Reliability Engineering

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Omnex provides training, consulting and software solutions to the international market with offices in the USA, Canada, Mexico, China (PRC), Germany, India, the Middle East, and SE Asia. Omnex offers over 400 standard and customized training courses in business, quality, environmental, food safety, laboratory and health & safety management systems worldwide.

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Course Objectives

- Understand reliability engineering concepts and the need for tools
- Familiarize with key terms and metrics in Reliability Engineering
- How to plan a reliability analysis?
- Learn the method of Life Data Analysis

Agenda

- Course Overview and Introductions
- Chapter 1: Overview of Reliability Engineering
- Chapter 2: Life Data Analysis
- Chapter 3: Reliability Planning
- Chapter 4: Accelerated Life Testing
- Chapter 5: Types of Distributions
- Chapter 6: Data Censoring
- Chapter 7: Output Parameters

A BRIEF INTRODUCTION TO OMNEX

Omnex Introduction

- International consulting, training and software development organization founded in 1985.
- Specialties:
  - Integrated management system solutions.
  - Elevating the performance of client organizations.
  - Consulting and training services in:
    - Quality Management Systems, e.g. ISO 9001, ISO/TS 16949, AS9100, QOS
    - Environmental Management Systems, e.g. ISO 14001
    - Health and Safety Management Systems, e.g. OHSAS 18001
- Leader in Lean, Six Sigma and other breakthrough systems and performance enhancement.
  - Provider of Lean Six Sigma services to Automotive Industry via AIAG alliance.

About Omnex

- Headquartered in Ann Arbor, Michigan with offices in major global markets.
- In 1995-97 provided global roll out supplier training and development for Ford Motor Company.
- Trained more than 100,000 individuals in over 30 countries.
- Workforce of over 400 professionals, speaking over a dozen languages.
- Former Delegation Leader of the International Automotive Task Force (IATF) responsible for ISO/TS16949.
- Served on committees that wrote QOS, ISO 9001:2000, QS-9000 and its Semiconductor Supplement, and ISO IWA 1 (ISO 9000 for healthcare).
- Member of AIAG manual writing committees for FMEA, SPC, MSA, Sub-tier Supplier Development, Error Proofing, and Effective Problem Solving (EPS).

Omnex is headquartered and operates from the United States through offices in Michigan.

The company maintains international operations in many countries to provide comprehensive services to clients throughout Western Europe, Latin America and the Pacific Rim.

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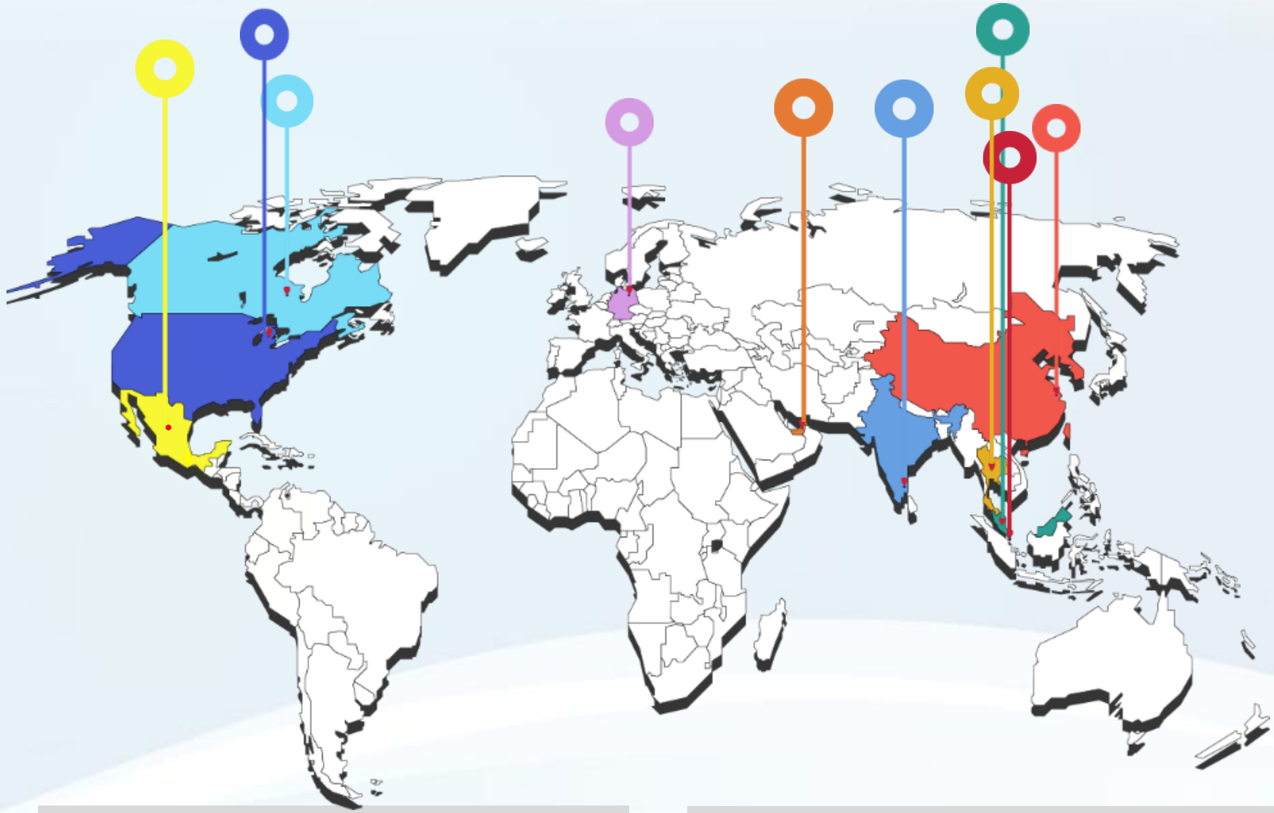

- **Omnex Global Head Quarters** (Michigan, USA)
  West Coast Operations (San Jose, CA)
- **Asia Pacific HQ** (Chennai, Pune, Delhi, Bangalore)
- **China (Shanghai, Guangzhou, Wuhan, Chengdu)**
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Rules of the Classroom

- ✓ Start and end on time
- ✓ Return from breaks and lunch on time
- ✓ All questions welcome
- ✓ Your input is valuable and is encouraged
- ✓ Don’t interrupt others
- ✓ One meeting at a time
- ✓ Listen – and respect others’ ideas
- ✓ No “buts” – keep an open mind
- ✓ Cell phones & pagers off or silent mode
- ✓ No e-mails, texting or tweeting during class
- ✓ If you must take a phone call or answer a text please leave the room for as short a period as possible

Icebreaker

- Instructor Information:
  - Name
  - Background
- Student Introductions:
  - Name
  - Position / Responsibilities
  - What is your involvement in the new product development process?
  - What are your experiences with Team Problem Solving / 8D?
  - Please share something unique and/or interesting about yourself.

Chapter 1

Overview of Reliability Engineering

Chapter 1: Overview – What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to describe:

- What is Reliability?
- Basic terms in Reliability engineering
- Key measures

Chapter Agenda

- 8 Dimensions of Product Quality
- What is Reliability?
- Why Reliability?
- When to use?
- Reliability vs Durability
- Key elements and measures

8D of Product Quality Management

What is Reliability?

- Generally defined as the ability of a product to perform, as
- expected, over certain time.
- Formally defined as the probability that an item, a product, piece of equipment, or system will perform its intended function for a stated period of time under specified operating conditions.
- In the simplest sense, reliability means how long an item (such as a machine) will perform its intended function without a breakdown.

Reliability is performance over time, probability that something will work when you want it to.

WHY RELIABILITY ENGINEERING?

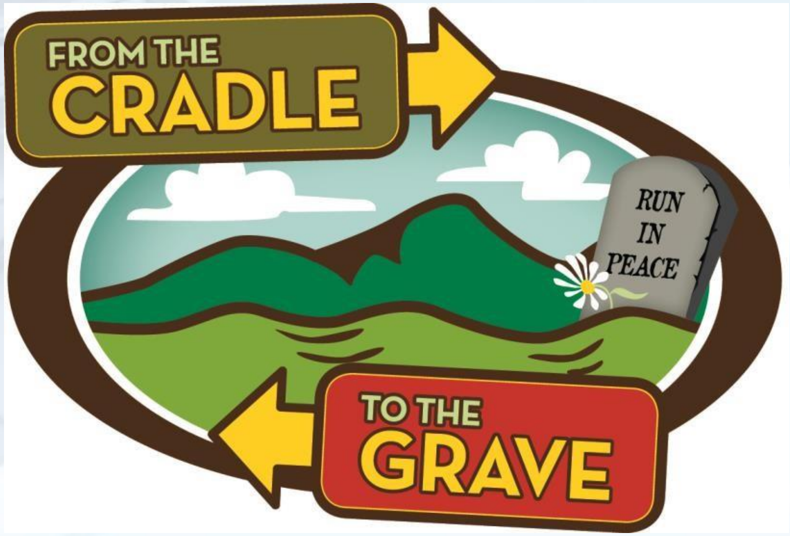
- Reliability, Availability, Maintainability, Safety and Quality are what the Customer says they are, not what the Engineers or the Designers say they are.
- Companies who control the Reliability of their products can only survive in the business in future as today's consumer is more “intelligent” and product aware.
- Liability for unreliable products can be very high.
- Complexity of products is ever increasing and thus challenge to Reliability Engineering is also increasing.
- Products are being advertised by their Reliability Ratings.

“PRIDE = Put Reliability In Daily Efforts”

When Should Reliability Be Applied?

"From the cradle to the grave."

i.e. The entire life cycle of the product.



Reliability (vs) Durability

- Reliability is the **likelihood** that a product will not fail within a specific time period.
- This is a key element for users who need the product to work without fail.

- Durability measures the **length** of a product's life. When the product can be repaired, estimating durability is more complicated.
- The item will be used until it is no longer economical to operate it. This happens when the repair rate and the associated costs increase significantly.

Key elements of Reliability

Probability (A value between 0 and 1, number of times that an event occurs (success) divided by total number trials)

- e.g. probability of 0.91 means that 91 of 100 items will still be working at state time under stated conditions

Performance (Some criteria to define when and how product fails, which also describes what is considered to be satisfactory system operation)

- e.g. amount of beam collisions, etc

Time (system working until time (t), used to predict probability of an item surviving without failure for a designated period of time)

Operating conditions

- These describe the operating conditions (environmental factors, humidity, vibration, shock, temperature cycle, operational profile, etc.) that correspond to the stated product life.

Basic Reliability Terms

- **Reliability**- The ability of an item to perform a required function under stated conditions for a stated period of time. It is usually denoted as probability or as a success

- **Failure** –The termination of ability of an item to perform a required function.

- **Observed Failure Rate** –For a stated period in life of an item, the ratio of the total number of failures in a sample to the cumulative of the time on that sample. The observed failure rate is associated with particular and stated time intervals(or summation of intervals) in the life of the item and under stated conditions.

Basic Reliability Terms

- **Observed Mean Time Between Failures (MTBF)** – For stated period in the life of an item, the mean value of the length of time between consecutive failures computed as the ratio of the cumulative observed time to the number failures under stated conditions.

