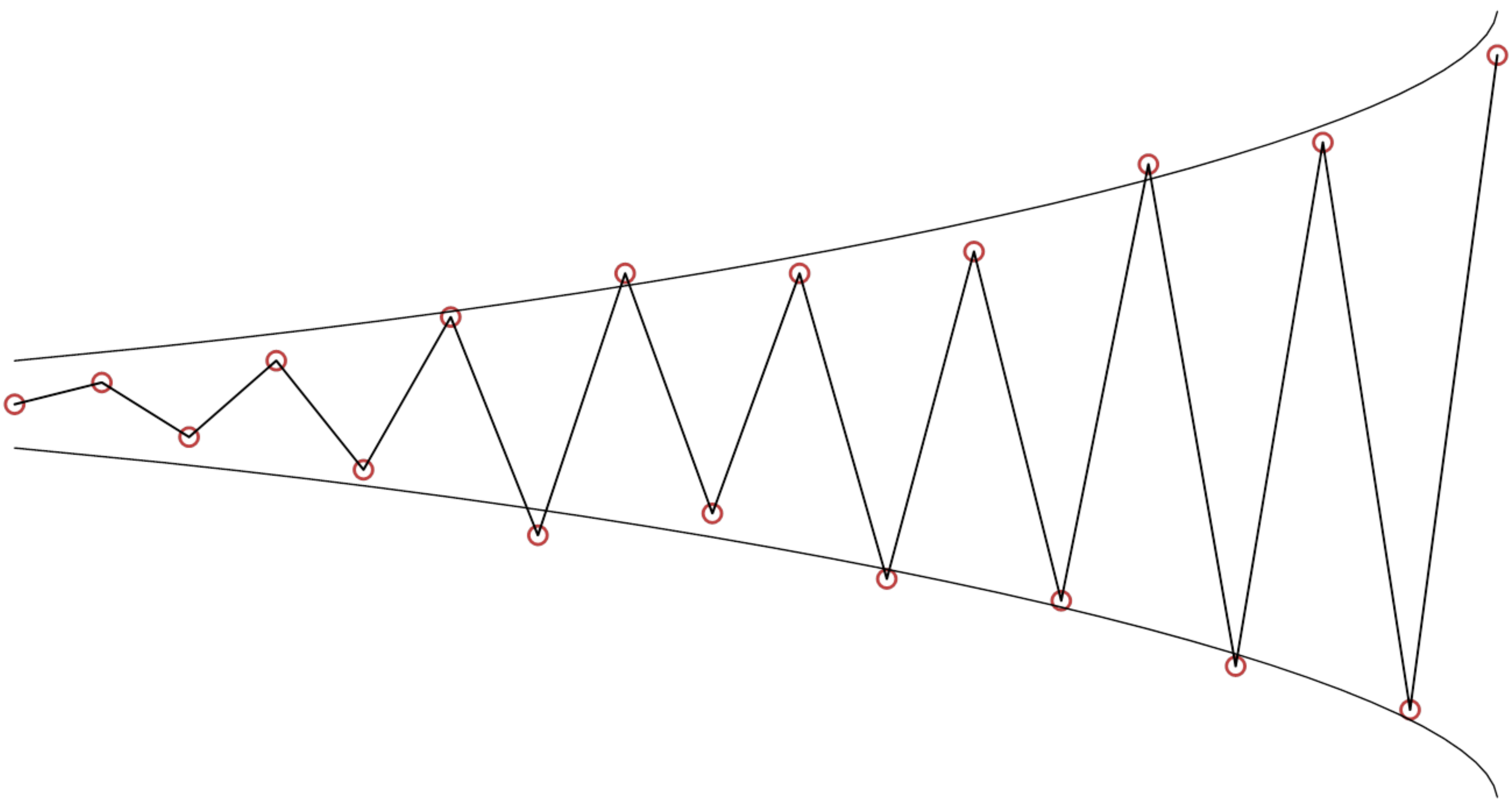
Regression Statistics	
r	0.982
r^2	0.963
Std Err	4.84
n	18

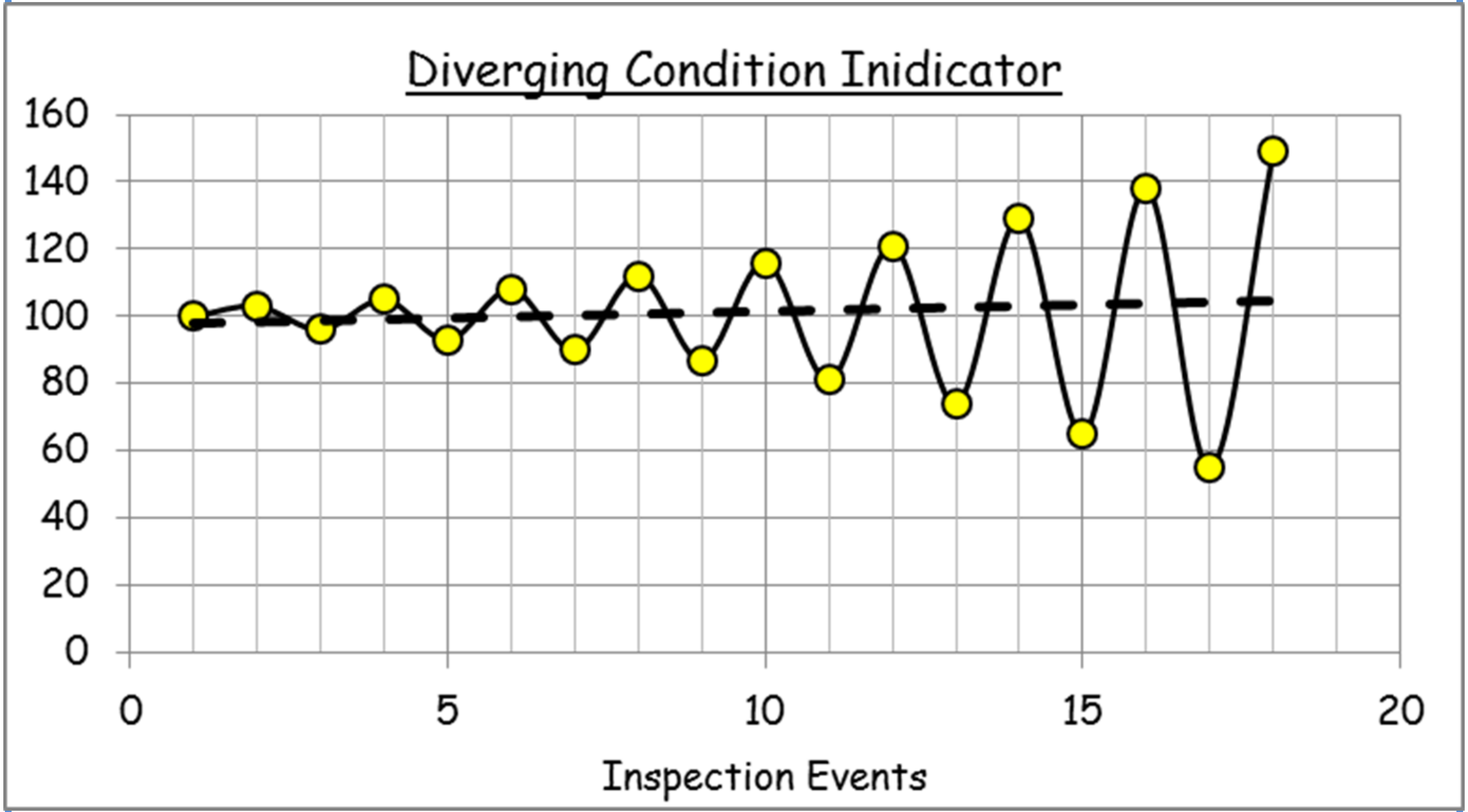
ANOVA	df	SS	MS	F	P-value
Regressior	1	9844.90	9844.90	420.94	0.00
Residual	16	374.21	23.39		
Total	17	10219.11			

	Coefficients	Std Err	t Stat	P-value	LCI 95%	UCI 95%
Intercept	144.05	2.38	60.57	0.00	139.00	149.09
Insp Int	-4.51	0.22	-20.52	0.00	-4.97	-4.04


Decreasing Residual Plot
Residuals
10
8
6
4
2
0
-2
-4
-6
-8
0
5
10
15
20
Insp Int

Diverging Condition Indicator



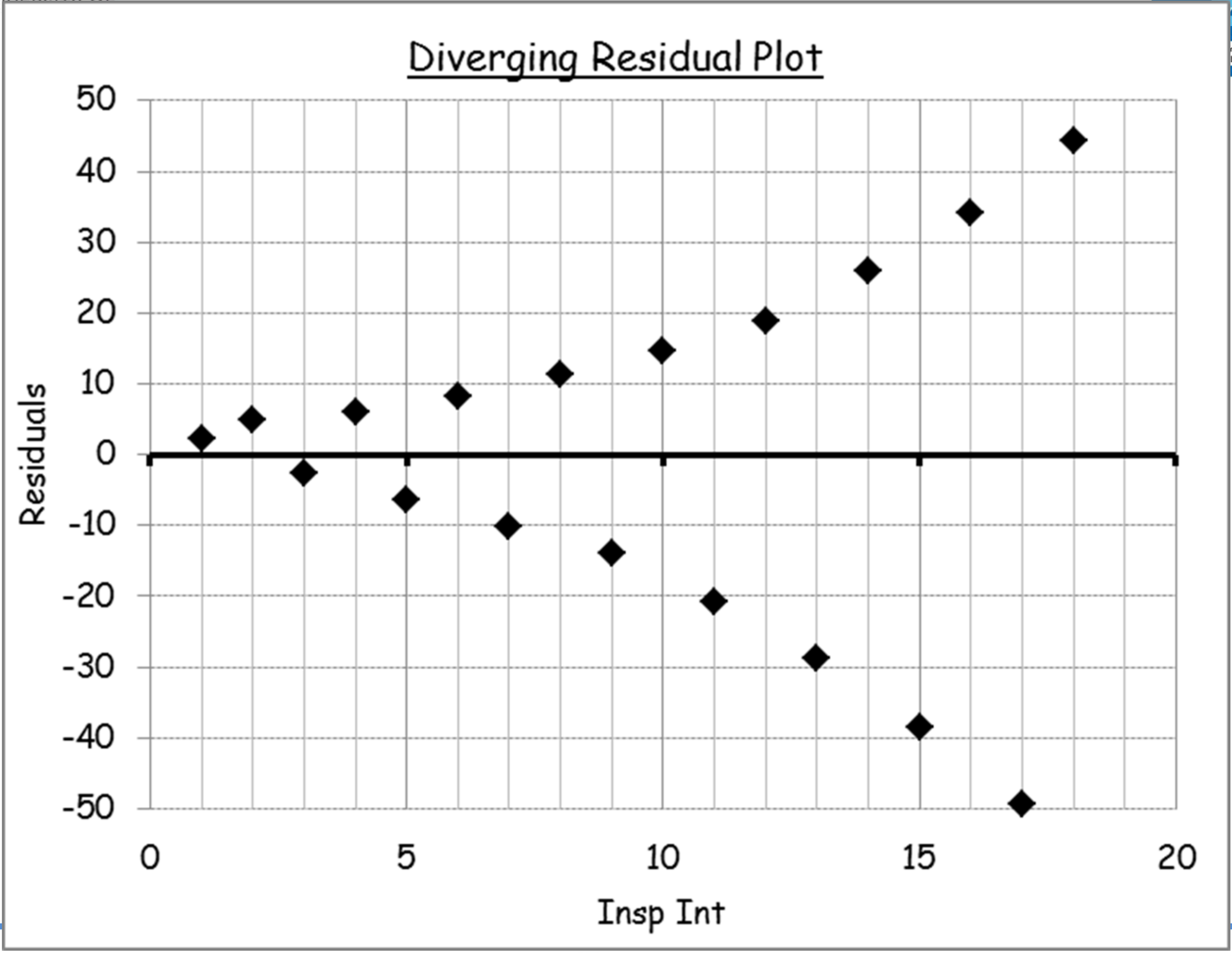

Diverging Condition Inidicator
160
140
120
100
80
60
40
20
0
0
5
10
15
20
Inspection Events

Diverging Condition Indicator

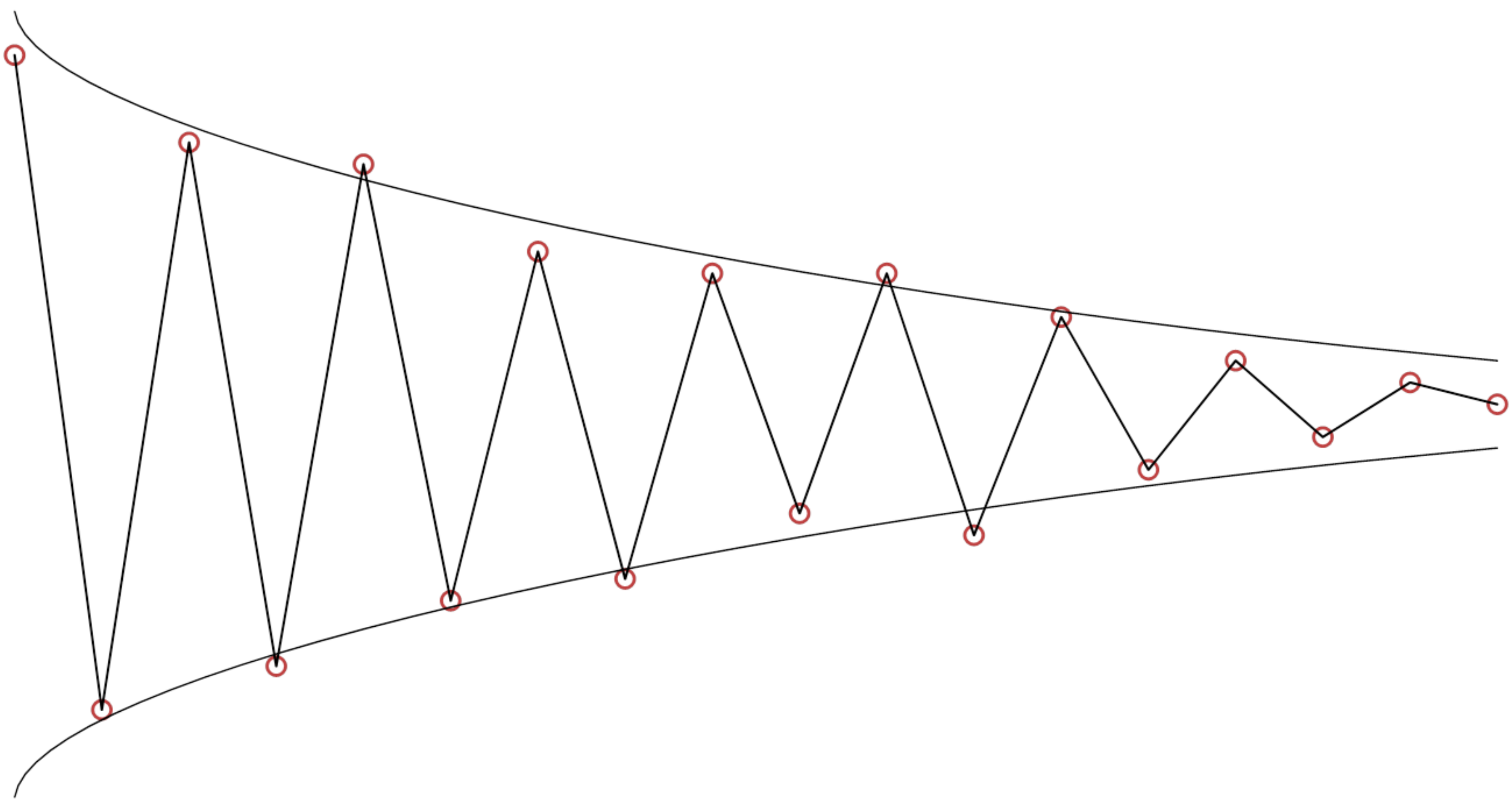
Regression Statistics	
r	0.089
r^2	0.008
Std Err	25.172
n	18