- **Observed mean time to failure (MTTF) -** For a stated period in the life of an item, the ratio of the cumulative time for a sample to the total number of failure in the sample during the period under stated condition

B10 life

- The B10 life metric originated in the ball and roller bearing industry, but has become a metric used across a variety of industries today.
- It's particularly useful in establishing warranty periods for a product.
- The "BX" or "Bearing Life" nomenclature, which refers to the time at which X% of items in a population will fail, speaks to these roots.
- So then, B10 life is the time at which 10% of units in a population will fail. Alternatively, you can think of it as the 90% reliability of a population at a specific point in its lifetime—or the point in time when an item has a 90% probability of survival.

Basic Reliability Metrics

Name	Definition
Guarantee	An assurance given by the manufacturer to the vendor that the product will work without failure for a stated period of time
Warranty	A written guarantee given to the purchaser of a new appliance, automobile, or other item by the manufacturer or dealer, usually specifying that the manufacturer will make any repairs or replace defective parts free of charge for a stated period of time.
Maintainability	The measure of the ability of an item to be retained in or retained in or restored to a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources Applies to a major tasks where many repetitions are expected and where considerable time isrequired
Availability	A tool for measuring the percent of time an item or system is in a state of readiness where it is operable and can be committed to use when called upon. Availability ceases because of a downing event that causes the item/to system become unavailable to initiate a mission when called upon Availability=MTBF/(MTBF+MTTR)
Reliability	The ability of an item to perform a required function under stated conditions for a stated period of time. It is usually denoted as probability or as a success .

Failure Rate

- As Reliability Engineering is concerned with analyzing failures and providing feedback to design and production to prevent future failures, it is only natural that a rigorous classification of failure types must be agreed upon.

- Reliability engineers usually speak of:

Failures Causes

Failure Modes

Failure Mechanisms

*A **failure** is an event at which the system stops to fulfill its specified function.*

- ***Reliability measurement*** is based on the failure rate

$$\text{Failure rate} = \frac{\text{Items Failed}}{\text{Total Operating Time}}$$

- Some products (Non-repairable) are scrapped when they fail e.g. bulb
- Other products (Repairable) are repaired e.g. washing machine.

How Do Products Really Fail?

- ***DESIGNED TO FAIL***
- ***MANUFACTURED TO FAIL***
- ***ASSEMBLED TO FAIL***
- ***SCREENED TO FAIL***
- ***STORED TO FAIL***
- ***TRANSPORTED TO FAIL***
- ***OPERATED TO FAIL***

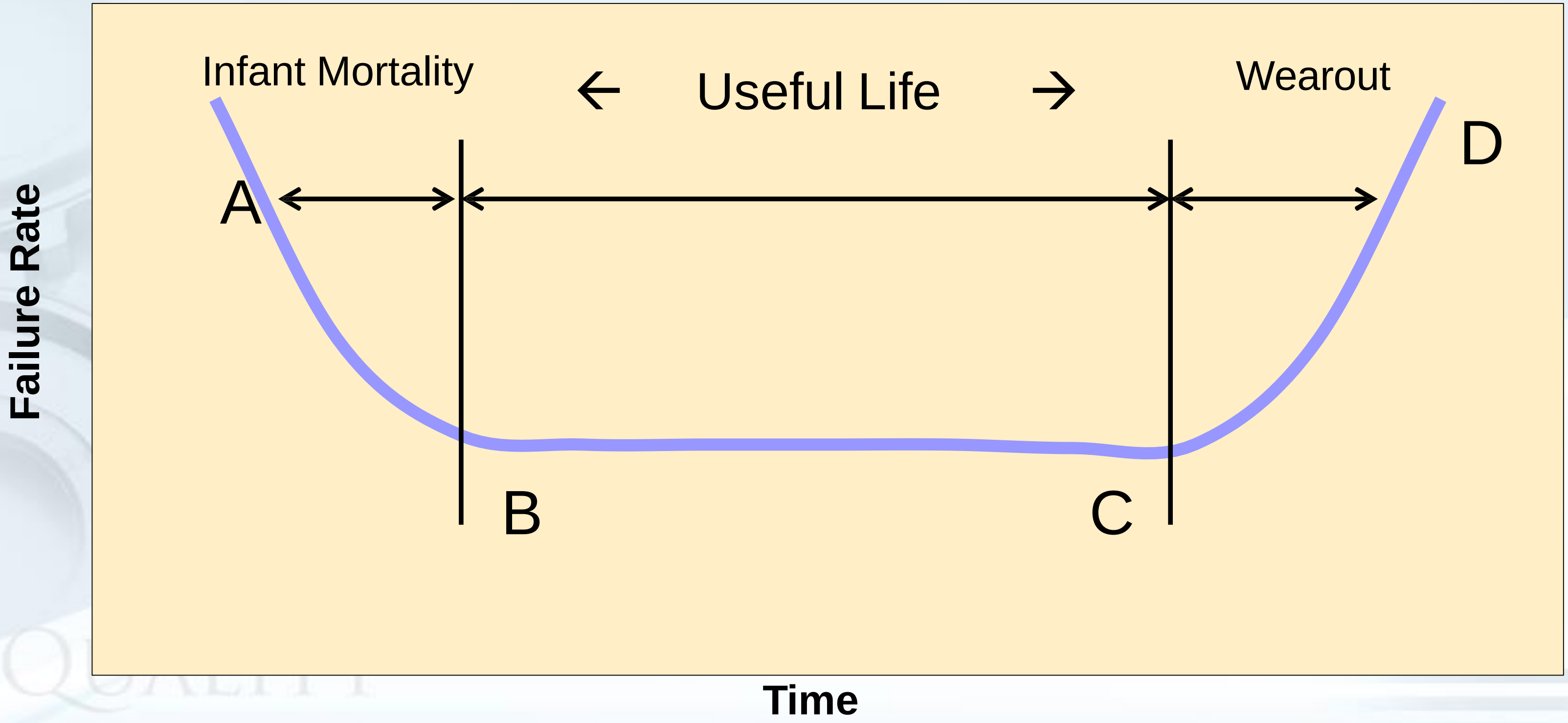
Two common types of failures:

1. Sudden failure (no indicators): Stress exceeds strength ….
2. Degradation (gradual wear out): degradation indicator such as crack growth, change of resistance, corrosion, … This is ideal for Condition-Based Maintenance

Other failures may occur because of human errors.

Failure rate over the life of a product

*The failure rate is expected to vary over the life of a product – **'Bathtub Curve'***



Bathtub Curve

A-B Early Failure / Infant mortality / Debugging / Break-in

- ‘Teething’ problems. Caused by design/material flaws

Eg: Joints, Welds, Contamination, Misuse, Misassembly

B-C Constant Failure / Useful life.

- Lower than initial failure rate and more or less constant until end of life

C-D End of life failure / Wear out phase.

- Failure rate rises again due to components reaching end of life

Eg: Corrosion, Cracking, Wear, Friction, Fatigue, Erosion, Lack of PM

Bathtub Curve: Summary Table

Phase	Failure Rate	Possible Causes	Possible improvement actions.
Burn-in (A-B)	Decreasing (DFR)	Manufacturing defects, welding, soldering, assembly errors, part defects, poor QC, poor workmanship, etc	Better QC, Acceptance testing, Burn-in testing, screening, Highly Accelerated Stress Screening, etc.
Useful Life (B-C)	Constant (CFR)	Environment, random loads, Human errors, chance events, 'Acts of God', etc	Excess Strength, redundancy, robust design, etc
Wear-out (C-D)	Increasing (IFR)	Fatigue, Corrosion, Aging, Friction, etc.	Derating, preventive maintenance, parts replacement, better material, improved designs, technology, etc.

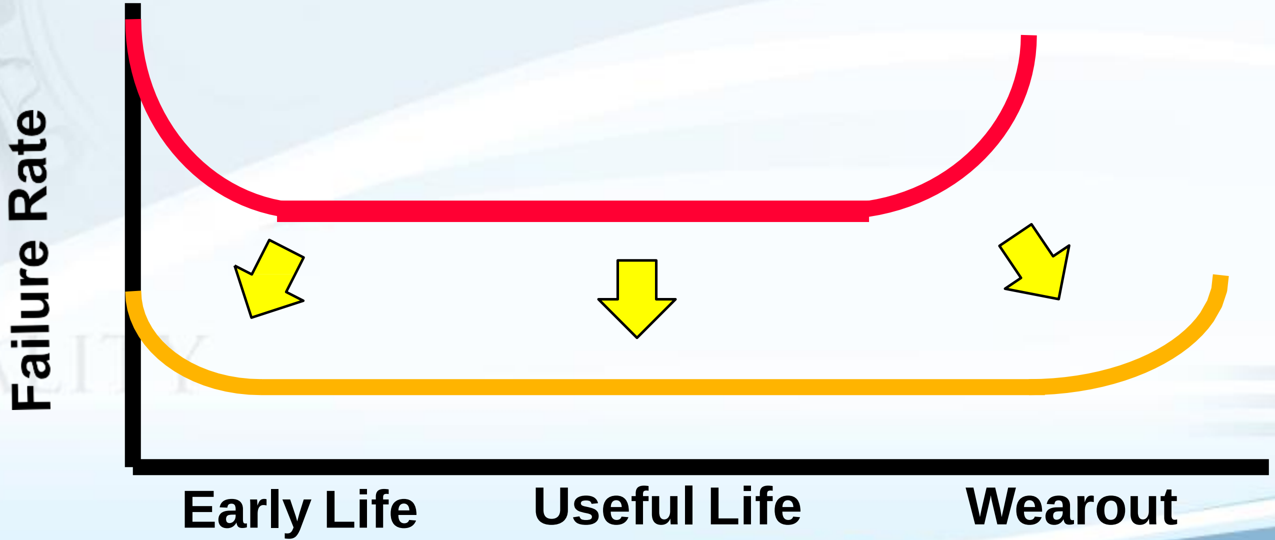
Managing Reliability

Reliability management is concerned with performance and conformance over the **expected life** of the product

A systems approach to planning for, designing in, verifying, and tracking the reliability of products throughout their life to achieve reliability goals.

- Reliability of a system is often specified by the failure rate λ. ƒ
- λ = failures per time unit (in a collection of systems)
- *For most technical products (incl. embedded systems), λ(t) is a "bath-tub curve":*

"Bathtub Curve"



Chapter 2

Measures of Reliability

Chapter 2: Measures of Reliability
What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to describe:

- Types of Measures used in RE
- How to calculate the measures in real time?

Chapter Agenda

- Reliability Measures
- Failure rate calculations
- Important analytical functions

Reliability Measures

Non-Repairable Systems:
Reliability=Availability
Failure Rate
MTTF
Time to First Failure
MRL (Mean Residual or remaining Life)

Repairable Systems:
Availability …. (Function of Reliability and Maintainability)
Failure Rate and Repair Rate
MTBF
MRL (Economic Justification)

Failure Rate for Repairable systems

MTBF θ = *Total time / Total Number of failures*

Average Failure Rate $\lambda = 1/\theta \rightarrow \lambda\theta = 1$

Example:

300 cars have accumulated 45000 hours, 10 failures are observed. What is the MTBF? What is the failure rate?

Note: *considering Car as repairable system, Use*

MTBF = 45000/10 = 4500 hours.

Average Failure rate = 10/45000 = 0.00022 per hour.

Failure rate for Non-repairable systems

Five oil pumps were tested with failure hours of 45, 33, 62, 94 and 105. What is the MTTF and failure rate?