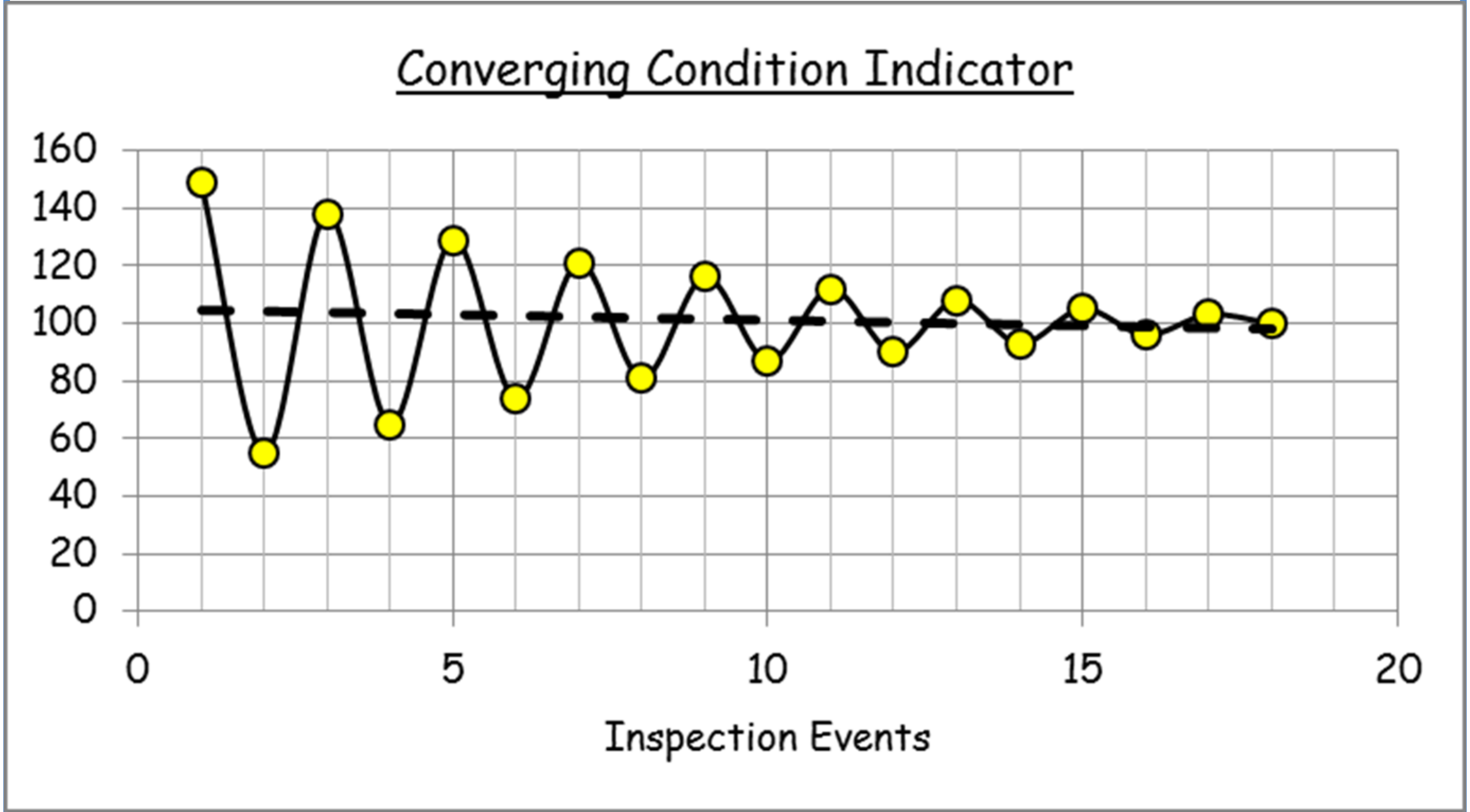
ANOVA	*df*	*SS*	*MS*	*F*	*P-value*
Regression	1	80.92	80.92	0.128	0.725
Residual	16	10138.19	633.64		
Total	17	10219.11			

	Coefficients	Std Err	*t Stat*	*P-value*	*LCI 95%*	*UCI 95%*
Intercept	97.34	12.38	7.86	0.000	71.10	123.58
Diverging	0.41	1.14	0.36	0.725	-2.02	2.83


Diverging Residual Plot
Residuals
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
5
10
15
20
Insp Int

Converging Condition Indicator



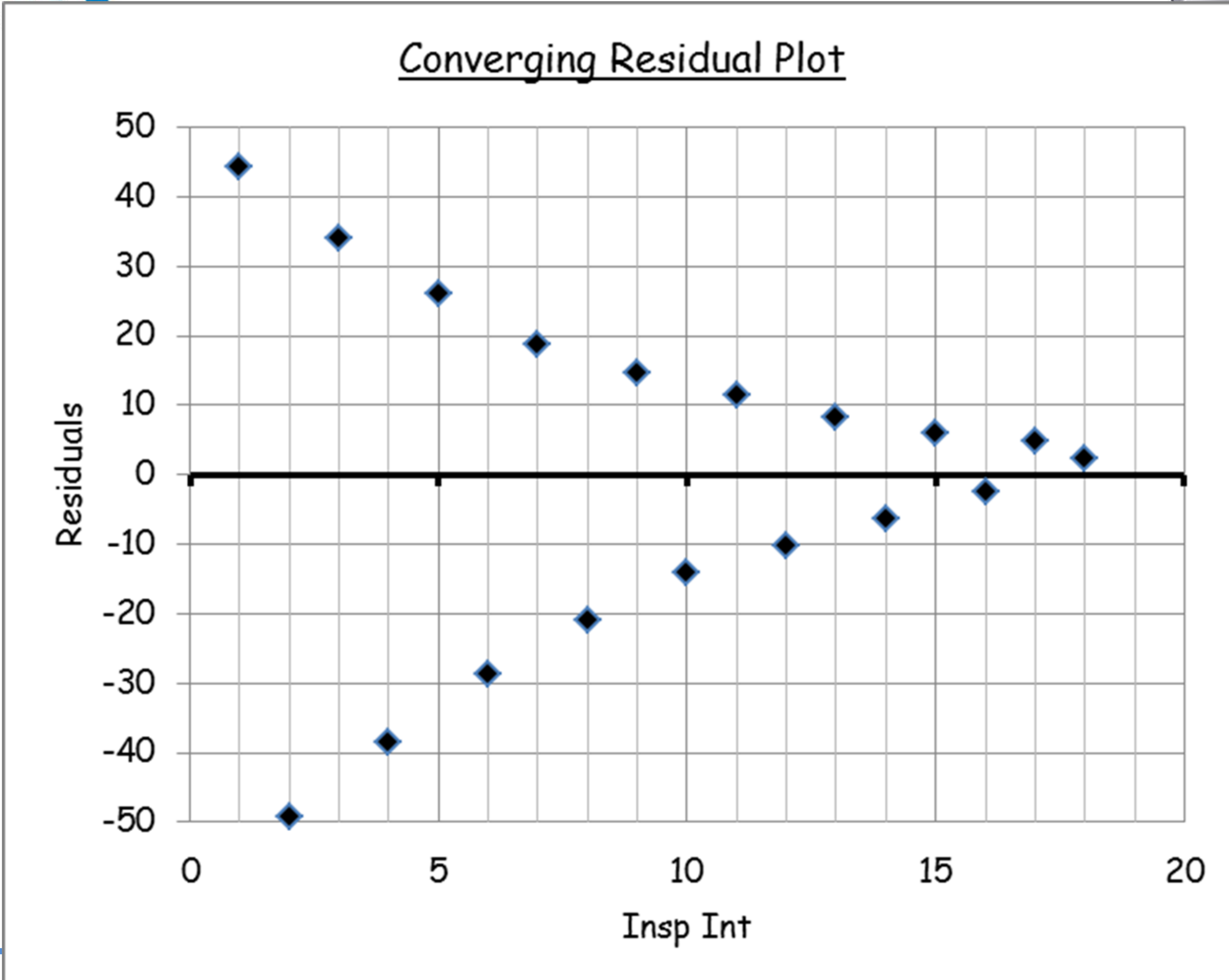

Converging Condition Indicator
160
140
120
100
80
60
40
20
0
0
5
10
15
20
Inspection Events

Converging Condition Indicator

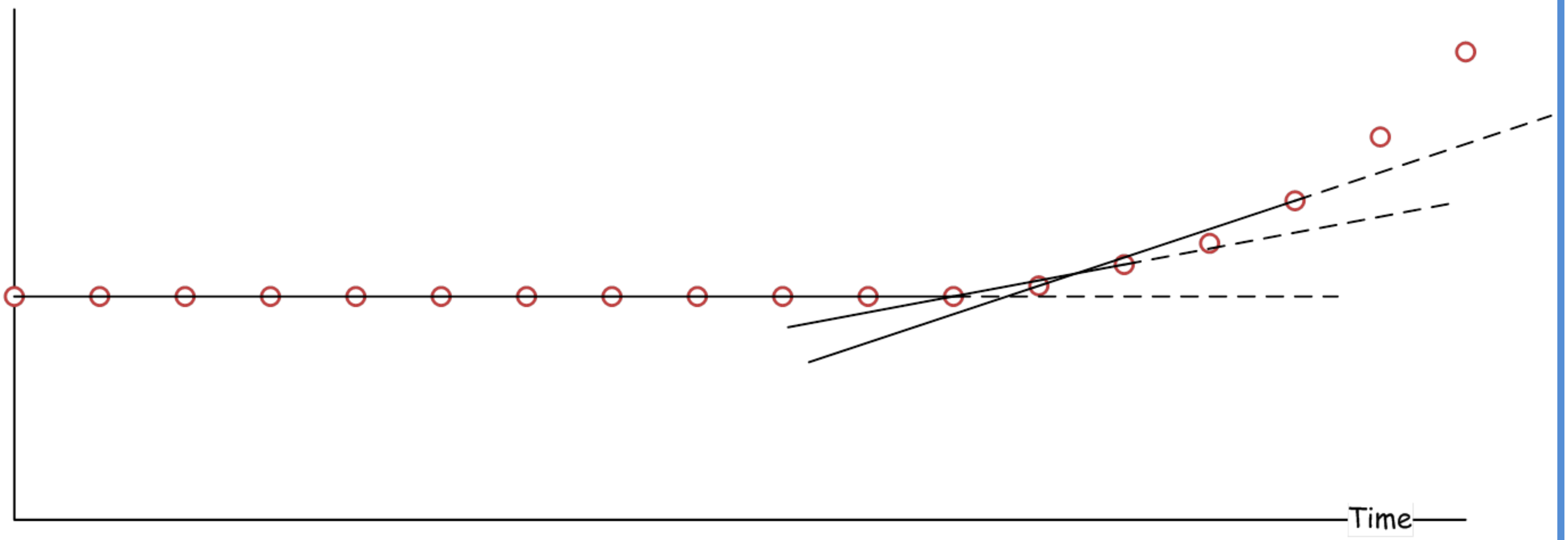
Regression Statistics	
r	0.089
r^2	0.008
Std Err	25.17
n	18

ANOVA	*df*	*SS*	*MS*	*F*	*P-value*
Regression	1	80.92	80.92	0.128	0.725
Residual	16	10138.19	633.64		
Total	17	10219.11			

Coefficients		Std Err	*t Stat*	*P-value*	*LCI 95%*	*UCI 95%*
Intercept	105.10	12.38	8.49	0.000	78.86	131.35
Converging	-0.41	1.14	-0.36	0.725	-2.83	2.02


Converging Residual Plot
Residuals
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
5
10
15
20
Insp Int