Note: considering pumps as non repairable systems, Use MTTF.

MTTF = (45+33+62+94+105) / 5 = 67.8 hours

- Failure rate = 5 / (45+33+62+94+105) = 0.0147 per hour.
- *Note that MTTF is a reciprocal of failure rate.*

Example:

50 components are tested for two weeks. 20 of them fail in this time, with an average failure time of 1.2 weeks.

What is the mean time till failure assuming a constant failure rate?

Answer:

No. Of failures = 20

Total time = 20*1.2 + 30*2 = 84 weeks

Failure rate = 20/84 = 0.238/week

Mean time till failure is estimated to be = (1/failure rate)

= 1/0.238 = 4.2 weeks.

Exercise

10 components were tested. The components (not repairable) failed as follows:

Component 1,2,3,4,5 failed after 75,125, 130, 325, 525 hours.

Find the failure rate and mean time till failure..

Calculating failure rate from historical information

– We can take in use, known historical information from records at site to estimate the failure rates of various components.

– For example, if you had 5 hydraulic pumps in standby mode and each ran for 2000 hours in standby and 3 failed during the standby time

The failure rate during standby mode is:

Total standby hours = 5(2000 hours) = 10000 hours
Failure rate in standby mode = 3 / 10,000
= 0.0003 failures per hour

Important Analytical Functions In Reliability Engineering

1. ***FAILURE PROBABILITY DENSITY FUNCTION***
2. ***FAILURE RATE FUNCTION***
3. ***RELIABILITY FUNCTION***
4. ***CONDITIONAL RELIABILITY FUNCTION***
5. ***MEAN LIFE FUNCTION***

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Reliability function and failure rate

For a pdf $f(x)$ for the time till failure, define:

Reliability function

Probability of surviving at least till age t, i.e., that failure time is later than t

$$R(t) = P(T > t) = \int_t^{\infty} f(t)dt = 1 - \int_0^t f(t)dt = 1 - F(t)$$

$F(t) = \int_0^t f(t)dt$ is the cumulative distribution function.

Failure rate

This is failure rate at time t given that it survived until time t: $\phi(t) = \dfrac{f(t)}{R(t)}$

Relationship between failure density and reliability

$$f(t) = -\frac{d}{dt} R(t)$$

Relationship Between h(t), f(t), F(t) and R(t), $h(t) = \frac{f(t)}{R(t)} = \frac{f(t)}{1 - F(t)}$

Remark: The failure rate h(t) is a measure of proneness to failure as a function of age, t.

Relationship Between MTBF/MTTF and Reliability

$$MTBF = MTTF = \int_0^{\infty} R(t)\,dt$$

Example

Trial data shows that 105 items failed during a test with a total operating time of 1 million hours. (For all items i.e. both failed and passed). Also, find the reliability of the product after 1000 hours i.e. *(t)* =1000

The failure rate (fph) $\lambda = \frac{105}{1000000} = 1.05x10^{-4} per\, hour$

Reliability at 1000 hours $= e^{-\lambda t}$

R(1000) $= e^{-(1.05x10^{4}\; x1000)}$ = 0.9

Therefore the item has a **90%** chance of surviving for 1000 hours

Example

The chart below shows operating time and breakdown time of a machine.

20.2	2.5	6.1	7.1	24.4	4.2	35.3	1.8	46.7

Operating time (blue) — Down time (orange)

a) Determine the MTBF.

Solution:

Total operating time = 20.2 + 6.1 + 24.4 + 4.2 + 35.3 + 46.7

= 136.9 hours

Contd..

- $\lambda = 4 / 136.9 = 0.02922$

- Therefore;
- θ = MTBF = $1/\lambda$ = 34.22 hours

- b) What is the system reliability for a mission *time of 20 hours?*

$$R = e^{-\lambda t} \quad t = 20 \text{ hours}$$

$$R = e^{-(0.02922)(20)}$$

R = 55.74%

Example relating MTTF,MTBF & MTTR

- As above, plant runs for 500 hours, has 200 hours downtime due to 5 failures.
  - MTTF = 500/5 = 100 hours
  - MTBF = (500+200)/5 = 140 hours
  - MTTR= 200/5= 40 hours

- Therefore MTBF = MTTF + MTTR

Data collection method

MTBF and MTTR Calculator

Month	February, 2009
Name of Machine	M_3
Operation availability (min/mo)	24,960

Frequence	11

MTBF (min)	2,095
MTTR (min)	175

No.	Date	Time Start	Time Finish	Down (min)	Replacement
1	01-Feb	10:00 AM	12:00 PM	120	Parts 56
2	03-Feb	10:00 AM	12:00 PM	120	Parts 98
3	04-Feb	10:00 AM	12:00 PM	120	Parts 33
4	05-Feb	10:00 AM	12:00 PM	120	Parts 11
5	06-Feb	10:00 AM	12:00 PM	120	Parts 12
6	07-Feb	10:00 AM	12:00 PM	120	Parts 98
7	15-Feb	6:00 AM	6:00 PM	720	Parts 09
8	22-Feb	2:00 PM	6:00 PM	240	Parts 12
9	25-Feb	10:30 AM	12:00 PM	90	Parts 98
10	25-Feb	3:30 PM	4:30 PM	60	Parts 09
11	26-Feb	10:30 AM	12:00 PM	90	Parts 12

Metrics for Reliability & Maintainability

Reliability	Maintainability
Time to Failure (pdf) f(t)	**Time to Repair (pdf)** g(t)
Reliability $R(t) = \int_t^{\infty} f(t)dt$	**Maintainability** $M(t) = \int_0^t g(t)dt$
Failure Rate $\lambda(t) = \frac{f(t)}{R(t)}$	**Repair Rate** $\mu(t) = \frac{g(t)}{1 - M(t)}$
Mean Time To Failure $MTTF = \int_{-\infty}^{\infty} f(t)dt$ $MTTF = \int_0^{\infty} R(t)dt$	**Mean Time To Repair** $MTTF = \int_{-\infty}^{\infty} g(t)dt$
Pdf of time to failure $f(t) = \lambda(t)R(t)$ $f(t) = \lambda(t)e^{-\int_0^t \lambda(t)dt}$	**Pdf of time to repair** $g(t) = \mu(t)(1 - M(t))$ $g(t) = \mu(t)e^{-\int_0^t \mu(t)dt}$

Repairs per Hour (RPH)

- The failure rate function (fph) in reliability corresponds the repair rate (rph) function in maintainability.
- Repair rate is the rate with which a repair action is performed and is expressed in terms of the number of repair actions performed and successfully completed per hour.
- rph is denoted by μ
- fph is denoted by λ

RPH = μ = repair rate = 1 / MTTR

FPH = λ = failure rate = 1 / MTBF

Exercise

- Given the following system repair times and frequencies of repair time observations, what is the mean time to repair (MTTR) and the maximum time to repair (Mct(max)) at the 95% level, Mmax95%?

Time	Freq.	Time	Freq.
0.2	1	3.3	2
0.3	1	4	2
0.5	4	4.5	1
0.6	2	4.7	1
0.7	3	5	1
0.8	2	5.4	1
1	4	5.5	1
1.1	1	7	1
1.3	1	7.5	1
1.5	4	8.8	1
2	2	9	1
2.2	1	10.3	1
2.5	1	22	1
2.7	1	24.5	1
3	2		

Method to calculate MTTR from repair times

$$MTTR = \overline{M_{ct}} = \bar{t} = e^{\left[\bar{t'} + \frac{1}{2}(\sigma_{t'})^2\right]}$$

S_{lnMct} = standard deviation of the natural logarithm of the repair times

$t' = \ln(M_{cti}) = \ln(t)$

$$\bar{t'} = \overline{ln(M_{ct})} = \frac{\sum t'_i}{N}$$

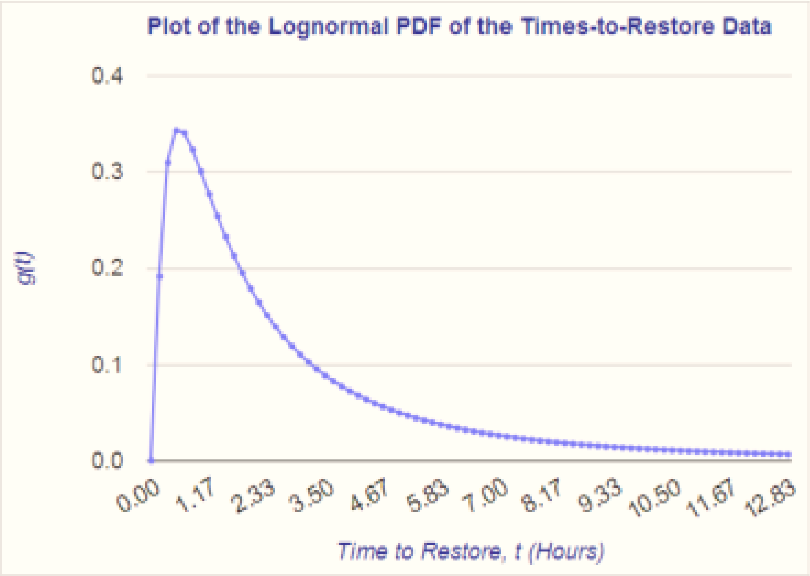
Analysis

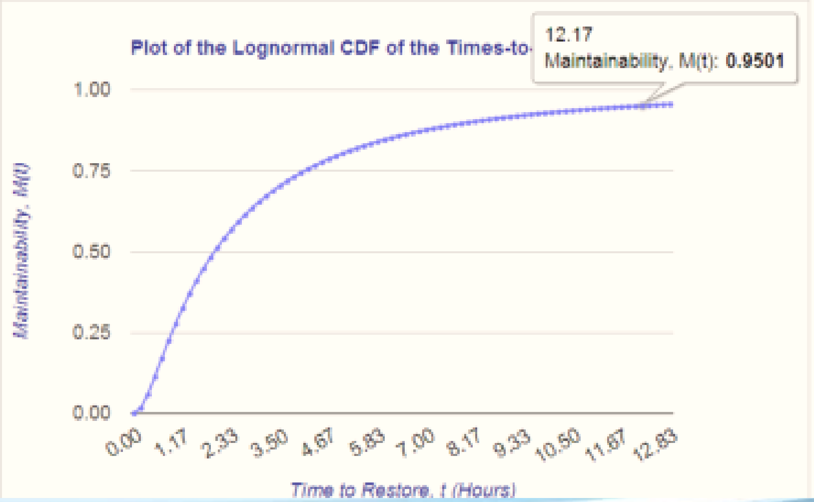
Time to Restore, t (Hours)	Probability Density, g(t)	Probability Density, g(t')	Cumulative Density Function, M(t)	Repair Rate $\mu(t) = \frac{g(t)}{1 - M(t)}$ (Repairs/Hour)
0.00	0.0000	0.0000	0.0000	0.0000
0.17	0.1914	0.0319	0.0159	0.1945
0.33	0.3097	0.1032	0.0577	0.3287
0.50	0.3430	0.1715	0.1121	0.3863
0.67	0.3403	0.2269	0.1690	0.4096
0.83	0.3231	0.2693	0.2243	0.4166
1.00	0.3006	0.3006	0.2763	0.4154
1.17	0.2770	0.3231	0.3244	0.4100
1.33	0.2540	0.3387	0.3687	0.4024
11.67	0.0083	0.0974	0.9461	0.1549
11.83	0.0081	0.0954	0.9475	0.1535
12.00	0.0078	0.0935	0.9488	0.1522
12.17	0.0075	0.0916	0.9501	0.1508
12.33	0.0073	0.0898	0.9513	0.1495
12.50	0.0070	0.0880	0.9525	0.1482
12.67	0.0068	0.0862	0.9537	0.1469
12.83	0.0066	0.0845	0.9548	0.1457

Interpretation

- Based of g(t) of 34.30%, we can conclude that Mode time to repair = 0.50 hours
- Based on M(t) of 50%, we can conclude that Median time to repair = 1.9325 hours
- MTTR = 3.5955 hours
- The time within which 95% of the maintenance actions are completed, Mmax= 12.0841 hours

Graphical Analysis





Failure in time (FIT)

- The term FIT (failure in time) is defined as a failure rate of 1 per billion hours.
- A component having a failure rate of 1 FIT is equivalent to having an MTBF of 1 billion hours.
- Most components have failure rates measured in 100's and 1000's of FITs.
- For components, such as transistors and ICs, the manufacturer will test a large lot over a period of time to determine the failure rate.
- For example, if one component has a failure rate of 100 FITs, another 200 FITs and another 300 FITs, then the total failure rate is 600 FITs and the MTBF is 1.67 million hours.

Parts per million (PPM)

- Since the failure rate is assumed to be a constant, it is acceptable to express Early life failure rate (ELFR) in terms of FIT.
- It is often desired to express the ELFR in PPM.
- However, PPM is a measure of the cumulative fraction failing per device, whereas FIT is a measure of fraction failing per device-hour.
- Thus, when ELFR is expressed in PPM, the early life period must also be specified.

Early life failure rate

- Early life failure rate (ELFR) measurement of a product is typically performed during product qualifications or as part of ongoing product reliability monitoring activities.
- These tests measure reliability performance over the products first several months in the field.

- ELFR(in ppm per tELF) = [tELF x 10^-3 x ELFR in FIT];
- ELFR(in FIT) = [1/(tELF x 10^-3) x ppm];
  Where early life period (tELF) is the specified early life period as defined by the user or the supplier.

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Chapter 3

Life Data Analysis

Chapter 3: Life Data Analysis– What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to describe:

- What is B10 life?
- How to calculate B10 life using Minitab?
- What is data censoring?
- How to interpret the result?

Chapter Agenda

- Case Study
- Data Collection
- Setting up Reliability Analysis
- Analysis
- Data Censoring
- Interpretation

Case Study

- Suppose we have tracked and recorded the battery life times over a certain number of years for 1,970 pacemakers.
- The reliability of pacemakers is critical, because patients' lives depend on these devices!
- We observed exact failure times—defined as the time at which a low battery signal was detected—for 1,019 of those pacemakers. The remaining 951 pacemakers never warned of a low battery, so they "survived."

Data Collection

- Our data is organized as follows:

C1	C2-T
Years	Failed or Survived
10.06	S
8.89	F
0.03	S
0.62	S
7.76	F
1.77	S
9.26	F
2.41	S
10.51	F
8.96	F

- When we have both observed failures and units surviving beyond a given time, we call the data “right-censored.” And we know from process knowledge that the Weibull distribution best describes the lifetime of these pacemaker batteries.

Setting Up the Reliability Analysis

- Because we have right-censored data and we know our distribution, we are ready to access Minitab's menu to compute the B10 life.
- We want to know the batteries' reliability—or probability of survival—at different times, so our variable of interest is the number of years a pacemaker battery has survived. In the Parametric Distribution Analysis dialog, you'll notice the Weibull distribution is already selected as the assumed distribution. We'll leave this default setting since we know the Weibull distribution best describes battery life times.

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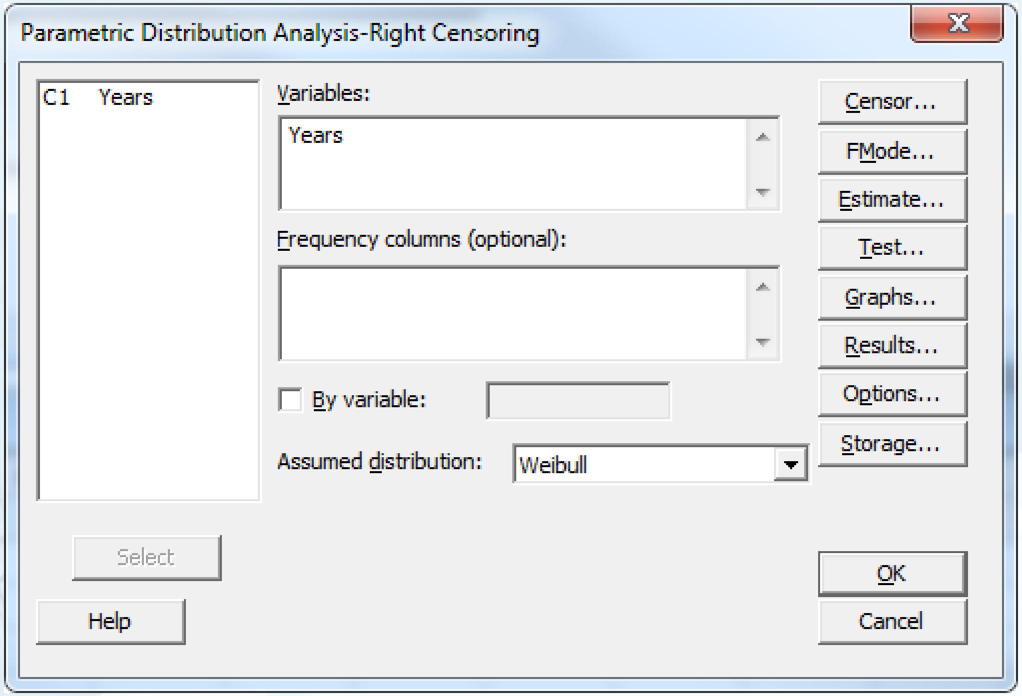
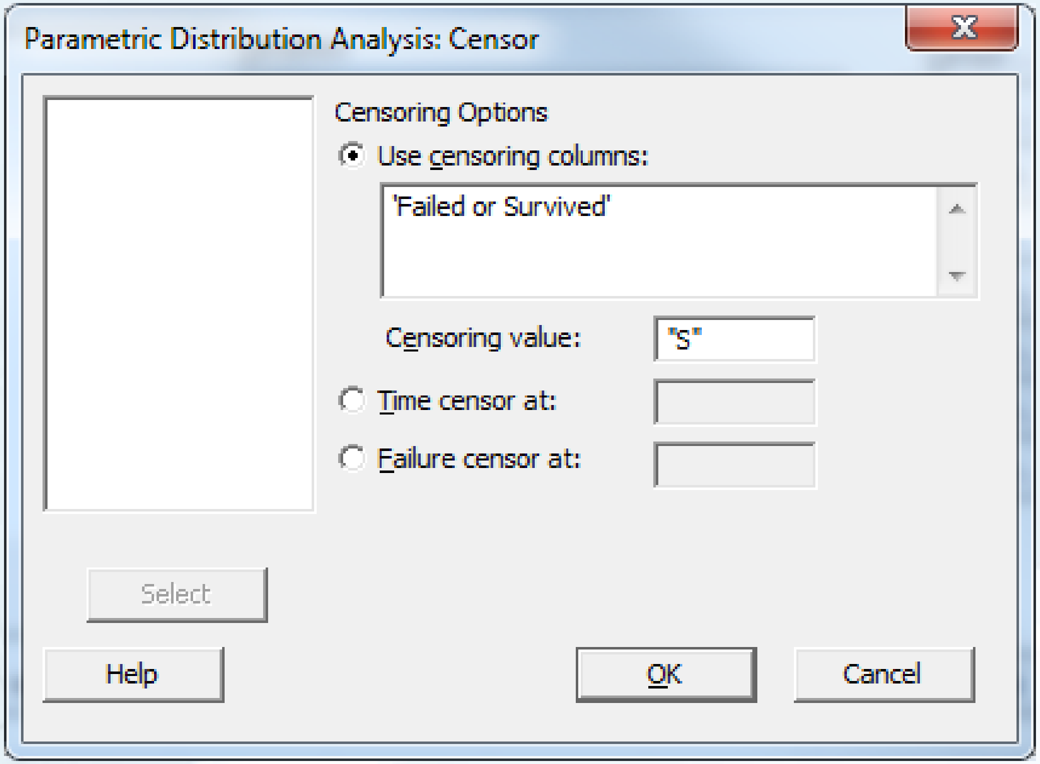
Analysis in Minitab



Statistics > Reliability/Survival > Distribution Analysis (Right Censoring) > Parametric Distribution Analysis

Data Censoring



- By clicking the button labeled ‘Censor’, we can include a censoring column that contains values indicating whether or not the pacemaker survived or failed at the recorded time.
- In our Minitab worksheet, “Failed or Survived” is the censoring column. Our censoring value is ‘S’, which stands for ‘Survived’, indicating no failure was observed during the pacemaker battery tracking period.

Interpreting the Table of Percentiles and B10 Life

Percent	Percentile
0.01	1.31823
0.1	2.21880
1	3.73805
2	4.37724
3	4.80300
4	5.13174
5	5.40362
6	5.63769
7	5.84461
8	6.03101
9	6.20131
10	6.35861

Where the Percent column displays 10, the corresponding Percentile value tells us that the B10 life of pacemaker batteries is **6.36 years**—or, to put it another way, 6.36 years is the time at which 10% of the population of pacemaker batteries will fail.