Fatigue Condition Indicator

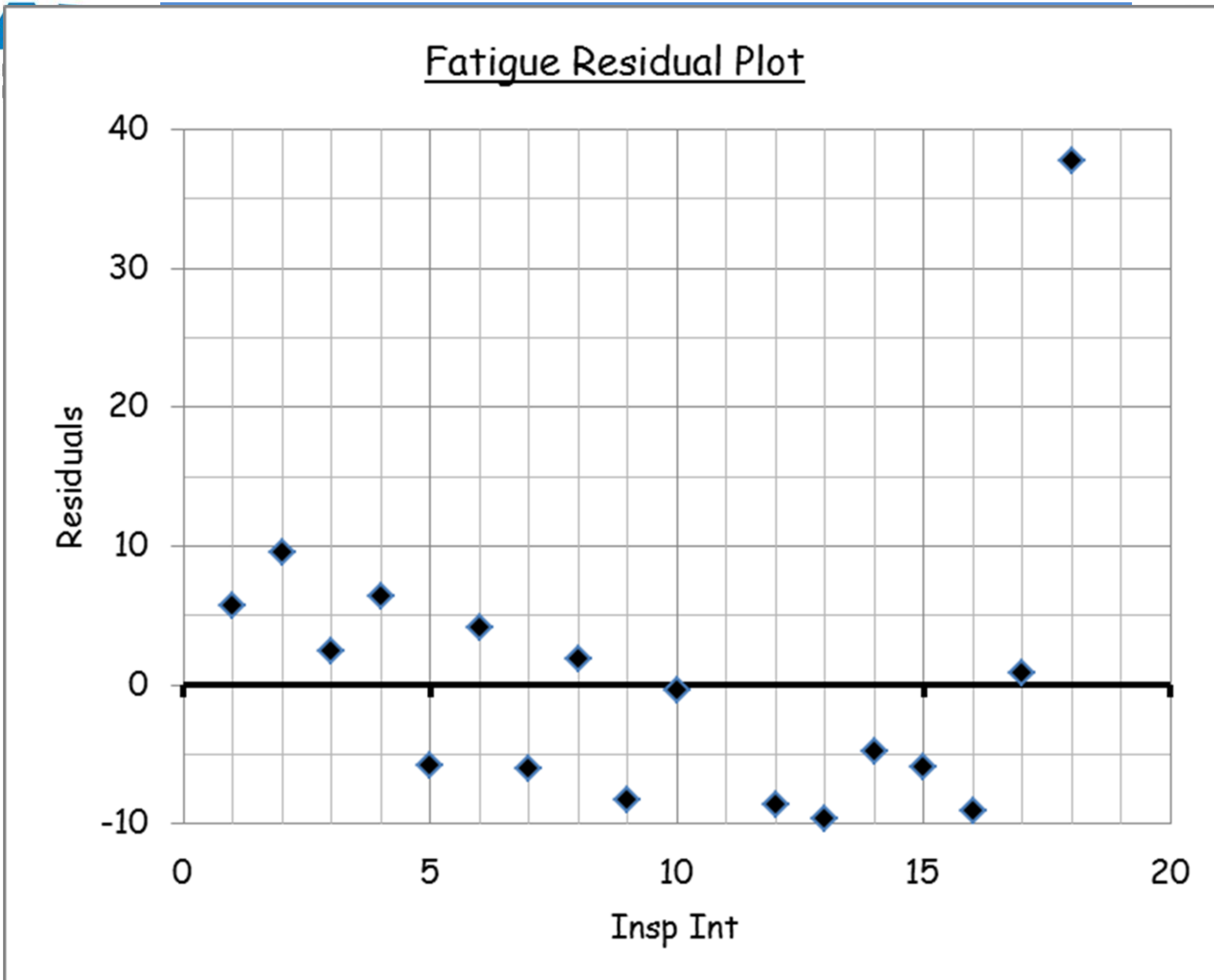


Fatigue Condition Indicator

Regression Statistics	
r	0.707
r^2	0.500
Std Err	11.64
n	18

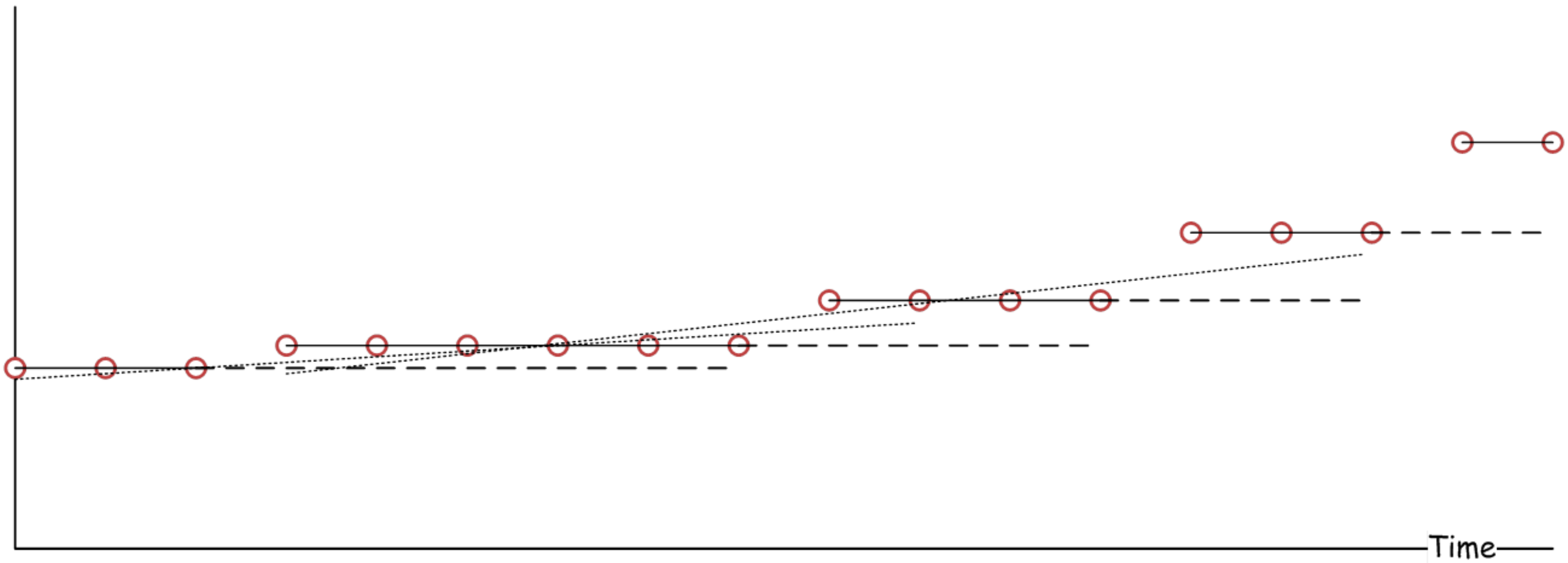
ANOVA	*df*	*SS*	*MS*	*F*	*P-value*
Regression	1	2166.36	2166.36	15.98	0.001
Residual	16	2169.25	135.58		
Total	17	4335.61			

Coefficients		Std Err	*t Stat*	*P-value*	*LCI 95%*	*UCI 95%*
Intercept	64.19	5.73	11.21	0.000	52.05	76.33
Fatigue	2.11	0.53	4.00	0.001	0.99	3.24



Fatigue Residual Plot
Residuals
40
30
20
10
0
-10
0
5
10
15
20
Insp Int

Step Condition Indicator



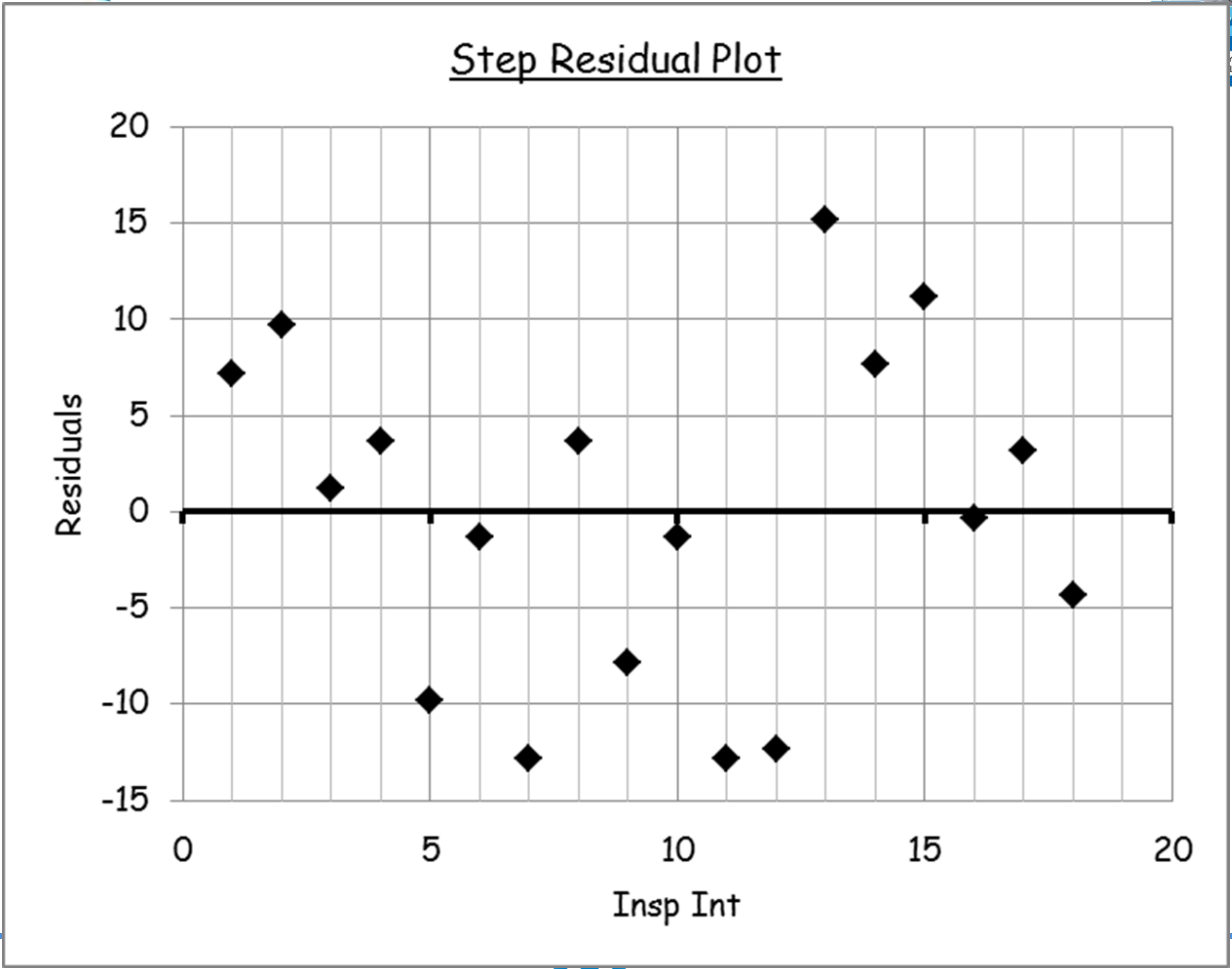

Stepped Condition Indicator
140
120
100
80
60
40
20
0
0
5
10
15
20
Inspection Events

Step Condition Indicator

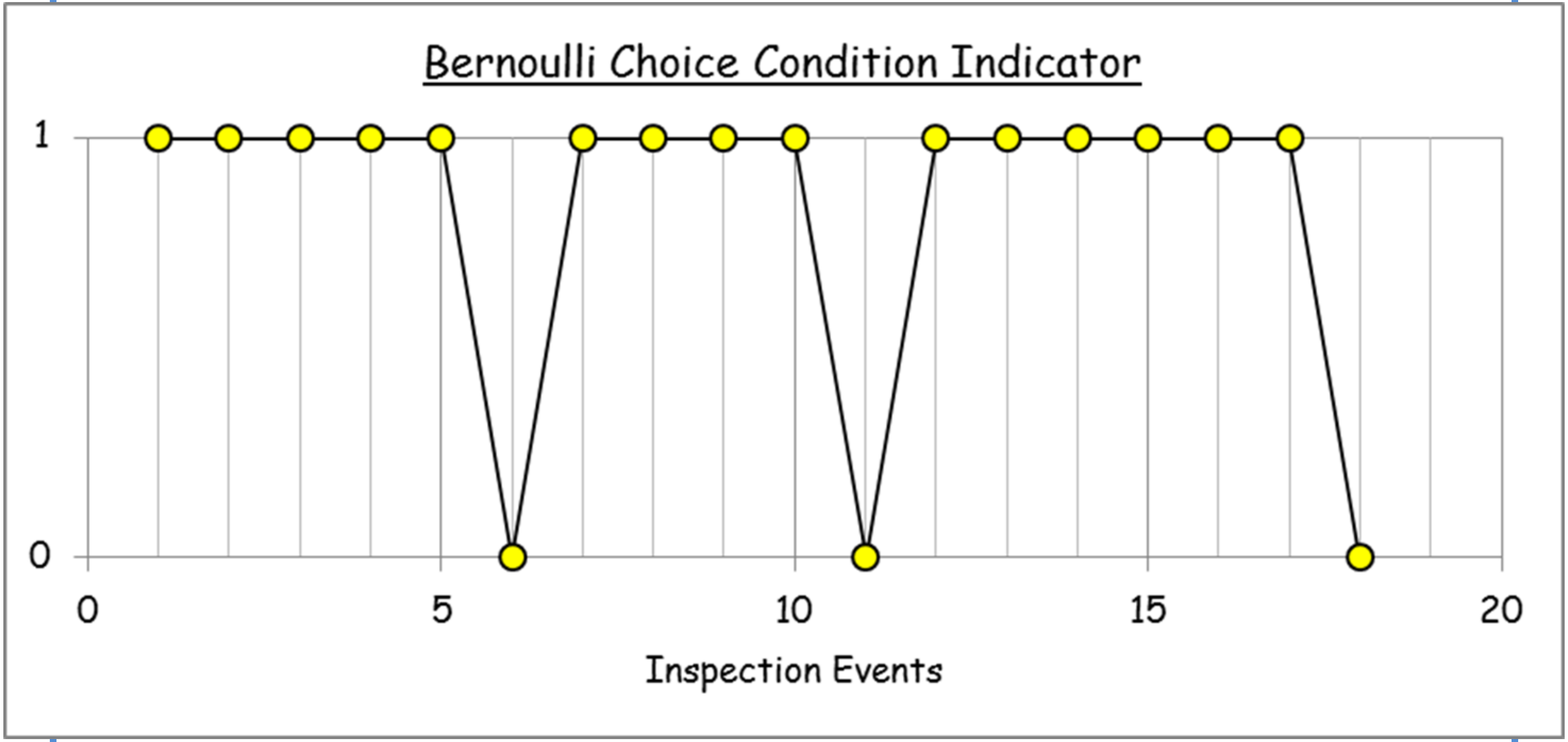
Regression Statistics	
r	0.908
r^2	0.825
Std Err	8.869
n	18

ANOVA	df	SS	MS	F	P-value
Regression	1	5943.88	5943.88	75.56	0.000
Residual	16	1258.57	78.66		
Total	17	7202.44			

	Coefficients	Std Err	t Stat	P-value	LCI 95%	UCI 95%
Intercept	61.28	4.36	14.05	0.000	52.04	70.53
Step	3.50	0.40	8.69	0.000	2.65	4.36


Step Residual Plot
20
15
10
5
0
-5
-10
-15
Residuals
0
5
10
15
20
Insp Int

Notional Attribute CBM Concept



Time Directed Maintenance, TDM

- Consumed life characterized by time in service, but…
- Single failure mechanism with single failure mode
- Failure mode correlated to operating time

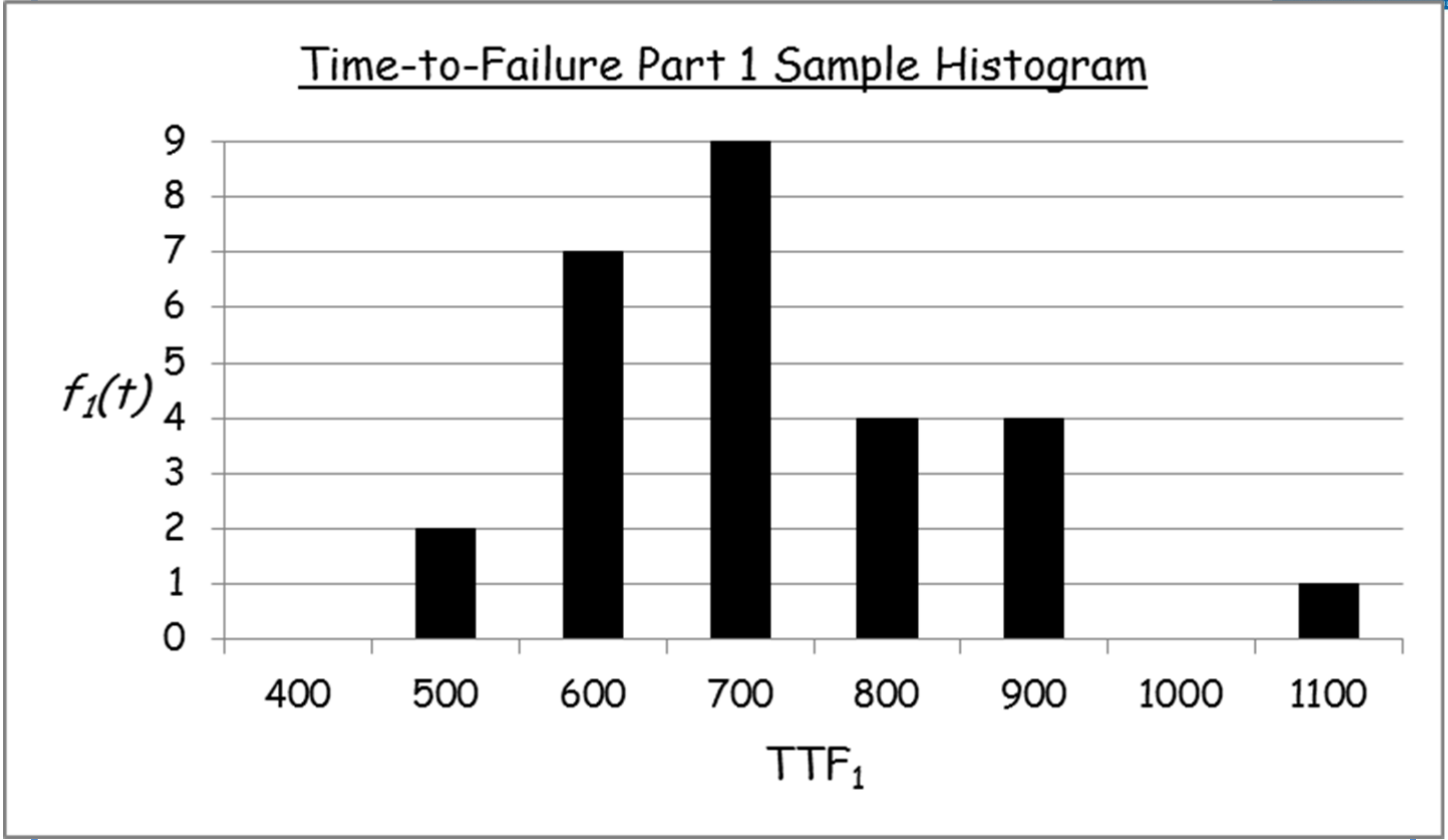
Time-to-Failure Data

Data - TTF_1		
490	695	725
457	613	645
508	538	728
595	538	663
613	699	845
581	659	842
685	721	1064
696	540	893
552	815	797