Softwares in market

- Minitab
- JMP
- SPSS

Chapter 4

Reliability Planning

Chapter 4: Reliability Planning – What We Will Cover

Learning Objectives

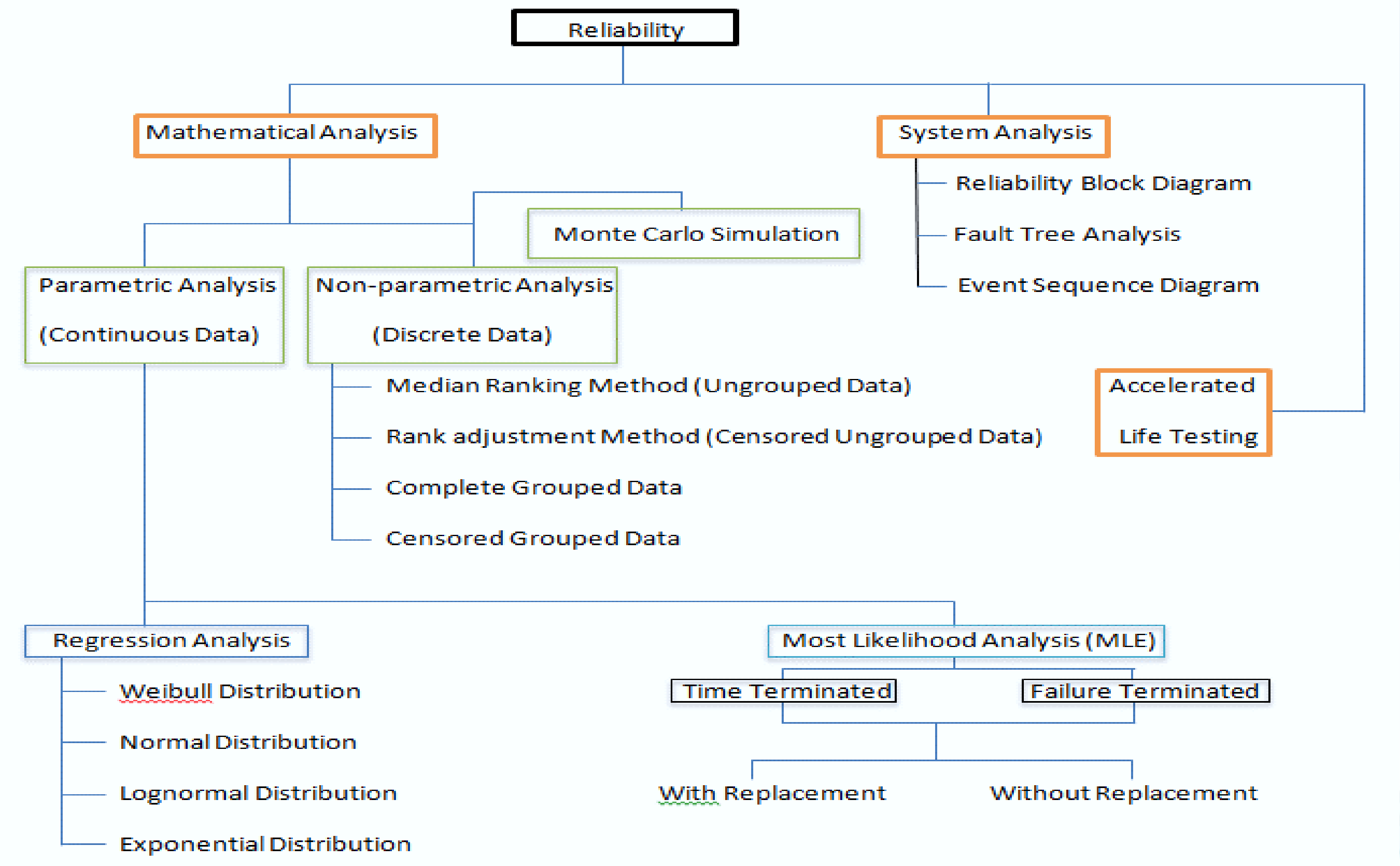
At the end of this chapter, you will be able to describe:

– How to plan a Reliability analysis?

Chapter Agenda

- Reliability Engineering Tools structure
- Planning
- Goal
- Modeling
- Estimation
- Track Progress
- Document

Reliability Engineering Tools



Reliability Planning

- A specific reliability plan may include any number of specific tasks. To build an effective plan you need the knowledge of the individual tools and techniques, plus how they may fit together to create an overall plan to achieve your goals.
- 5 Step Approach:
  - Reliability Goals
  - Reliability Modeling
  - Reliability Estimates
  - Track Progress
  - Write the Reliability Case
- The intent of a reliability plan is to support decision making across the team and by management as you work to achieve a product that meets you customer's reliability expectations.

Reliability Goal

- Establish complete reliability goals that include function, environment characterization, probability of success (reliability) and duration.
- Set specific goals for
  - setup/installation (early life)
  - the warranty period and
  - the expected customer use period
- For example, for an inkjet printer the goals may be stated as a device that prints b/w or color (reference engineering specification document for other functional details), in the home or office environment (reference environmental and use characterization documents for details), with:
  - 99% probability of successfully operating without failure for the first month after purchase,
  - 95% probability of successfully operating without failure for first year (warranty),
  - 90% probability of successfully operating without failure for 5 years (use life).

Reliability Modeling

- Create a reliability model using reliability block diagram
- Must include the breakdown of the reliability goals to the major elements of the system.
  - For example, for a desktop computer, including display, motherboard, power supply, etc. Consider the internal temperature for the motherboard is higher than for the ambient.
- Make sure when each element meets their reliability goal the system meets the overall goal, too

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Reliability Estimates

- Estimate reliability of each element of the model — and compare/adjust the goals to still achieve the overall goal.
- Compare the power supply, motherboard, and other elements reliability performance to the goal and roll up to system goal expected performance including a breakdown of what failures to expect and when.
- Use engineering judgment, vendor data, literature, field data, and internal life testing to create suitable estimates to populate the model.
- Identify large areas as poor or uncertain estimates and take steps to get better life estimates, also identify areas that do not meet budgeted target and evaluate options that still achieve the objective.

Track Progress

- Track reliability issues like any defect, bug, or prototype failure, that would have caused a system failure impacting the use of the system by the customer.
- Track date/time of arrival of the issue and plot using mean cumulative function or reliability growth models (plot count of failures (Y) vs time (X) – look for the rate of arrival to taper off as the design mature. This requires actually fixing the issues as testing continues.
- This shows progress resolving issues and if the team is finding and solving enough issues fast enough.

Write Reliability Case

- Create a report that details the rationale for expected reliability performance.
- It should include:
  - Goal
  - Model
  - Evidence supporting reliability estimates
  - What is known, unknown (or not well known) and degree of risk to reliability performance

Sample Test Plan

Test Plan Inputs				
Number of Simultaneous Stresses	1			
Test Plan Type	2 Level Statistically Optimum Plan			
BX% Life Estimate Sought	10			
Available Test Time	10000			
Number of Units Available	40			
Lifetime Distribution	Weibull			
Beta	3.5			
Stress1				
Life-Stress Relationship	Power			
Use Stress Value	60			
Maximum Stress Value	120			
Probabilities of Failure (%) at Time=10000				
P(Time, Use Stress)	0.06			
P(Time, Maximum Stress)	99.999			
Recommended Test Plan				
Stress Level	**Stress Value**	**Unit Allocation (%)**	**Unit Allocation (Qty)**	**Probability of Failure**
Low Stress Level	95.39823	70.6	28.24	0.356023
High Stress Level	120	29.4	11.76	0.99999
BX% Life Estimate				
Time at Which Unreliability (Tp)=10%	43778.01748			
Standard Deviation of Tp	14379.70074			

Reliability Planning using Minitab

- Minitab's reliability test plans have two main functions.
  - To determine the sample size and testing time needed to estimate model parameters.
  - To demonstrate that you have met specified reliability requirements.

Test Plan Contents

- A test plan includes:
  - The number of units you need to test.
  - A stopping rule: the amount of time you must test each unit or the number of failures that must occur.
  - Success criterion: the number of failures allowed while the test still passes (for example, all units are tested for the specified amount of time and there are no failures).

Test Plans on Minitab

- Demonstration test plan
  - To determine the test time or sample size required to demonstrate reliability requirements, create a demonstration test plan.
  - In Minitab, choose Stat > Reliability/Survival > Test Plans > Demonstration.
- Estimation test plan
  - To determine the sample size required to estimate reliability parameters, create an estimation test plan.
  - In Minitab, choose Stat > Reliability/Survival > Test Plans > Estimation.
- Accelerated life test plan
  - To determine sample sizes for an accelerated life test, create an accelerated life test plan.
  - In Minitab, choose Stat > Reliability/Survival > Test Plans > Accelerated Life Testing.

Demonstration Test Plan

- Use Demonstration Test Plan to determine the sample size or testing time needed to demonstrate, with some level of confidence, that the reliability exceeds a given standard.
- A demonstration test plan is used with two types of demonstration tests:
  - Substantiation tests provide statistical evidence that a redesigned system has suppressed or significantly reduced a known cause of failure.
  - Reliability tests provide statistical evidence that a reliability specification has been achieved.

Demo Test Plan on Minitab

- Minitab provides an m-failure test plan for substantiation and reliability testing.
  - If more than m failures occur in an m-failure test, the test fails.
- Example
  - The reliability goal for a turbine engine combustor is a 1st percentile of at least 2000 cycles. An engineer uses a demonstration test plan to determine the number of combustors needed to demonstrate the reliability goal using a 1-failure test plan.
- To create a demonstration test plan, choose

  Stat > Reliability/Survival > Test Plans > Demonstration

Case Study: Demonstration Test Plan

- Engineers determine that early transmission failures occurring on a track-type tractor are due to the failure of a ball bearing. The failure times for this ball bearing follow a Weibull distribution with a shape of 1.3 and scale of 1,000 hours. The engineers have 3 redesigned units available for testing.
- Determine how long to test each unit using a 0-failure test plan.
- Note: 0 is the maximum number of failures allowed according to the demonstration test plan.

Method

- Choose Stat > Reliability/Survival > Test Plans > Demonstration.
- Under Minimum Value to be Demonstrated, select Scale (Weibull or expo) or location (other dists), and enter 1000.
- In Maximum number of failures allowed, enter 0.
- Select Sample sizes and enter 3.
- Under Distribution Assumptions, in Distribution, select Weibull. In Shape (Weibull) or scale (other distributions), enter 1.3.
- Click OK.

Results

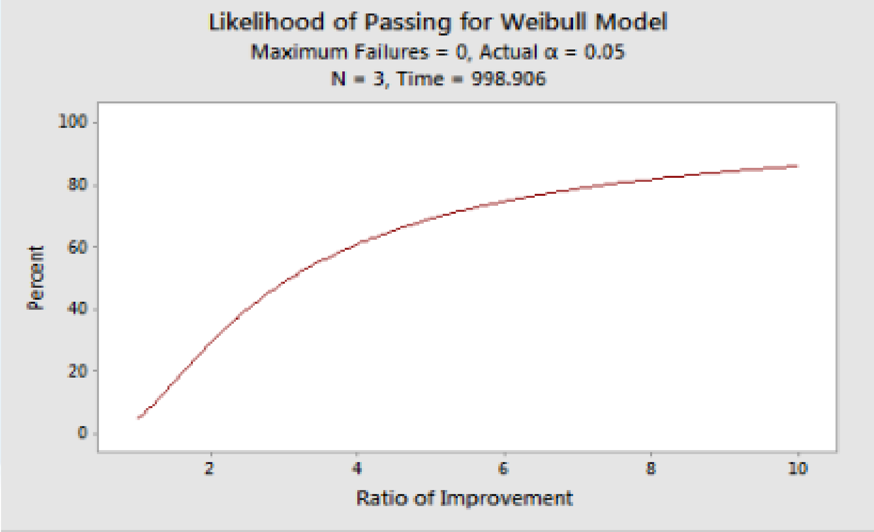
Demonstration Test Plans

Substantiation Test Plan
Distribution: Weibull, Shape = 1.3
Scale Goal = 1000, Actual Confidence Level = 95%

Test Plans

Failure Test	Sample Size	Testing Time
0	3	998.906

Probability of Passing Demonstration Test



Interpretation of Result

- At a 95% level of confidence and a sample size of 3, the testing time required to demonstrate that the scale of the new system exceeds 1000 hours is **998.906 hours**.
- The probability of passing graph shows that the probability that the 0-failure test will pass increases steadily as the ratio of improvement increases from 0 to 10. However, **even at a ratio as high as 10, the test has just over an 80% chance of passing**.
- If the (unknown) true scale parameter were 4000, then the ratio of improvement = 4000/1000 = 4, and the test has a probability of passing of approximately 61%.
- Because the likelihood of passing this demonstration test is not very high, even when the ratio of improvement is fairly high, the engineers may want to **increase the sample size**, or **increase the maximum number of allowable failures**.