Descriptive Statistics	
Mean	673.96
Standard Deviation	139.20
Kurtosis	0.910
Skewness	0.811

TTF_1	$f_1(t)$
400	0
500	2
600	7
700	9
800	4
900	4
1000	0
1100	1
$\Sigma f_1(t) =$	27

Time-to-Failure Histogram



Fit Data to 3-Parameter Weibull Median Ranks Regression

- First: Fit the 2-Parameter Weibull
- Then: Select a value for the location parameter, γ
  - Choose the mid-time between 0 and T_{min}
  - Calculate $X_\gamma = X_i - \gamma$
  - Calculate r^2 for X_γ & Y
- If: r^2 for $X_\gamma < r^2$ for the 2-Parameter Weibull, use the 2-Parameter Weibull
- If: r^2 for $X_\gamma > r^2$ for the 2-Parameter Weibull, fit the 3-Parameter Weibull

Fit Data to 2-Parameter Weibull Median Ranks Regression

- Gather raw data
- Rank order raw data from lowest to highest
- Assign index to rank ordered data
- Calculate X - Ln(x)
- Calculate F(x)
- Calculate Y - Ln[Ln(1/(1-F(x)))]
- Perform Median Ranks Regression
  - Excel Method 1
    - Plot data scatter
    - Insert "Trendline" with r-sq, R^2
    - Calculate Weibull parameters
  - Excel Method 2
    - Run Data Analysis Linear Regression
    - Calculate Weibull parameters
- Evaluate parameter estimators using R^2
  - $R^2 \equiv$ coefficient of determination
  - R^2 is a measure of data fit

$$0 \le R^2 \le 1$$

- Bartlett's Median Ranks estimator for F(x)

$$\hat{F}(x) = \frac{i - 0.3}{n + 0.4}$$

- Formulation of linear equation for Median Ranks Regression

$$y_0 = -\beta Ln(\eta)$$

$$b = \beta$$

$$Y = y_0 + bX$$

- Weibull parameter estimation

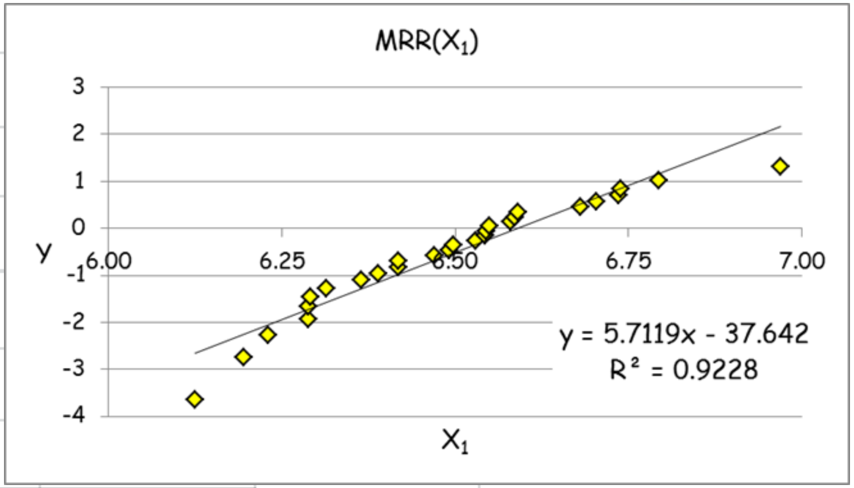
$$\beta = b$$

$$\eta = Ln^{-1}\left(\frac{y_0}{\beta}\right) = e^{-\left(\frac{y_0}{\beta}\right)}$$

2-P Weibull Median Ranks Regression

TTF_1	i	F	X_1	Y
457	1	0.026	6.125	-3.654
490	2	0.062	6.194	-2.748
508	3	0.099	6.230	-2.266
538	4	0.135	6.288	-1.931
538	5	0.172	6.288	-1.670
540	6	0.208	6.292	-1.456
552	7	0.245	6.314	-1.272
581	8	0.281	6.365	-1.109
595	9	0.318	6.389	-0.962
613	10	0.354	6.418	-0.828
613	11	0.391	6.418	-0.703
645	12	0.427	6.469	-0.585
659	13	0.464	6.491	-0.474
663	14	0.500	6.497	-0.367
685	15	0.536	6.529	-0.263
695	16	0.573	6.544	-0.161
696	17	0.609	6.545	-0.062
699	18	0.646	6.550	0.038
721	19	0.682	6.581	0.137
725	20	0.719	6.586	0.238
728	21	0.755	6.590	0.342
797	22	0.792	6.681	0.451
815	23	0.828	6.703	0.567
842	24	0.865	6.736	0.694
845	25	0.901	6.739	0.840
893	26	0.938	6.795	1.022
1064	27	0.974	6.970	1.299

2-P Weibull Median Ranks Regression



Regression Statistics	
r	0.961
r^2	0.923
Adj r^2	0.920
Std Err	0.338
n	27

ANOVA	df	SS	MS	F	P-value
Regression	1	34.02	34.02	298.67	0.000
Residual	25	2.85	0.11		
Total	26	36.87			

	Coefficients	Std Err	t Stat	P-value	LCI 95%	UCI 95%
y_0	-37.64	2.15	-17.53	0.000	-42.06	-33.22
β_1	5.71	0.33	17.28	0.000	5.03	6.39
η_1	727.81					

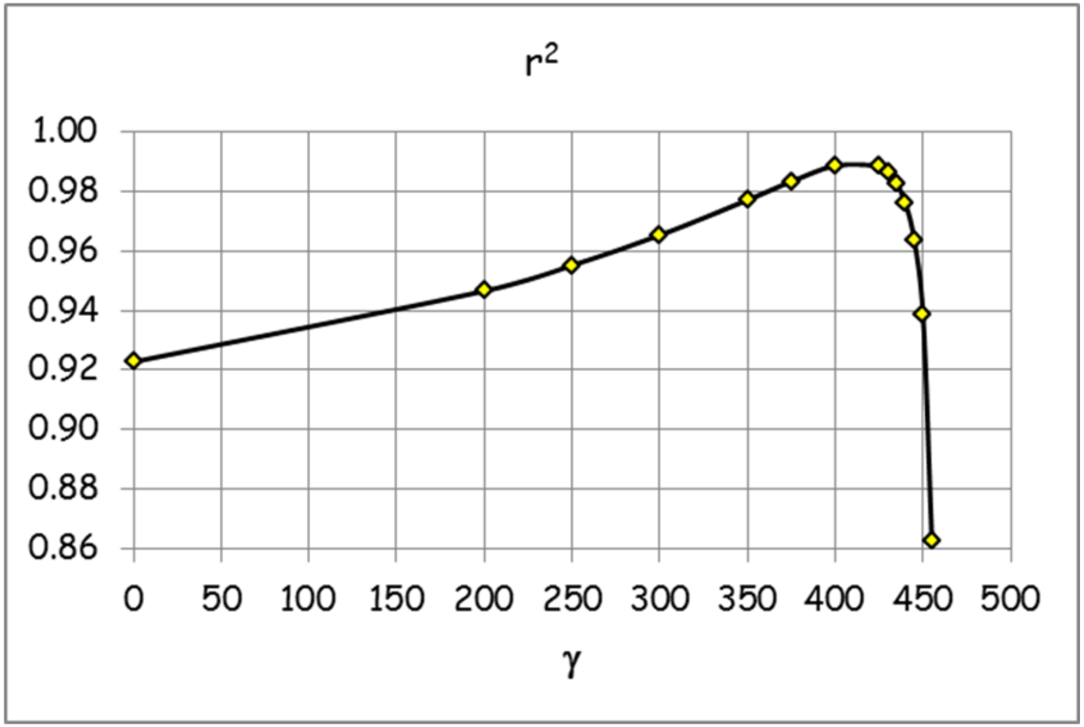
TTF Location Parameter, γ

TTF_1	i	F	$X_{\gamma 1}$	y
457	1	0.026	4.043	-3.654
490	2	0.062	4.500	-2.748
508	3	0.099	4.682	-2.266
538	4	0.135	4.927	-1.931
538	5	0.172	4.927	-1.670
540	6	0.208	4.942	-1.456
552	7	0.245	5.024	-1.272
581	8	0.281	5.198	-1.109
595	9	0.318	5.273	-0.962
613	10	0.354	5.361	-0.828
613	11	0.391	5.361	-0.703
645	12	0.427	5.501	-0.585
659	13	0.464	5.557	-0.474
663	14	0.500	5.572	-0.367
685	15	0.536	5.652	-0.263
695	16	0.573	5.687	-0.161
696	17	0.609	5.690	-0.062
699	18	0.646	5.700	0.038
721	19	0.682	5.771	0.137
725	20	0.719	5.784	0.238
728	21	0.755	5.793	0.342
797	22	0.792	5.984	0.451
815	23	0.828	6.028	0.567
842	24	0.865	6.091	0.694
845	25	0.901	6.098	0.840
893	26	0.938	6.201	1.022
1064	27	0.974	6.498	1.299

TTF Location Parameter, γ

γ	r^2
0	0.92276
200	0.94658
250	0.95517
300	0.96532
350	0.97713
375	0.98333
400	0.98862
425	0.98854
430	0.98643
435	0.98262
440	0.97589
445	0.96362
450	0.93844
455	0.86283

	$X_{\gamma 1}$	y
$X_{\gamma 1}$	1	
y	0.99430	1
r^2 =	0.98862	



3-P Weibull Failure Math Model - TTF

Regression Statistics						
r	0.994					
r^2	0.989					
Adj r^2	0.988					
Std Err	0.130					
n	27					
ANOVA	*df*	*SS*	*MS*	*F*	*P-value*	
Regression	1	36.45	36.45	2172.77	0.000	
Residual	25	0.42	0.02			
Total	26	36.87				
Coefficients		*Std Err*	*t Stat*	*P-value*	*LCI 95%*	*UCI 95%*
y_0	-12.07	0.25	-48.60	0.00	-12.58	-11.55
β_1	2.10	0.05	46.61	0.00	2.01	2.20
η_1	310.4					
$\gamma 1$	400					

95% LCL TTF		
Goal Seek:		
T_{LCL} =	475.56	-hrs
$F(T_{LCL})$ =	0.050	

3-P Weibull Failure Math Model

$$f_1(t) := \begin{cases} 0 & \text{if } 0 \le t < \gamma_1 \\ \left(\frac{\beta_1}{\eta_1}\right)\cdot\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1 - 1}\cdot e^{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1}} & \text{if } t \ge \gamma_1 \end{cases}$$

$$h_1(t) := \left(\frac{\beta_1}{\eta_1}\right)\cdot\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1 - 1}$$

$$F_1(t) := \begin{cases} 0 & \text{if } 0 \le t < \gamma_1 \\ 1 - e^{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1}} & \text{if } t \ge \gamma_1 \end{cases}$$

$$\alpha := 0.05$$

$$t_{1LCL} := 475.5$$

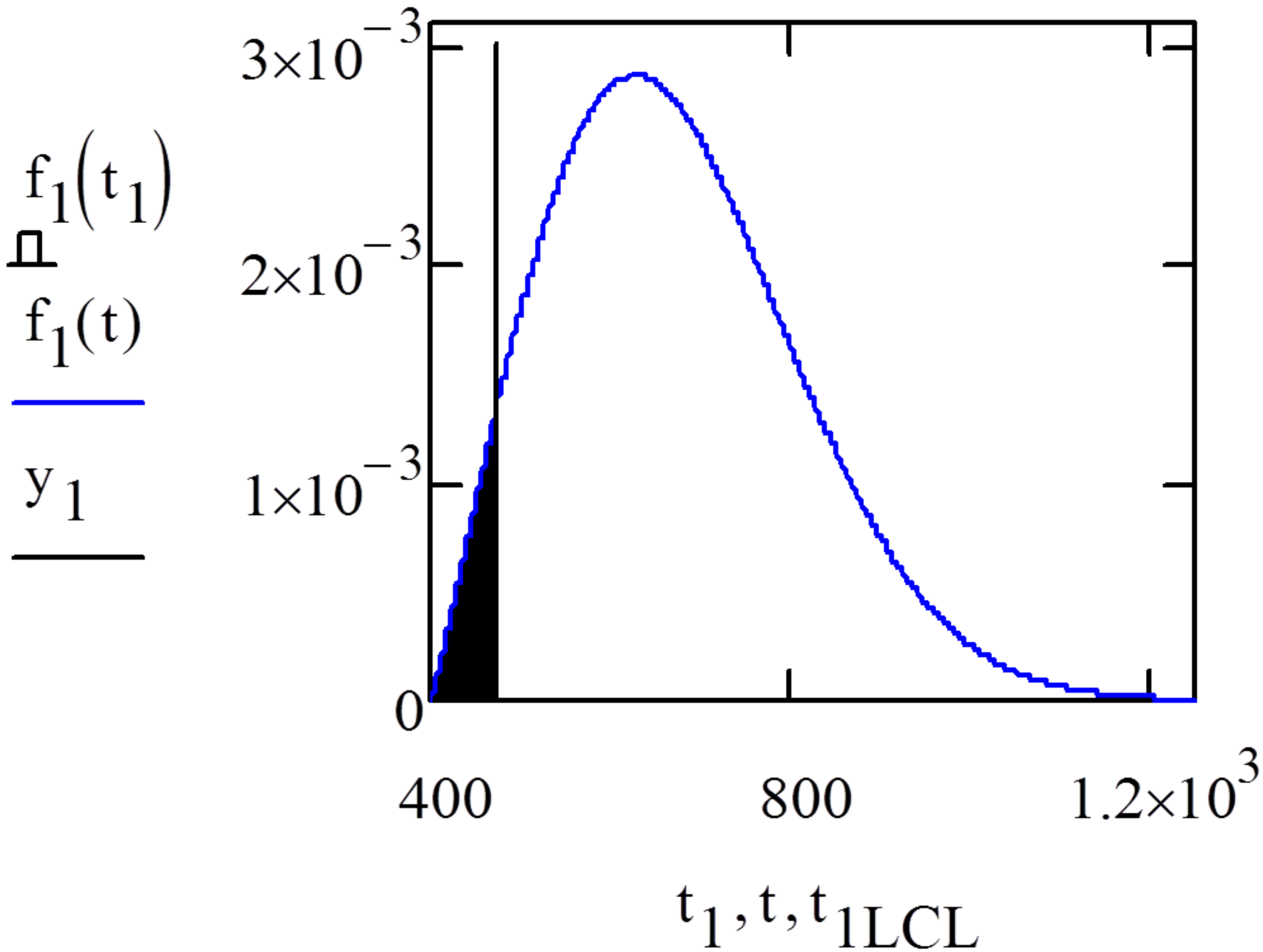
$$F_1(t_{1LCL}) = 0.050$$

$$S_1(t) := \begin{cases} 1 & \text{if } 0 \le t < \gamma_1 \\ e^{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1}} & \text{if } t \ge \gamma_1 \end{cases}$$