Estimation Test Plan

- Use Estimation Test Plan to determine the number of test units that you need to estimate percentiles or reliability values with a specified degree of precision.
- For example:
  - How many units should be tested to estimate the 10th percentile with a 95% lower confidence bound within 100 hours of the estimate?
  - How many cables does an engineer need to test until failure to predict the survival probability of the cables at a force of 5000 pounds?
- An estimation test plan is performed before collecting reliability data and requires prior information about the distribution of the data.

Estimation Test Plan on Minitab

- To create an estimation test plan, choose

  Stat > Reliability/Survival > Test Plans > Estimation

Case Study: Estimation Test Plan

- Engineers are developing a new type of insulation. They want to determine the sample sizes necessary to estimate the 10th percentile when the distance from the lower bound to the estimate is within 100, 200, or 300 hours. The engineers will perform reliability tests on small specimens for 1000 hours. They use the following information for the test plan:
  - Approximately 12% of the specimens are expected to fail in the first 500 hours of the test.
  - Approximately 20% of the specimens are expected to fail by the end of 1000 hours.
  - The failure times for the insulation follow a Weibull distribution.

Method

- Choose Stat > Reliability/Survival > Test Plans > Estimation
- Under Parameter to be Estimated, select Percentile for percent, and enter 10.
- From Precisions as distances from bound of CI to estimate, select Lower bound, and enter 100 200 300.
- From Assumed distribution, select Weibull.
- In the upper Percentile box, enter 500. In the upper Percent box, enter 12.
- In the lower Percentile box, enter 1000. In the lower Percent box, enter 20.
- Click Right Cens. In Time censor at, enter 1000.
- Click OK in each dialog box.

Result

Estimation Test Plans

```
Type I right-censored data (Single Censoring)

Estimated parameter: 10th percentile
Calculated planning estimate = 393.094
Target Confidence Level = 95%
Precision in terms of a one-sided confidence interval that gives a lower bound
     for the parameter.

Planning Values
Percentile values 500, 1000 for percents 12, 20
Planning Distribution

Distribution    Scale     Shape
     Weibull  6464.18  0.803708

Test Plans

                                  Actual
Censoring              Sample  Confidence
     Time  Precision     Size       Level
     1000        100      354     95.0011
     1000        200       61     95.0892
     1000        300       15     95.1695
```

Interpretation of Result

- To calculate the sample sizes, Minitab uses a Weibull distribution with a scale of 6464.18 and a shape of 0.8037.
- With a censoring time of 1000 hours and a target confidence level of 95% for a one-sided confidence interval, the calculated sample sizes for each precision value are as follows:
  - **354 units** must be tested to estimate a lower bound for the 10th percentile within 100 hours.
  - **61 units** must be tested to estimate a lower bound for the 10th percentile within 200 hours.
  - **15 units** must be tested to estimate a lower bound for the 10th percentile within 300 hours.

Chapter 5

Accelerated Life Testing

Chapter 5: Accelerated Life Testing–What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to describe:

– What is Accelerated Life Testing?

– How it is done?

Chapter Agenda

- What is is ALT?
- Types of ALT?

Accelerated testing

- A test method of increasing loads to quickly produce age to failure data with only a few data points are then scaled to reflect normal loads
- The benefits of this testing is to save time and money while quantifying the relationship between stress and performance along with identifying design at low cost
- It is used to correlate with real life conditions
- It is useful method for solving old, nagging problems within a production process

Purpose

- Accelerated testing shortens the test time as the tests are conducted at higher stress levels to expediting the failure time to be days instead of month or years.
- Challenges faced by designer :
  - Long test time to complete life testing of product
  - Constraints on timelines
  - Cost as function of time
  - Reliability growth
  - Low failure - Testing even a very large sample at normal conditions would yield few or no failures in a reasonable time.
  - High longevity - The product must be reliable for a much longer time than can be reasonably tested at normal conditions.
  - High wear-out - The primary cause of failure occurs over an extended amount of time

Types of ALT

- Qualitative Accelerated Testing
  - HALT
  - HASS
- Quantitative Accelerated Testing
  - SSALT
  - CSALT
  - CISALT

Highly Accelerated Testing (HALT)

- To identify potential failure modes or uncover defects of a product.
- Test the component to failure under highly stressed conditions.
- Study the failure modes and analyze to the root cause.
- Fix the root cause to make the product more robust.
- Does not help in predicting the life of the product.

Highly Accelerated Stress Screening (HASS)

- Used to monitor the production process.

- All products are subjected to the same
- stresses during HALT but, at a lower level.

- It identifies process related defects.

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Quantitative Accelerated Testing

- Planned/Controlled accelerated testing from which TTF under normal usage conditions can be derived.
- Models to be used for a specific agent of failure have been postulated.
- Accelerated Factor(AF)=TTFnormal / TTFstress
- AF is used to derive the normal TTF from accelerated TTF.
- Quantitative ALT helps predict the life of the product.

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ALT Plan

- An accelerated life test evaluates the relationship between failure time and at least one accelerating variable.
- Use this test to answer questions such as the following:
  - When are highly reliable components expected to fail?
  - What is the effect of a factor on the lifetime of a product?
  - What factor settings will maximize the lifetime of the product?
- To perform an accelerated life test, choose

  Stat > Reliability/Survival > Accelerated Life Testing

Data considerations for ALT

- The response variable should be continuous
- If you have censored observations, you must include them in your analysis to obtain accurate reliability estimates.
- You can have two predictors for an accelerated life test, but at least one predictor must be an accelerating variable. The second predictor can be either a second accelerating variable or a factor.
- Use engineering knowledge about the relationship between failure time and the accelerating variable to choose the appropriate model.

Case Study: ALT

- A reliability engineer wants to investigate electrical current leakage between transistors in an electronic device. When current leakage reaches a certain threshold value, the electronic device fails. To accelerate failures for testing, the devices were tested under much higher than normal temperatures. Devices were inspected for failure every two days.
- The engineer performs an accelerated life test to estimate the time until failure for the device under normal operating conditions (55° C) and worst-case operating conditions (85° C). The engineer wants to determine the B5 life, which is the estimated amount of time until 5% of the devices are expected to fail.

Data Collection

StartTime	EndTime	Count	Temp	NewTemp
0	2	0	125	55
2	4	1	125	85
4	6	1	125	
6	8	0	125	
8	10	0	125	
10	12	1	125	
12	14	1	125	
14	*	46	125	
0	2	5	150	
2	4	2	150	
4	6	2	150	
6	8	2	150	
8	10	2	150	
10	12	2	150	
12	14	3	150	
14	*	34	150	
0	2	8	175	
2	4	6	175	
4	6	5	175	
6	8	4	175	
8	10	3	175	
10	12	5	175	
14	*	15	175	
12	14	5	175	

Method

- Choose Stat > Reliability/Survival > Accelerated Life Testing.
- Select Responses are uncens/arbitrarily censored data.
- In Variables/Start variables, enter StartTime.
- In End variables, enter EndTime.
- In Freq. columns, enter Count.
- In Accelerating var, enter Temp.
- From Relationship, select Arrhenius.
- From Assumed distribution, select Weibull.
- Click Estimate. Under Percentile and Probability Estimation, select Enter new predictor values, then enter NewTemp.
- In Estimate percentiles for percents, enter 5, then click OK.
- Click Graphs. In Design value to include on plots, enter 55.
- Under Relation plot, in Plot percentiles for percents, enter 5, then select Display failure times on plot.
- Click OK in each dialog box

Result

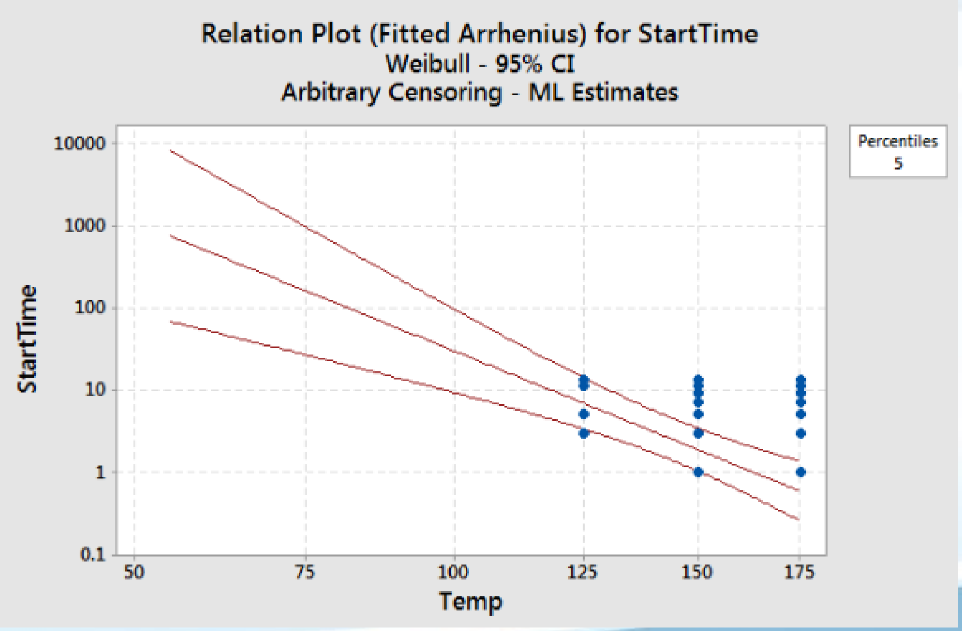
Accelerated Life Testing: StartTime versus Temp

```
* NOTE * 21 cases were used
* NOTE * 3 cases contained missing values or was a case with zero frequency.

Response Variable Start: StartTime  End: EndTime
Frequency: Count

Censoring

Censoring Information    Count
Right censored value        95
Interval censored value     58

Estimation Method: Maximum Likelihood

Distribution:   Weibull

Relationship with accelerating variable(s):   Arrhenius
```

```
Regression Table

                        Standard                          95.0% Normal CI
Predictor      Coef        Error      Z      P        Lower       Upper
Intercept  -17.0990      4.13633  -4.13  0.000     -25.2061    -8.99195
Temp       0.755405     0.157076   4.81  0.000     0.447542     1.06327
Shape      0.996225     0.136187                   0.762071     1.30232

Log-Likelihood = -191.130

Table of Percentiles

                                 Standard    95.0% Normal CI
Percent  Temp  Percentile        Error      Lower      Upper
      5    55     759.882      928.717    69.2500    8338.21
      5    85     81.0926      63.2317    17.5897    373.855
```

Interpretation of Result

- Based on the results in the table of percentiles, we can conclude the following:
  - At the design temperature (55° C), 5% of the devices will fail after approximately 760 days (slightly over 2 years).
  - At the worst-case temperature (85° C), 5% of the devices will fail after approximately 81 days.
- These results are also displayed in the relation plot.



Chapter 6

Types of Distribution

Chapter 6: Types of Distribution – What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to describe:

- What are the different types of distribution?
- Insight into Weibull Distribution

Chapter Agenda

- Parametric analysis
- Regression analysis
- Distribution analysis
- Types of distributions
- When to use them

Parametric Analysis

- Parametric Analysis is fitting the data to a known distribution and estimating the parameters of the distribution.
- Parametric Analysis is done by using two most commonly used methods :
  - **Regression Analysis**
  - **Most Likelihood Method**
- Having got a fit, a statistic is calculated to estimate the goodness of the fit after which a confidence interval of the parameters can be found.

Regression Analysis

- Most commonly used **continuous** distribution are
  - Weibull Distribution
  - Normal Distribution
  - Lognormal Distribution
  - Exponential Distribution
- First we linearize the basic CDF by making the required transformation. From that we find parameters of the distribution.

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Distribution Analysis

Distribution Analysis involves identifying the statistical distribution that the field data follows and estimates of reliability and confidence intervals based on the identified distribution

- The most basic types of Distribution Analysis involve having a complete set of data for the population or sample population and knowing all failure times (uncensored) or failure times and times at which the field study was ended (censored).
- Specialized software can be used to perform this analysis.

Data Collection

Minimum Data Needs for each item

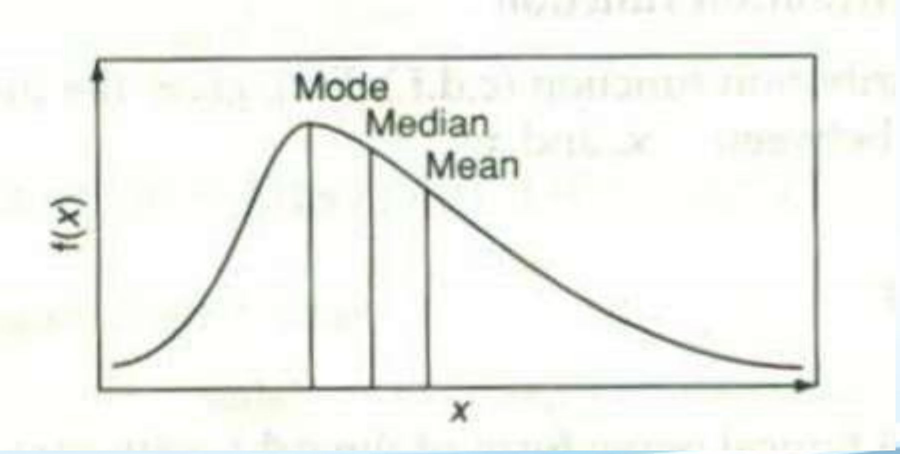
- **Design Configuration**
- **When Produced**
- **How Many Produced**
  - **Total Population**
  - **Or Sample Population being studied**
- **When Entered Service**
- **When Failed**
- **How Many Failed**

Additional Data Needed to better identify Failure Modes and Corrective/Preventive Action

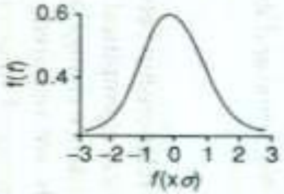
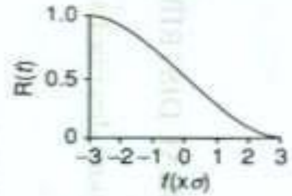
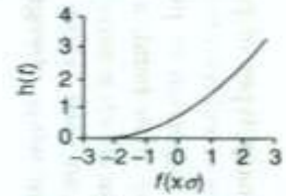
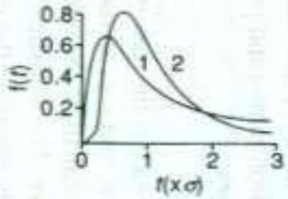
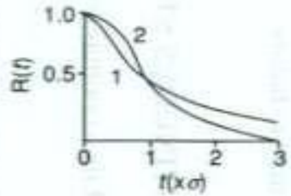
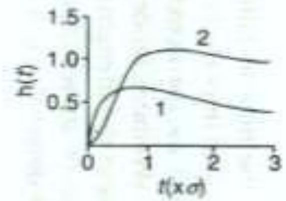
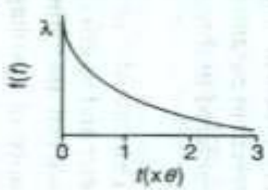
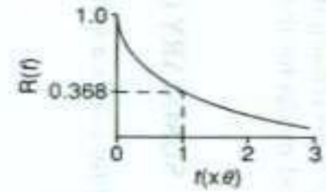
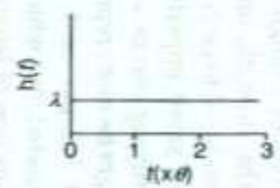
- **Usage Application and Environment**
- **How Failed – Failure Mode**
- **Immediate Action Taken to Repair or Replace**
- **Time to Repair or Replace**
- **Root Cause of Failure**

Basic Statistics

Mean	Median	Mode
The sample mean can be used to estimate the population mean , which is the average of all possible outcomes	It is the measure of the central tendency, which is the mid point of the distribution It is the point at which half the measured values fall to either side	It is the value at which the distribution peaks.



Distribution Types

Type of distribution	Parameters	Prabability density function, f(t)	Reliability function, R(t) = I − F(t)	Hazard function (instantaneous failure rate). $h(t) = \frac{f(t)}{R(t)}$
Normal	Mean, μ Standard deviation, σ	 $f(t) = \frac{1}{\sigma(2\pi)^{1/2}} \exp\left[-\frac{(t-\mu)^2}{2\sigma^2}\right]$	 $R(t) = \int_t^{\infty} f(t)\,dt$	 $h(t) = \frac{f(t)}{R(t)}$ (general expression)
Lognormal	Mean, μ Standard deviation, σ	 $f(t) = \frac{1}{\sigma t(2\pi)^{1/2}} \exp\left[-\frac{(\ln t-\mu)^2}{2\sigma^2}\right]$	 $R(t) = \int_t^{\infty} f(t)\,dt$	 $h(t) = \frac{f(t)}{R(t)}$ (general expression)
Exponential	Failure rate, λ MTBF (=SD), θ $\theta = \lambda^{-1}$	 $f(t) = \lambda \exp(-\lambda t)$	 $R(t) = \exp(-\lambda t)$	 $h(t) = \lambda = \theta^{-1}$

Distribution Types

Gamma

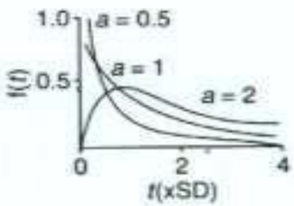
Failure rate, λ

Events per failure, or Time to ath failure

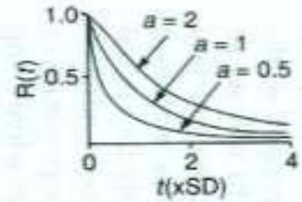
SD = $a^{1/2}/\lambda$

Note: when a is an integer

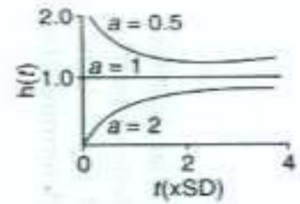
$\Gamma(a) = (a-1)!$



$$f(t) = \frac{\lambda}{\Gamma(a)}(\lambda t)^{a-1}\exp(-\lambda t)$$



$$R(t) = \frac{\lambda^a}{\Gamma(a)}\int_t^\infty t^{a-1}\exp(-\lambda t)\,dt$$

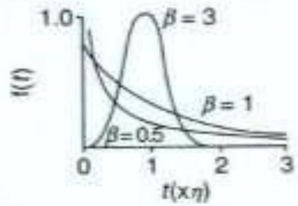


$$h(t) = \frac{f(t)}{R(t)}$$ (general expression)

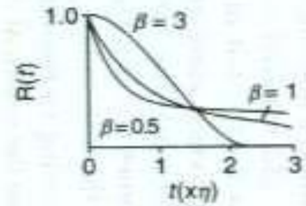
Weibull

Shape, β Scale (characteristic life), η

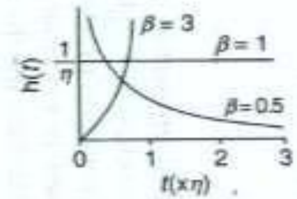
Location (minimum life), γ Curves shown for $\gamma = 0$



$$f(t) = \frac{\beta}{\eta^\beta}(t-\gamma)^{\beta-1}\exp\left[\left(\frac{t-\gamma}{\eta}\right)^\beta\right]$$



$$R(t) = \exp\left[-\left(\frac{t-\gamma}{\eta}\right)^\beta\right]$$



$$h(t) = \frac{\beta(t-\gamma)^{\beta-1}}{\eta^\beta}$$

Extreme value

Type I

Type II is ln (EV)

Type III (min) is Weibull

Scale, σ

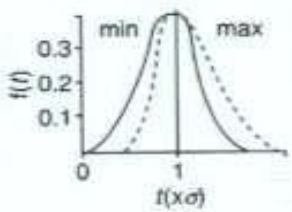
Location (mode), μ

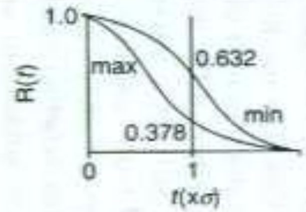
SD = 1.283σ

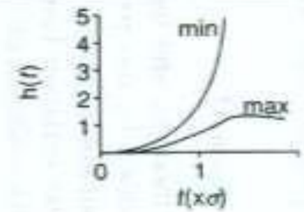
Means = $\mu \cdot 0.577\sigma$

+ for max

− for min







Maximum values

$$f(t) = \frac{1}{\sigma}\exp\left\{\frac{(t-\mu)}{\sigma}\left[-\exp\left(-\frac{t-\mu}{\sigma}\right)\right]\right\}$$

$$R(t) = \exp\left[-\exp\left(-\frac{t-\mu}{\sigma}\right)\right]$$

$$h(t) = \frac{1}{\sigma}\exp\left(-\frac{t-\mu}{\sigma}\right)$$

Minimum values

$$f(t) = \frac{1}{\sigma}\exp\left[\frac{t-\mu}{\sigma}\left(-\exp\frac{t-\mu}{\sigma}\right)\right]$$

$$R(t) = \exp\left[-\exp\left(\frac{t-\mu}{\sigma}\right)\right]$$

$$h(t) = \frac{1}{\sigma}\exp\left(\frac{t-\mu}{\sigma}\right)$$

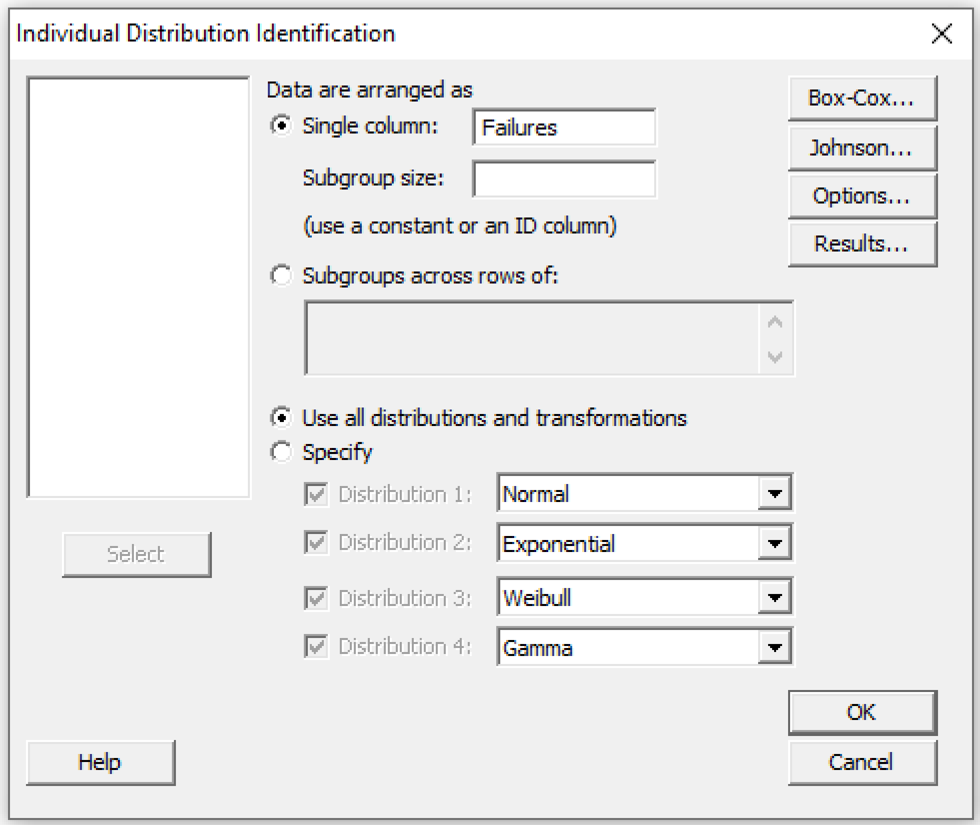
Example

There are 35 failure times listed below. Check if the distribution follows exponential distribution.