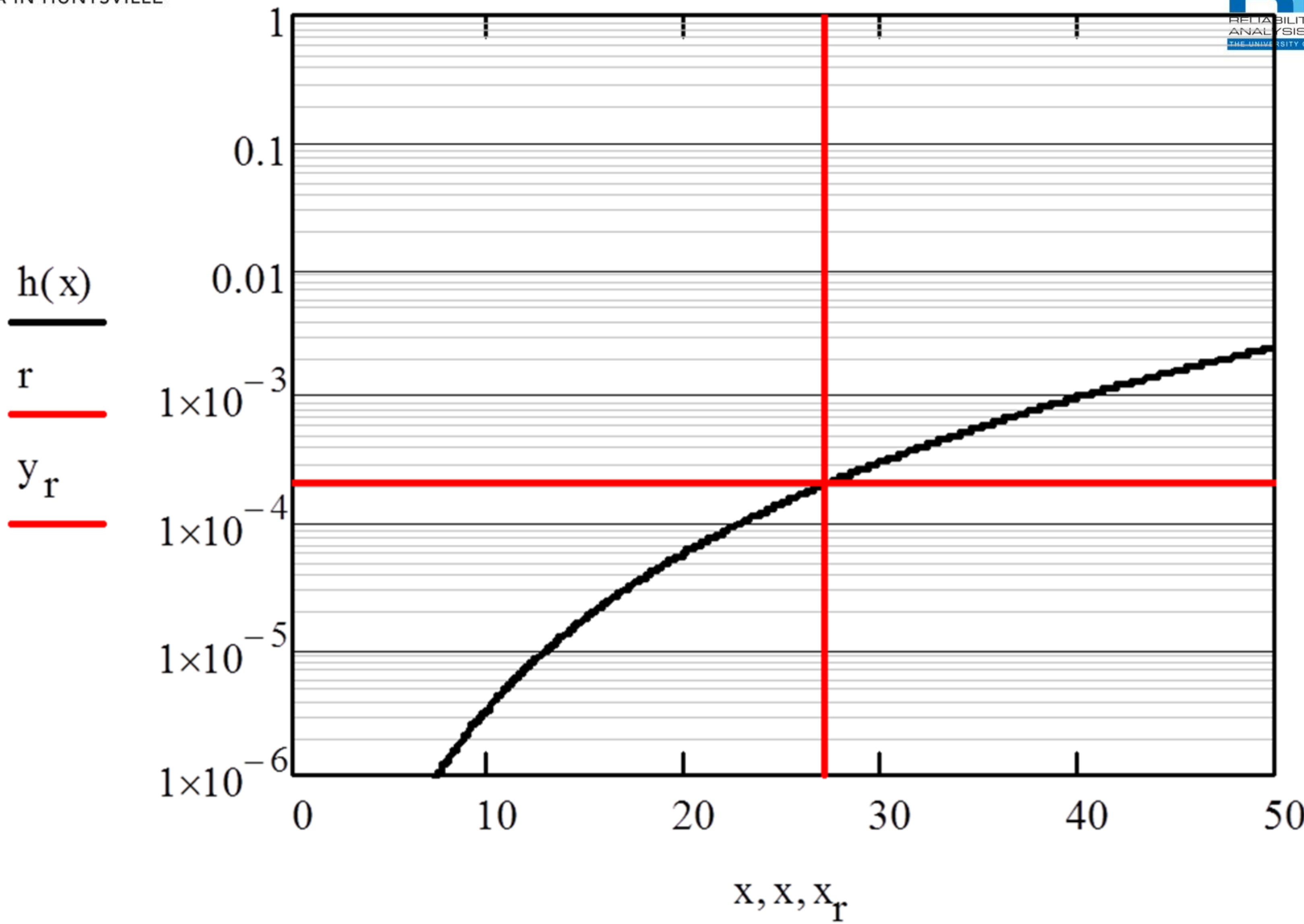
$$\theta_1 := \int_0^{\infty} S_1(t)\, dt$$

$$\theta_1 = 674.917$$

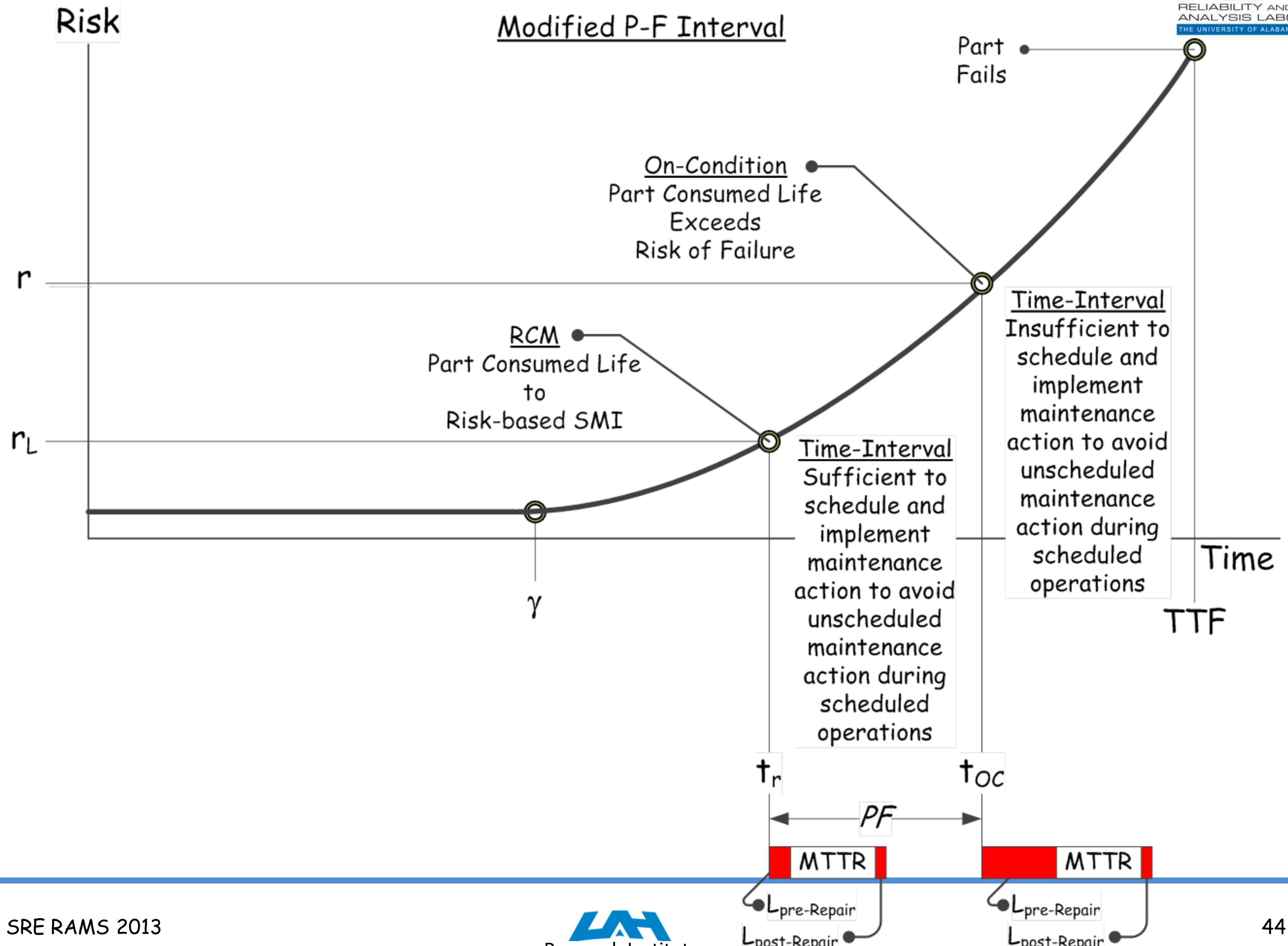
Failure Math Model pdf - f(t)



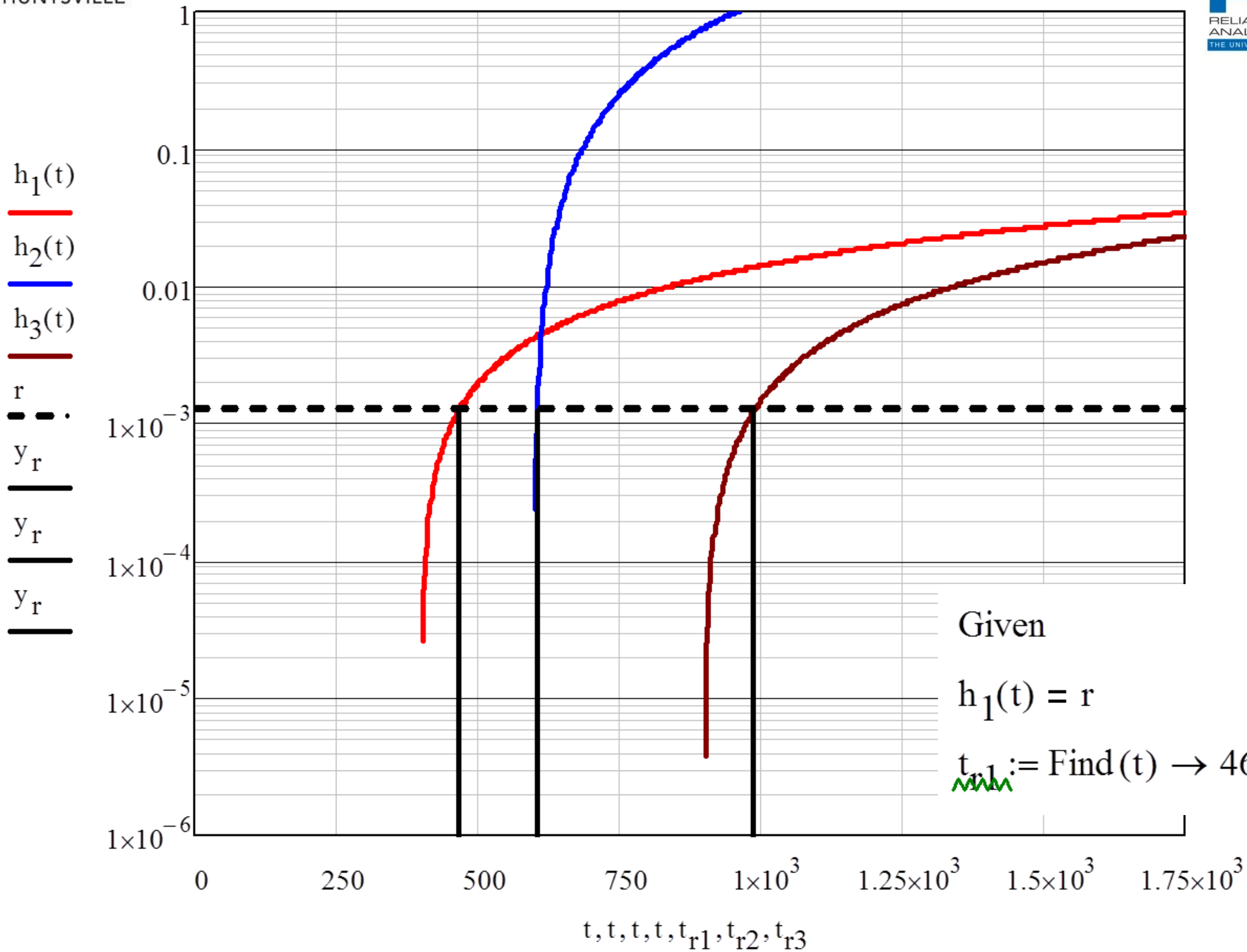
Risk Threshold & Hazard Function



Risk Threshold Logic



Part Alternatives Hazard Functions & Risk Threshold



Given

$h_1(t) = r$

$t_{r1} := \mathrm{Find}(t) \rightarrow 467.058$

Parts Alternatives Risk-based Scheduled Maintenance Interval, SMI

Risk Threshold		
	$r =$	0.00125
Part 1	$t_r =$	467
Part 2	$t_r =$	606
Part 3	$t_r =$	989

Exponential v Weibull Failure Math Models

TTF :=

	0
0	457
1	490
2	508
3	538
4	538
5	...

$\beta_1 := 2.103$

$\eta_1 := 310.4$

$\gamma_1 := 400$

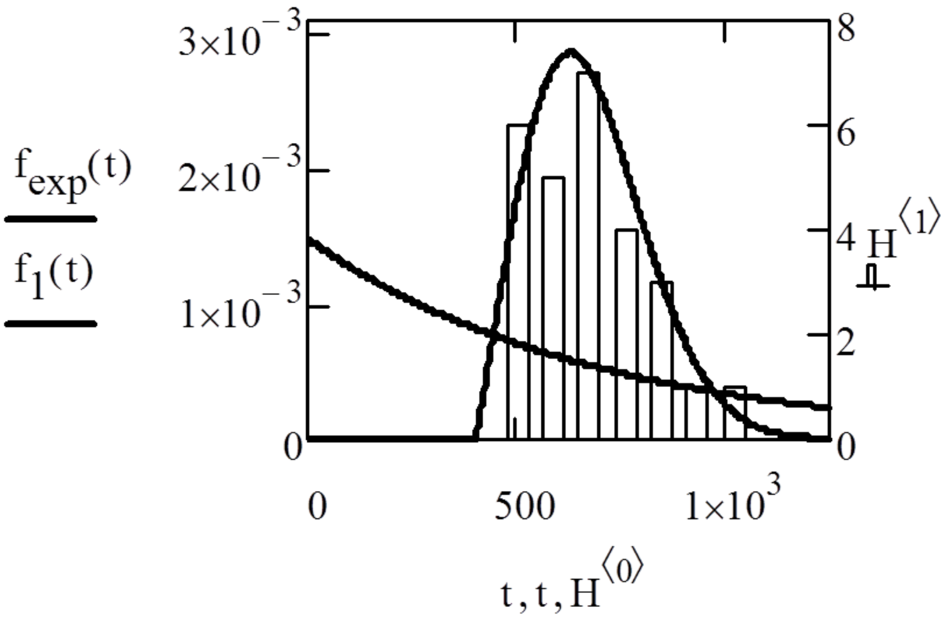
$$f_1(t) := \begin{cases} 0 & \text{if } 0 \le t < \gamma_1 \\ \left(\frac{\beta_1}{\eta_1}\right)\cdot\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1 - 1}\cdot e^{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1}} & \text{if } t \ge \gamma_1 \end{cases}$$

$$H = \begin{pmatrix} 500.357 & 6 \\ 587.071 & 5 \\ 673.786 & 7 \\ 760.5 & 4 \\ 847.214 & 3 \\ 933.929 & 1 \\ 1.021\times 10^3 & 1 \end{pmatrix}$$

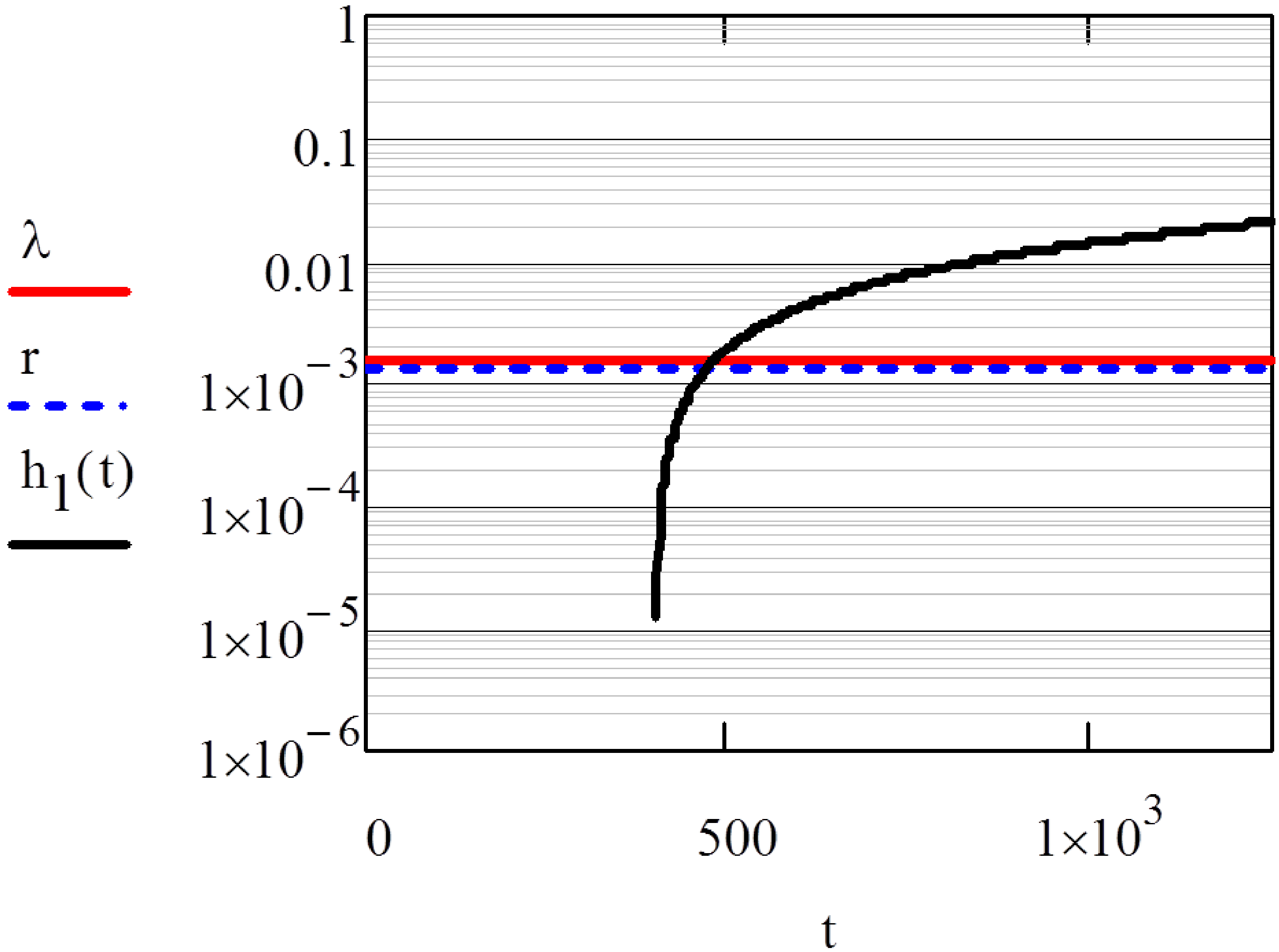
$\theta := \text{mean}(TTF) = 673.963$

$\lambda := \frac{1}{\theta} = 1.484\times 10^{-3}$

$f_{exp}(t) := \lambda\cdot e^{-\lambda\cdot t}$



Exponential v Weibull Hazard Function w/Risk Threshold



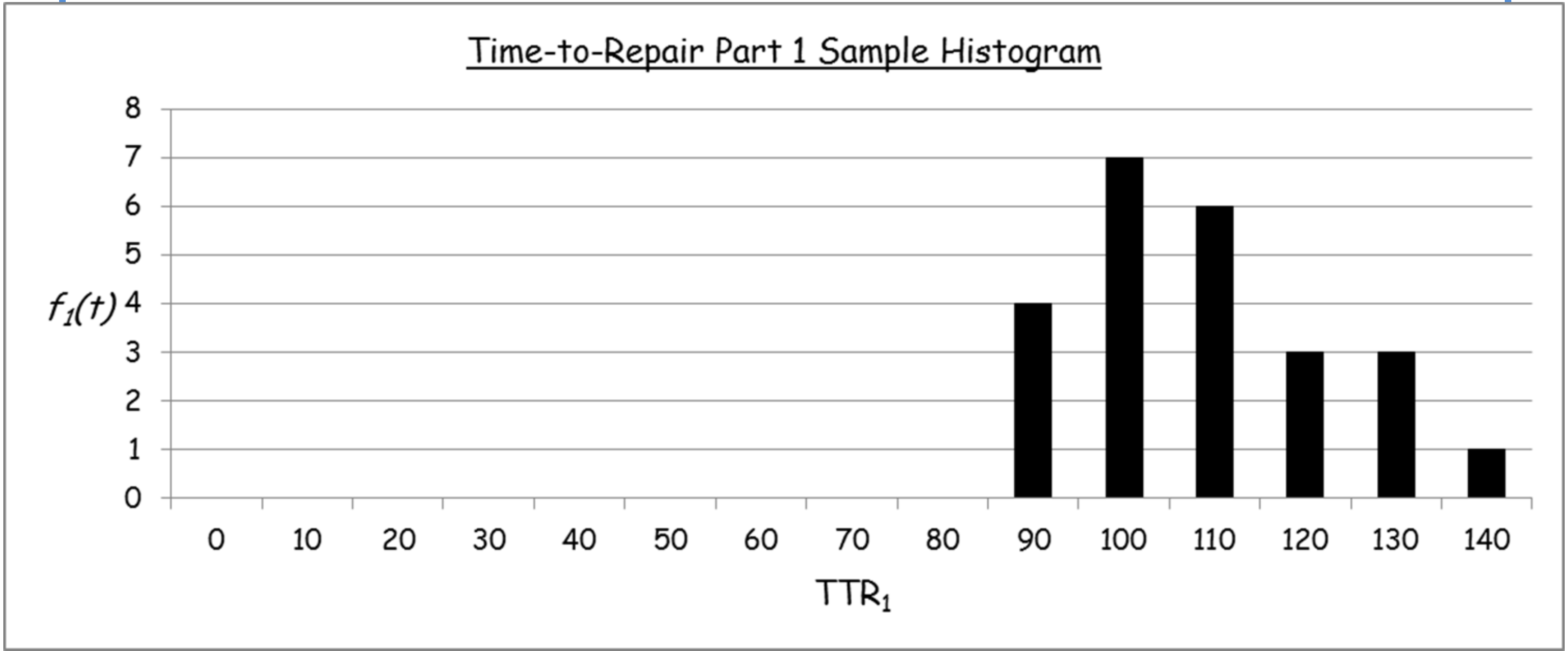
Time-to-Repair Data

Data - TTR_1		
132	108	95
126	105	89
97	87	128
88	98	115
85	105	92
114	96	98
107	110	91
106	116	129

Descriptive Statistics	
Mean	106.75
Standard Deviation	15.96
Kurtosis	-0.838
Skewness	0.476

TTR_1	$f_1(t)$
0	0
10	0
20	0
30	0
40	0
50	0
60	0
70	0
80	0
90	4
100	7
110	6
120	3
130	3
140	1
$\Sigma f_1(t) =$	24

Time-to-Repair Histogram



3-P Weibull Failure Math Model

$$f_{r1}(t) := \begin{cases} 0 & \text{if } 0 \le t < \gamma_1 \\ \left(\dfrac{\beta_1}{\eta_1}\right)\cdot\left(\dfrac{t-\gamma_1}{\eta_1}\right)^{\beta_1 - 1} \cdot e^{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1}} & \text{if } t \ge \gamma_1 \end{cases}$$

$$S_{r1}(t) := \begin{cases} 1 & \text{if } 0 \le t < \gamma_1 \\ e^{-\left(\frac{t-\gamma_1}{\eta_1}\right)^{\beta_1}} & \text{if } t \ge \gamma_1 \end{cases}$$

$$t_{r1UCL} := 2.282$$

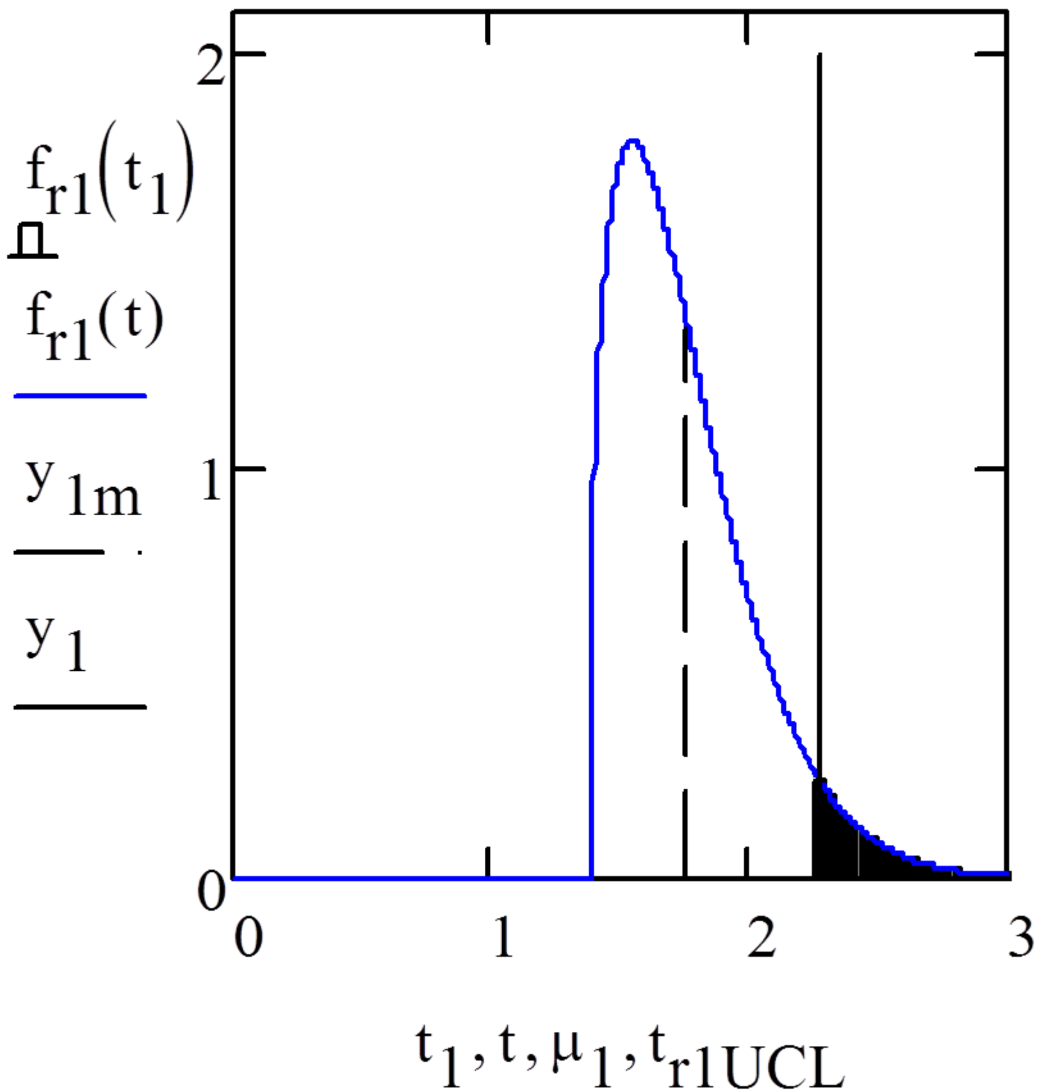
$$F_{r1}(t) := \int_0^t f_{r1}(t)\,dt$$

$$\mu_1 := \int_0^\infty S_{r1}(t)\,dt$$

$$F_{r1}\left(t_{r1UCL}\right) = 0.950$$

$$\mu_1 = 1.756$$

Repair Math Model



LDT Math Model - Baseline

pre-Repair Logistics Downtime				
	T_{min}	T_{mode}	T_{max}	T_{avg}
SME 1	2.50	2.75	2.75	2.67
SME 2	2.88	3.50	3.25	3.21
SME 3	5.13	5.00	5.25	5.13
T_{avg}	3.50	3.75	3.75	3.667

post-Repair Logistics Downtime				
	T_{min}	T_{mode}	T_{max}	T_{avg}
SME 1	0.50	0.75	1.00	0.75
SME 2	1.00	1.25	1.13	1.13
SME 3	1.50	1.25	1.75	1.50
T_{avg}	1.00	1.08	1.29	1.125

pre-Repair LDT Math Model

$TTR_{min} := 2.67$

$TTR_{mode} := 3.2$

$TTR_{max} := 5.125$

$$f(t) := \begin{cases} \dfrac{2\cdot(t - TTR_{min})}{(TTR_{max} - TTR_{min})\cdot(TTR_{mode} - TTR_{min})} & \text{if } TTR_{min} \le t \le TTR_{mode} \\ \dfrac{2\cdot(TTR_{max} - t)}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})} & \text{if } TTR_{mode} < t \le TTR_{max} \end{cases}$$

$$\theta := \frac{TTR_{min} + TTR_{mode} + TTR_{max}}{3}$$

$\theta = 3.665$

$$F(t) := \begin{cases} \dfrac{(t - TTR_{min})^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{mode} - TTR_{min})} & \text{if } TTR_{min} \le t \le TTR_{mode} \\ 1 - \dfrac{(TTR_{max} - t)^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})} & \text{if } TTR_{mode} < t \le TTR_{max} \end{cases}$$

$\alpha := 0.05$

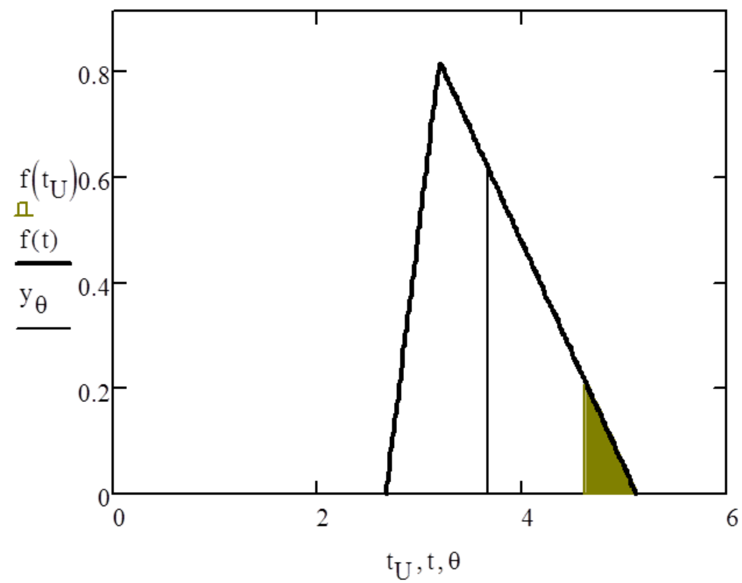
Given

$$1 - \alpha = 1 - \frac{(TTR_{max} - t)^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})}$$

$CL := \text{Find}(t) \rightarrow (4.63889944455905010765.611100555440949892)$

$UCL := 4.639$

$F(UCL) = 0.950$



Baseline

post-Repair LDT Math Model

$TTR_{min} := 0.75$

$TTR_{mode} := 1.125$

$TTR_{max} := 1.5$

$$f(t) := \begin{cases} \dfrac{2\cdot(t - TTR_{min})}{(TTR_{max} - TTR_{min})\cdot(TTR_{mode} - TTR_{min})} & \text{if } TTR_{min} \le t \le TTR_{mode} \\ \dfrac{2\cdot(TTR_{max} - t)}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})} & \text{if } TTR_{mode} < t \le TTR_{max} \end{cases}$$

$$\theta := \frac{TTR_{min} + TTR_{mode} + TTR_{max}}{3}$$

$\theta = 1.125$

$$F(t) := \begin{cases} \dfrac{(t - TTR_{min})^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{mode} - TTR_{min})} & \text{if } TTR_{min} \le t \le TTR_{mode} \\ 1 - \dfrac{(TTR_{max} - t)^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})} & \text{if } TTR_{mode} < t \le TTR_{max} \end{cases}$$