GIVEN DATA				
1476	300	98	221	157
182	499	552	1563	36
246	442	20	796	31
47	438	400	279	247
210	284	553	767	1297
214	428	597	2025	185
467	401	210	289	1024

Minitab

- Stat→ Quality tools → Individual Distribution Identification



- Enter Failures into Single Column

Distribution identification test

Goodness of Fit Test

Distribution	AD	P	LRT P
Normal	2.528	<0.005	
Box-Cox Transformation	0.394	0.357	
Lognormal	0.691	0.065	
3-Parameter Lognormal	0.346	*	0.186
Exponential	0.567	0.401	
2-Parameter Exponential	0.516	>0.250	0.338
Weibull	0.477	0.233	
3-Parameter Weibull	0.475	0.247	0.786
Smallest Extreme Value	3.902	<0.010	
Largest Extreme Value	0.991	0.011	
Gamma	0.452	>0.250	
3-Parameter Gamma	0.467	*	1.000
Logistic	1.694	<0.005	
Loglogistic	0.444	0.227	
3-Parameter Loglogistic	0.314	*	0.537
Johnson Transformation	0.237	0.768	

- The distribution with **highest p value** is the significant distribution.
- Exclude all terms with word "Transformation"
- In this case, the failure data follows **exponential distribution** with highest p value of 0.401

Chapter 6

Data Censoring

Chapter 1: Overview – What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to describe:

- What is data censoring?
- Why censoring is needed?
- How to do data censoring in Minitab?

Chapter Agenda

- Data censoring
- Types of data censoring

Data Censoring

- In reliability analysis, failure data frequently contain individual times to failure. For example, you might collect times to failure for units operating at a particular temperature. You might also collect samples of times to failure under different temperatures, or under different combinations of stress variables.
- Sometimes you record exact times to failure. Other times, the exact times to failure of some test units are unknown. In this case, the data are called censored.

Types of Censoring

- Failure data are often censored in some way. Therefore, you may have any of the following types of observations:
  - Exact times to failure
  - Right-censored data
  - Interval-censored data
  - Left-censored data

Exact failure time data

- The exact time that each item failed is known. For example, an engineer tests electric fans and records the exact time to failure of each fan.

Right Censored data

- Failures are seen only if they occur before a particular time. A unit surviving longer than that time is considered a right-censored observation.
- Right-censored data are sometimes **time-censored** or **failure-censored**.
  - Time censoring means that you perform the study for a specified period of time. All units still operating at the end of the study are time-censored. Time censoring is also known as Type I censoring on the right.
  - Failure censoring means that you conduct the study until you observe a specified number of failures. Failure censoring is also known as Type II censoring on the right.

Example

- Suppose that an engineer tests five fan belts.
- Three fan belts fail in 67 hours, 76 hours, and 104 hours.
- The remaining two fan belts are still operating when the engineer stops the test at 110 hours.
- These last two fan belts are right-censored at 110 hours.

Item	Unit	Failure Time
1	Failed	18.5
2	Failed	20.5
3	Failed	22.0
4	Failed	23.5
5	Failed	24.3
6	Failed	25.0
7	Failed	25.6
8	Failed	26.3
9	Failed	27.0
10	Failed	29.0
11	Failed	32.0
12	Failed	33.0
13	Censored	33.0
14	Censored	33.0
15	Censored	33.0

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Interval Censored data

- Failures occur between two particular times. Interval-censored data contain uncertainty as to when units actually fail.
- For example, suppose that instead of recording exactly when ten transistors fail, an engineer inspects them every 12 hours. Therefore, the engineer knows the status of each transistor (failed or still operating) only at the time of each inspection. Instead of exact failure times, the engineer records the data as failure time intervals. So, for example, a transistor may fail between 60 and 72 hours.

Left Censored data

- Failures occur before a particular time. Left-censored data are a special case of interval-censored data in which failure times occur sometime between zero and an inspection time.
- For example, glass capacitors are put on test at high voltage levels to accelerate their failure times. Engineers examine the capacitors every 12 hours to see which have failed. At the first inspections, 2 capacitors have failed. The failure times for these two units are left censored.

Chapter 7

Output Parameters

Chapter 7: Output parameters
What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to describe:

– What are output parameters for Weibull analysis?

– Glimpse into shape, scale and threshold parameters

Chapter Agenda

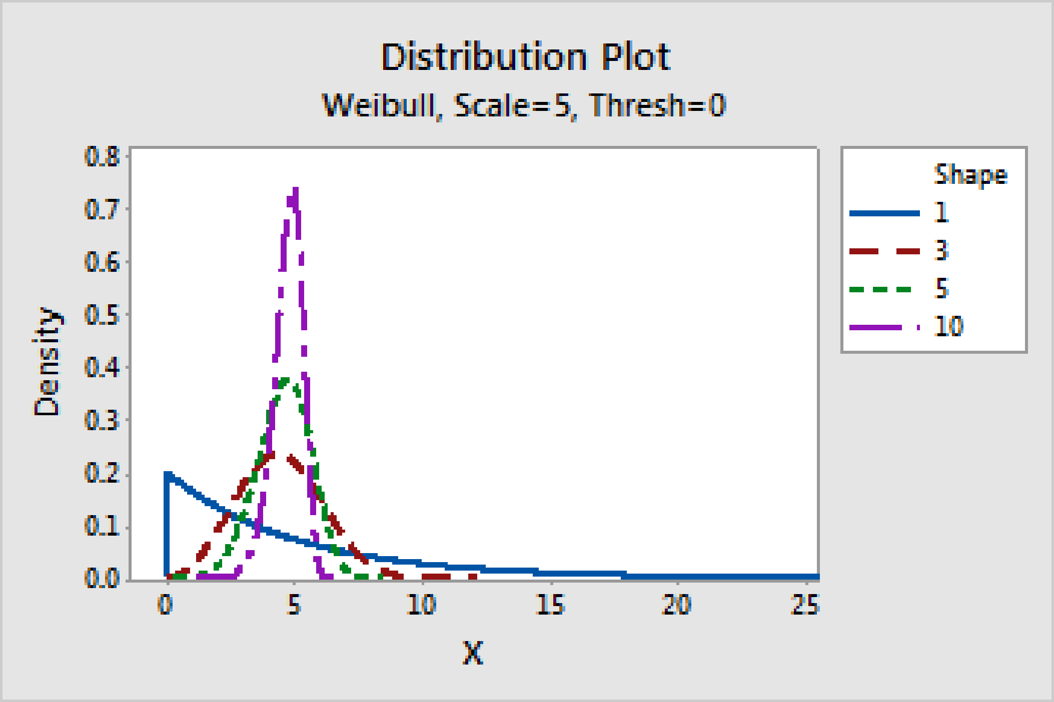
- Types of output parameters
- Shape Parameter
- Scale Parameter
- Threshold Parameter

Weibull Distribution

- The Weibull distribution is described by the shape, scale, and threshold parameters, and is also known as the 3-parameter Weibull distribution.
- The case when the threshold parameter is zero is called the 2-parameter Weibull distribution. The 2-parameter Weibull distribution is defined only for positive variables.
- A 3-parameter Weibull distribution can work with zeros and negative data, but **all data for a 2-parameter Weibull distribution must be greater than zero.**
- Depending on the values of its parameters, the Weibull distribution can take various forms.

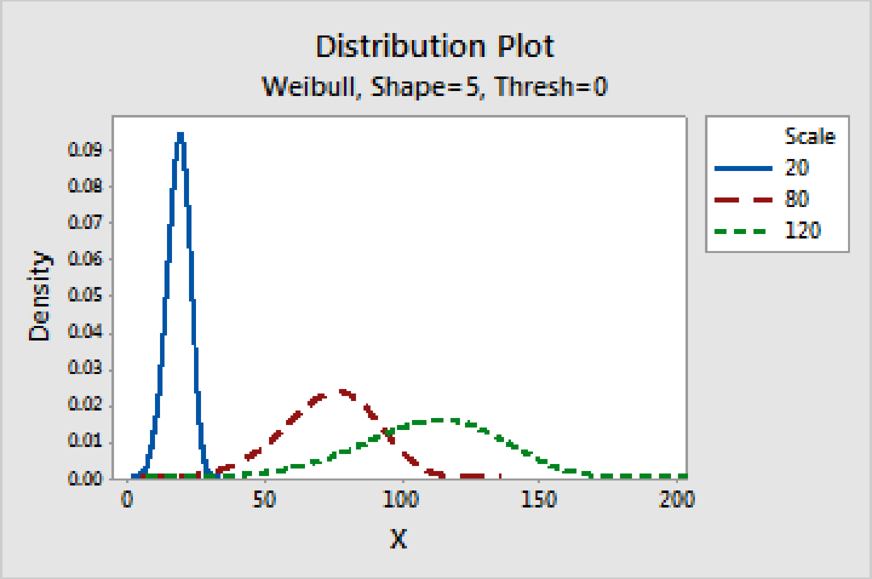
Shape Parameter (β)

- The shape parameter describes how your data are distributed. A shape of 3 approximates a normal curve. A low value for shape, say 1, gives a right-skewed curve. A high value for shape, say 10, gives a left-skewed curve.



Scale Parameter (η)

- The scale, or characteristic life, is the 63.2 percentile of the data. The scale defines the position of the Weibull curve relative to the threshold, which is analogous to the way the mean defines the position of a normal curve. A scale of 20, for example, indicates that 63.2% of the equipment will fail in the first 20 hours after the threshold time.



Threshold Parameter (θ)

- The threshold parameter describes the shift of the distribution away from 0.
- A negative threshold shifts the distribution to the left, and a positive threshold shifts the distribution to the right. All data must be greater than the threshold.
- The 2-parameter Weibull distribution is the same as the 3-parameter Weibull with a threshold of 0.
- For example, the 3-parameter Weibull (3,100,50) has the same shape and spread as the 2-parameter Weibull (3,100), but is shifted 50 units to the right.

Thank You!

Questions?

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