$\alpha := 0.05$

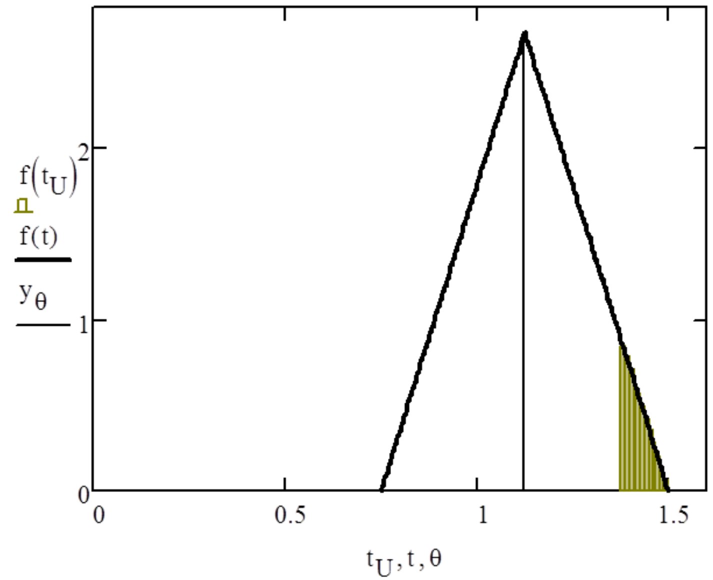
Given

$$1 - \alpha = 1 - \frac{(TTR_{max} - t)^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})}$$

$CL := Find(t) \rightarrow (1.3814145877436857751\ 1.6185854122563142249)$

$UCL := 1.381$

$F(UCL) = 0.950$



Baseline

pre-Repair LDT Math Model

$TTR_{min} := 0.5$

$TTR_{mode} := 0.67$

$TTR_{max} := 1$

$$\theta := \frac{TTR_{min} + TTR_{mode} + TTR_{max}}{3}$$

$\theta = 0.723$

$$f(t) := \begin{cases} \dfrac{2\cdot(t - TTR_{min})}{(TTR_{max} - TTR_{min})\cdot(TTR_{mode} - TTR_{min})} & \text{if } TTR_{min} \le t \le TTR_{mode} \\[2ex] \dfrac{2\cdot(TTR_{max} - t)}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})} & \text{if } TTR_{mode} < t \le TTR_{max} \end{cases}$$

$$F(t) := \begin{cases} \dfrac{(t - TTR_{min})^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{mode} - TTR_{min})} & \text{if } TTR_{min} \le t \le TTR_{mode} \\[2ex] 1 - \dfrac{(TTR_{max} - t)^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})} & \text{if } TTR_{mode} < t \le TTR_{max} \end{cases}$$

$\alpha := 0.05$

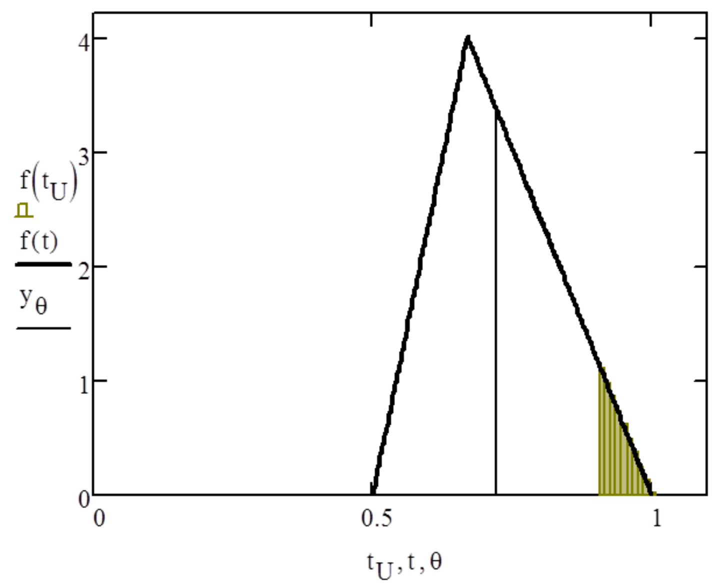
Given

$$1 - \alpha = 1 - \frac{(TTR_{max} - t)^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})}$$

$CL := Find(t) \rightarrow (1.0908295106229247 \;\; 0.909170489377075250$

$UCL := 0.90917$

$F(UCL) = 0.950$



Preventive Maintenance

post-Repair LDT Math Model

$TTR_{min} := 0.33$

$TTR_{mode} := 0.5$

$TTR_{max} := 1.1875$

$$f(t) := \begin{cases} \dfrac{2\cdot(t - TTR_{min})}{(TTR_{max} - TTR_{min})\cdot(TTR_{mode} - TTR_{min})} & \text{if } TTR_{min} \le t \le TTR_{mode} \\[2ex] \dfrac{2\cdot(TTR_{max} - t)}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})} & \text{if } TTR_{mode} < t \le TTR_{max} \end{cases}$$

$$\theta := \frac{TTR_{min} + TTR_{mode} + TTR_{max}}{3}$$

$\theta = 0.672$

$$F(t) := \begin{cases} \dfrac{(t - TTR_{min})^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{mode} - TTR_{min})} & \text{if } TTR_{min} \le t \le TTR_{mode} \\[2ex] 1 - \dfrac{(TTR_{max} - t)^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})} & \text{if } TTR_{mode} < t \le TTR_{max} \end{cases}$$

$\alpha := 0.05$

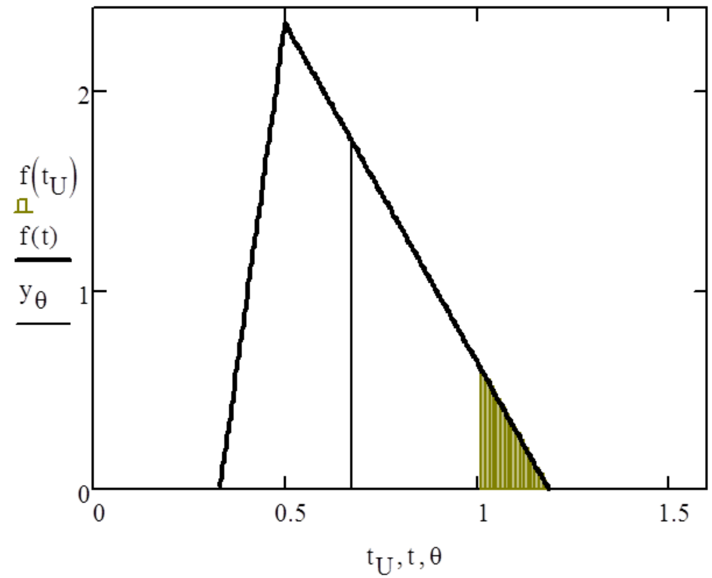
Given

$$1 - \alpha = 1 - \frac{(TTR_{max} - t)^2}{(TTR_{max} - TTR_{min})\cdot(TTR_{max} - TTR_{mode})}$$

$CL := \text{Find}(t) \rightarrow (1.01581260238444989471.3591873976155501053)$

$UCL := 1.0158$

$F(UCL) = 0.950$



Preventive Maintenance

Deterministic Reliability, Maintainability & Availability

Deterministic Reliability, Maintainability & Availability Parameters						
Part 1	MTBF, θ	MTTR, μ	Operational Availability, A_O			
			Baseline		w/PM	
			Mean	95% LCL_{LDT}	Mean	95% LCL_{LDT}
Mean	675	1.76	0.99039	0.98861	0.99535	0.99458
95% $CL_{\theta,\mu}$	476	2.28	0.98535	0.98284	0.99232	0.99123

Reliability Simulation Inputs

Empirical Parameters			
Weibull Model Fit			
Failure Model			
$\beta 1$	2.103		
$\eta 1$	310.4	-hr	
$\gamma 1$	400	-hr	
Repair Model			
β_1	1.398		
η_1	24.71	-min	
	0.412	-hr	
γ_1	83	-min	
	1.38	-hr	

Log Downtime	T_{min}	T_{mode}	T_{max}	T_{avg}
pre-Repair LDT	2.67	3.20	5.13	3.67
post-Repair LDT	0.75	1.13	1.50	1.13
95% UCL			ΣLDT =	4.79
pre-Repair LDT				4.64
post-Repair LDT				1.38
			$\Sigma LDT_{95\%}$ =	6.02

Log Downtime	T_{min}	T_{mode}	T_{max}	T_{avg}
pre-Repair LDT	0.50	0.67	1.00	0.72
post-Repair LDT	0.33	0.50	1.19	0.67
95% UCL			ΣLDT =	1.40
pre-Repair LDT				0.91
post-Repair LDT				1.02
			$\Sigma LDT_{95\%}$ =	1.92

Baseline Maintenance Labor Inputs

Baseline	pre-Repair Logistics Downtime			
Labor		Time-to-Repair		
Allocation			post-Repair Logistics Downtime	
Master	1	1	0	/hr
Journeyman	1	2	1	/hr
Helper	2	2	1	/hr
Labor Cost				/hr
Master	$115.76	$115.76	$0.00	/hr
Journeyman	$73.97	$147.94	$73.97	/hr
Helper	$82.15	$82.15	$41.08	/hr
Sum	$271.89	$345.86	$115.05	/hr

PM Maintenance Labor Inputs

PM	pre-Repair Logistics Downtime			
Labor		Time-to-Repair		
Allocation			post-Repair Logistics Downtime	
Master	0	1	0	/hr
Journeyman	0	2	1	/hr
Helper	2	2	0	/hr
Labor Cost				/hr
Master	$0.00	$115.76	$0.00	/hr
Journeyman	$0.00	$147.94	$73.97	/hr
Helper	$82.15	$82.15	$0.00	/hr
Sum	$82.15	$345.86	$73.97	/hr

Maintenance Costs Inputs

Spare Parts Expenses					EOQ	Acq	Emergency	
Part	N	tgr	Q	TAT	Cost	Cost	Cost	TAT
Part 1	1	0	1	96	$2,575	$2,575	$3,975	24

Lost Opportunity	$9,125	/hr
Fixed Costs	$1,375	/Event
Inv Carry Costs	$1.38	/hr

Direct Overhead	$r/hr
Specialty Tool	$4.01
Facility	$140.22

Part Life-Cycle Simulation Factors

Mission duration		
2 8-hr shifts per day		
for a 5-day week		
τ =	80	-hrs
for:	50	wks/yr

System Useful Life		
T_{Life} =	10	-yrs
T_{LC} =	40000	

		Ln()
$R_{Allocation}$ =	0.9885	-0.0116
α =	0.05	-2.9957

n =	258.998	=ln(a)/ln($R_{Allocation}$)

Baseline Reliability Simulation Report

Simulation Report for Part 1 Baseline

Results from 259 runs of sim time 40000-hrs

Part 1	Minimum	Mean	Maximum	St.Dev	95% CL	SEM	95% CL
Availability	0.98984	0.99051	0.99137	0.00030	0.99002	0.00002	0.99048
MTBF	628.51	683.68	734.35	19.74	651.09	1.23	681.65
MDT	6.32	6.54	6.80	0.08	6.68	0.005	6.55
MMT	1.67	1.76	1.88	0.03	1.81	0.002	1.76
LDT		4.79			4.86		4.79
System Failures	54	58.00	63	1.66		0.10	58.17

PM Reliability Simulation Report

Simulation Report for Part 1 - PM							
Results from 259 runs of sim time 40000-hrs							
Part 1	Minimum	Mean	Maximum	St.Dev	95% CL	SEM	95% CL
Availability	0.99305	0.99328	0.99342	0.00006	0.99318	0.000004	0.99328
MTBF	467.32	467.43	467.49	0.03	467.38	0.00	467.42
MDT	3.10	3.16	3.27	0.03	3.73	0.00	3.16
MMT	0.75	1.71	2.38	0.04	1.78	0.00	1.71
LDT	0.83	1.40	2.19		1.95		1.45
System Failures	85	85	85				

Reliability Simulation Summary

RAM Summary Information						
RAM	Deterministic		Baseline Simulation		PM Simulation	
Parameter	Mean	95% CL	Mean	95% CL	Mean	95% CL
MTBF	675	476	684	651	467	467
MTTR	1.76	2.28	1.76	1.81	1.71	1.78
MLDT	4.79	6.02	4.79	4.86	1.40	1.95
MDT	6.55	8.30	6.54	6.68	3.11	3.73

Labor, Materials, Overhead & Lost Opportunity Costs Table

Cost Summary Information							
Cost	Deterministic		Baseline Simulation		PM Simulation		
Parameter	Mean	95% CL	Mean	95% CL	Mean	95% CL	
C_{ICC}	-$33.12	-$33.12	-$33.12	-$33.12	-$33.12	-$33.12	/Day
C_{Part}	-$2,575	-$2,575	-$2,575	-$2,575	-$2,575	-$2,575	/Event
C_{Labor}	-$1,733	-$2,209	-$1,733	-$1,774	-$865	-$986	/Event
preRepLDT	$996	$1,261	$996	$1,018	$197	$251	
TTR	$607	$789	$608	$628	$591	$616	
postRepLDT	$129	$159	$129	$128	$77	$119	
C_{DOH}	-$253	-$329	-$253	-$262	-$247	-$257	/Event
C_{Fixed}	-$1,375	-$1,375	-$1,375	-$1,375	-$1,375	-$1,375	/Event
ΣC_{Event}	-$5,936	-$6,489	-$5,936	-$5,986	-$5,062	-$5,193	/Event
C_{LostOp}	-$59,732	-$75,756	-$59,708	-$60,916	-$28,339	-$34,082	/Event
$\Sigma C_{Event+LostOp}$	-$65,669	-$82,244	-$65,644	-$66,902	-$33,401	-$39,274	/Event

Engineering Economics Basics

$$NPV = \sum_{t=0}^{n} PV_{i,t}$$

$$PV_{i,t} = A_{i,t}\left[\frac{(1+i)^t - 1}{i(1+i)^t}\right]$$

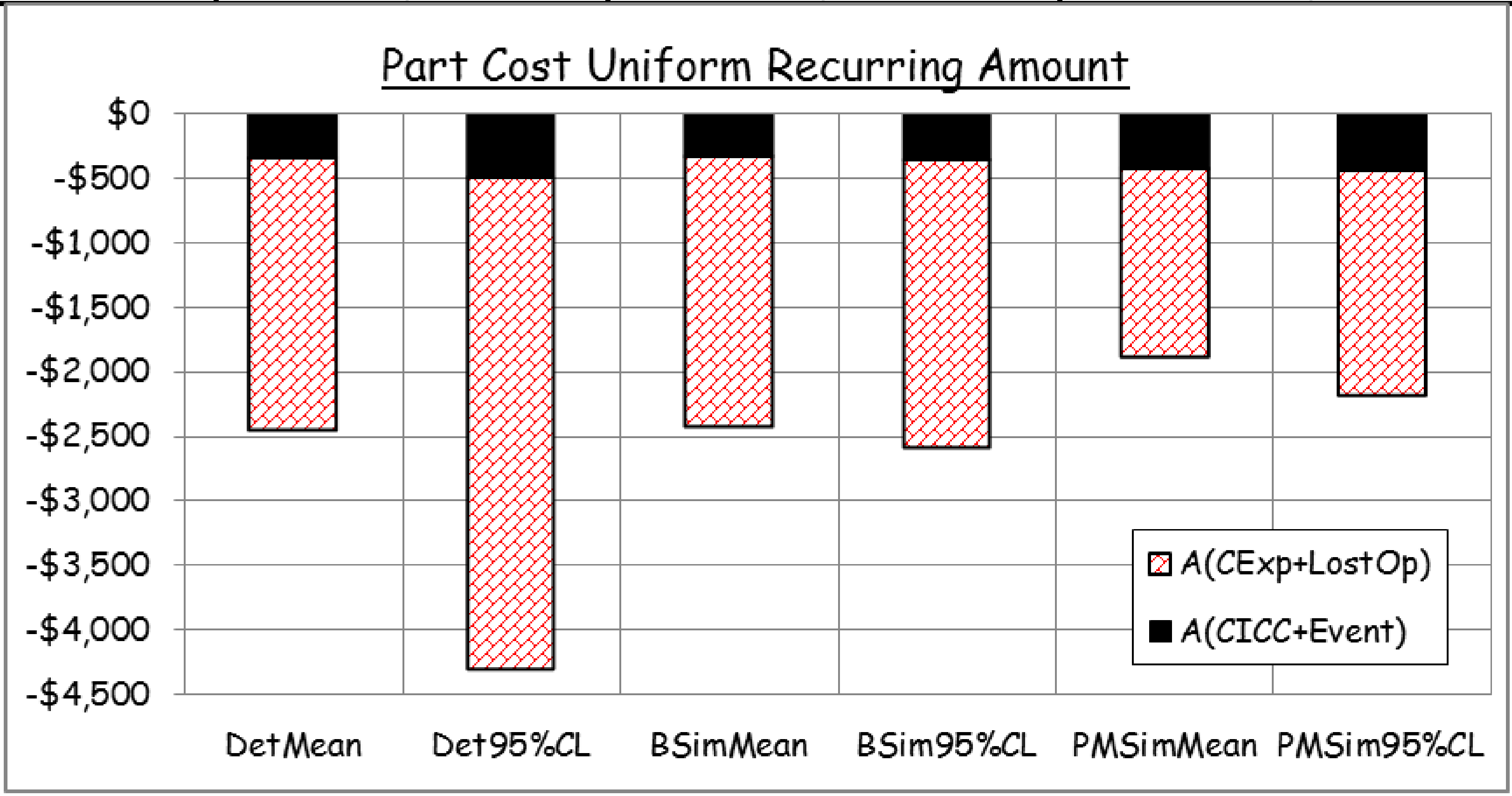
$$A_{eqv} = NPV\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$$

Economic Analysis Expensed Costs & Lost Opportunity Costs

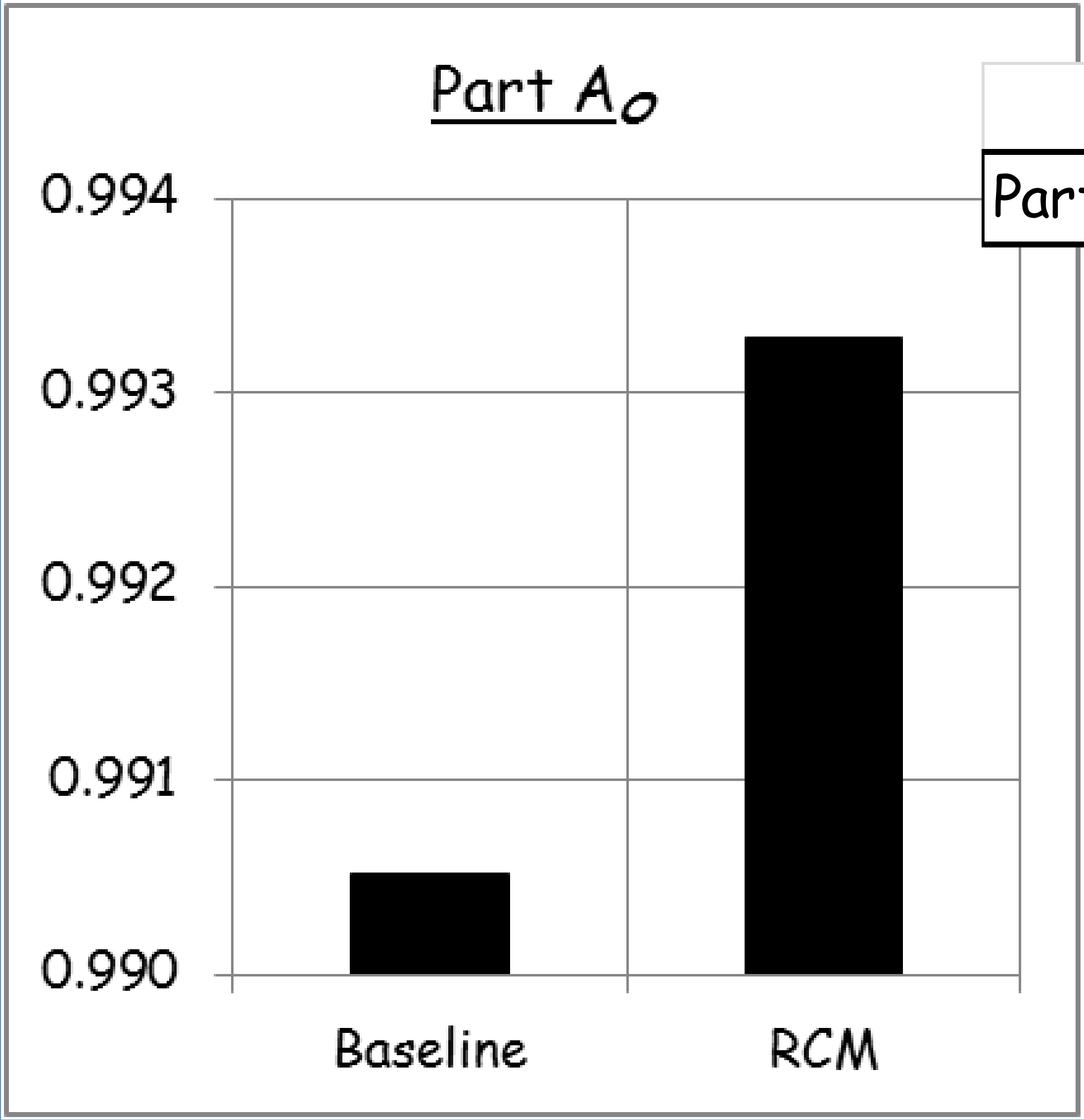
Economic Analysis						
Economic	Deterministic		Baseline Simulation		PM Simulation	
Parameters	Mean	95% CL	Mean	95% CL	Mean	95% CL
$PV(C_{ICC})$	-$928	-$655	-$940	-$896	-$644	-$644
$PV(C_{Event})$	-$8,475	-$9,035	-$8,474	-$8,525	-$7,615	-$7,745
$NPV(C_{ICC+Event})$	-$9,403	-$9,690	-$9,414	-$9,421	-$8,259	-$8,389
$A(C_{ICC+Event})$	-$335	-$490	-$332	-$348	-$425	-$432
$PV(C_{LostOp})$	-$59,360	-$75,423	-$59,331	-$60,549	-$28,217	-$33,934
$NPV(C_{Exp+LostOp})$	-$68,763	-$85,113	-$68,745	-$69,970	-$36,475	-$42,323
$A(C_{Exp+LostOp})$	-$2,453	-$4,306	-$2,421	-$2,587	-$1,877	-$2,178

Part Uniform Recurring Equivalent Cost

	Det_{Mean}	$Det_{95\%CL}$	$BSim_{Mean}$	$BSim_{95\%CL}$	$PMSim_{Mean}$	$PMSim_{95\%CL}$
$A(C_{ICC+Event})$	-$335	-$490	-$332	-$348	-$425	-$432
$A(C_{Exp+LostOp})$	-$2,118	-$3,816	-$2,090	-$2,239	-$1,452	-$1,747



Part Operational Availability



	Baseline	RCM
Part A_O	0.99051	0.99328

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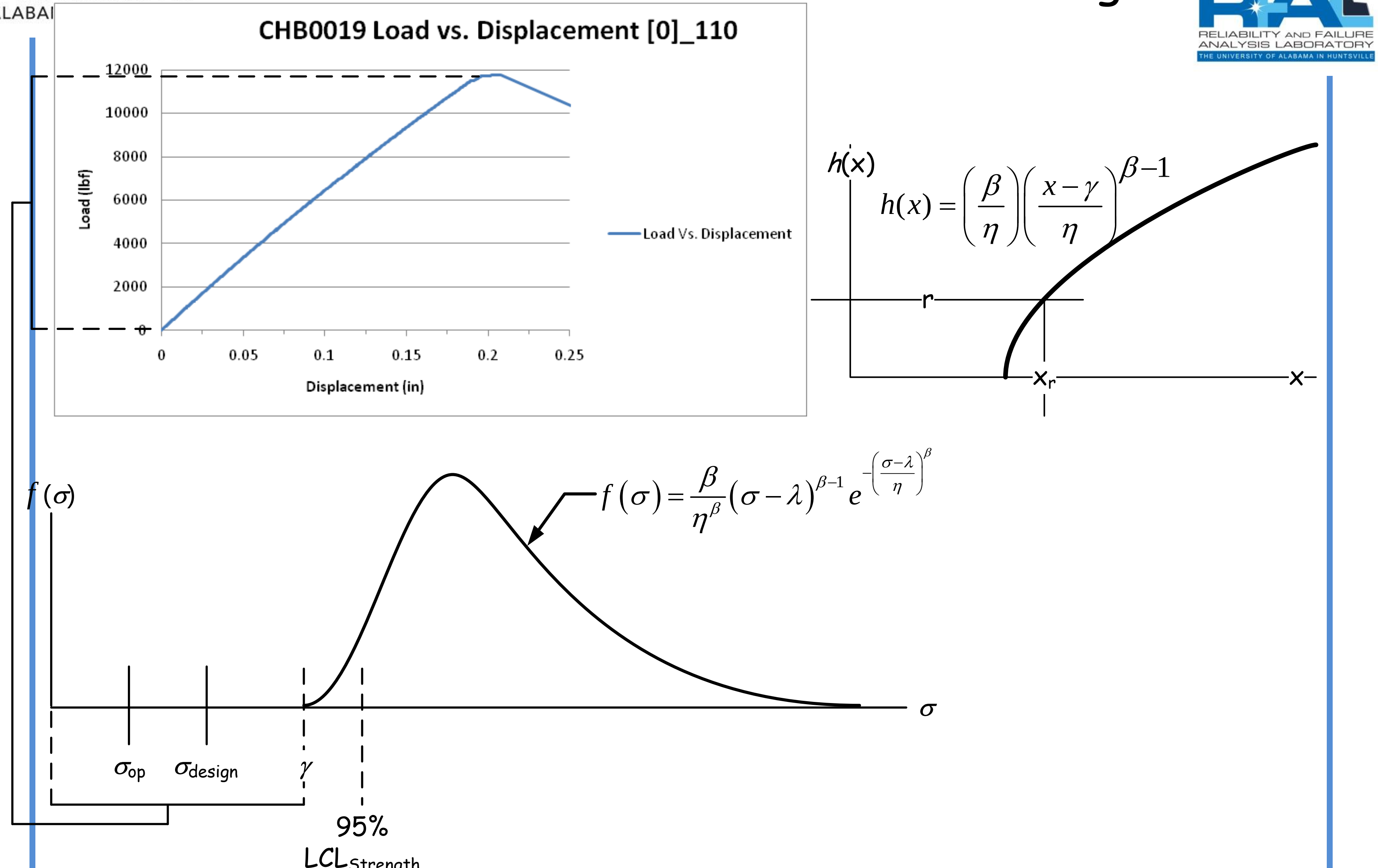
Stress-Directed Maintenance, SDM

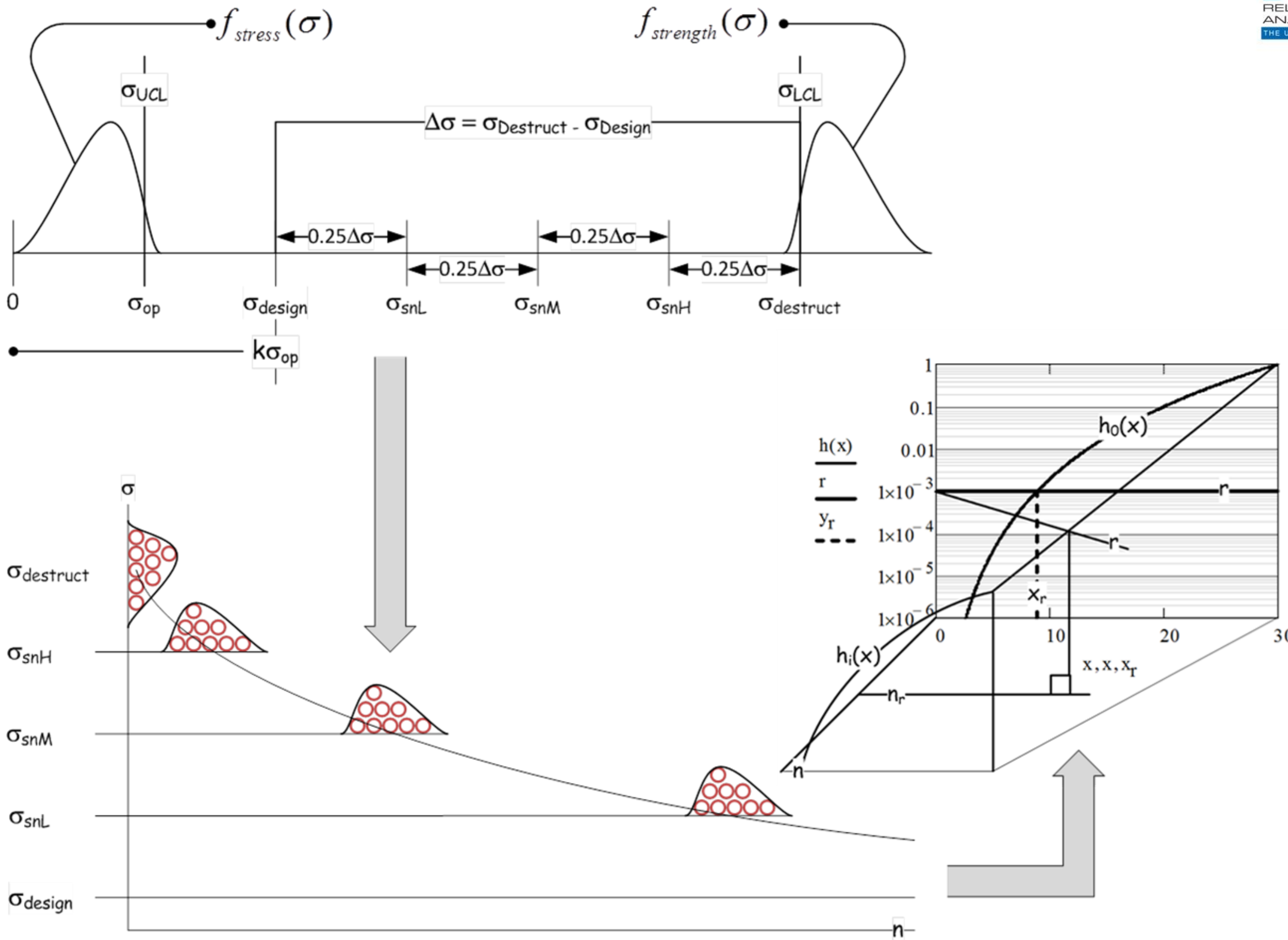
RELIABILITY AND FAILURE ANALYSIS LABORATORY
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

- Consumed life characterized by applied stress profile
- Measures failure mechanisms acting on part
- Not well developed for use by practioner

SDM - The Present - Static Loading



SDM - The Future - Wearout



Fatigue Analysis s-n Curve

Summary

- RCM yields definition of scheduled maintenance interval for critical parts
- RCM measures part consumed life constrined by a risk threshold
- RCM metrics:
  - CBM – Condition indicator
  - TDM – Time in service
  - SDM – Stress load profile