

4.2.1 Weibull Exercises

Using a Weibull Analysis software application

Module 4.2A

1

Perkins engine

A Perkins diesel D200 series engine was monitored on board ship over 10 years and the following figure indicates the failure pattern of the engine. It is assumed that after each failure the engine is returned to the "as new" condition by maintenance.

Time (Months)	Event
0	Engine new
8	Failure
26	Renewal
64	Failure
87	Renewal
106	Failure
120	Renewal

From the diagram, this engine failed and was renewed at the following ages:

- 8, 26-8=18, 64-26=38, and so on.

2

Use OREST to perform the following:

1. Using Trend Analysis determine at the 5% significance level whether a Weibull analysis on this data is feasible. That is to say, there should be **no significant change** (growth or deterioration) in reliability over the period covered.

2. Fit a Weibull distribution to the data. Plot the Weibull, Probability Density, Survival, Hazard, and Cumulative Distribution functions.

3. From the Kolmogorov-Smirnov goodness-of-fit test is your data sample **adequately represented** by a Weibull distribution?

4. Examine the Hazard Function curve. From the shape of the curve, does this item become more unreliable as it ages?

3

Enter general data

1

Data Input

Data Input

2

Add Component...

3

New Component Data Input

Component Name

Perkins Engine

Preventive Replacement Cost

100

Age Unit

Month

Failure Replacement Cost

1000

Cost Unit

\$

Number of Components in Service

Planning Horizon

Is Event Data Grouped?

Yes

No

Component Description

OK

Cancel

4

Input event data

OREST - Data Input

Components | Event Data | Operating Cost

List of Components

Air Filter

Bearing

Clutch

Perkins Engine

Perkins2

Starter motor

View Component...

Add Component...

Edit Component...

Delete Component...

Update Database

Import Data

Print Data

Export Data

Close

Event Data for the Current Component

Record No.	Age	Frequency	Event Type
1	8	1	F
2	18	1	F
3	38	1	F
4	23	1	F
5	19	1	F
6	14	1	F

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Perform Trend Analysis

1

Data Analysis

Trend Analysis

Weibull Analysis

2

Event Data In Chronological Order

	Age	Event Type
1	8	F
2	18	F
3	38	F
4	23	F
5	19	F
6	14	F

Trend Analysis

Enter Significance Level (percentage)

Test Statistic

P-Value

Test Result

Plot Failure Data

Trend Test

3

Data Summary

Number of Failures

Age Unit

Observation Duration

Trend Test

Test Statistic

p-Value

Test Result

4

Total Number of Failures in Running Time

5

Save Result

6

# Perform Weibull analysis

Trend Analysis

Weibull Analysis

Fit Weibull

Weibull Report

Save Model

Current Component

Perkins2

Data Summary

Data Type

Ungrouped

Number of Failures

6

Age Unit

Months

Number of Suspensions

0

Estimated Parameters

Shape

2.09

Mean Life

20.21

Median Life

19.14

Scale

22.81

Standard Deviation

10.16

B10 Life

7.77

Location

0

Characteristic Life

22.81

Goodness of Fit - Kolmogorov-Smirnov Test

Kolmogorov-Smirnov Test Statistic

0.21

p-Value

0.92

Test Result

The hypothesis that the Weibull fits the data is NOT rejected at 5% significance level.

Weibull Probability Plot

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## Plot the graphs

Graphs

Hazard Rate

Failure PDF

Failure CDF

Reliability

Hazard Rate Function

Failure PDF Function

Failure CDF Function

Reliability Function

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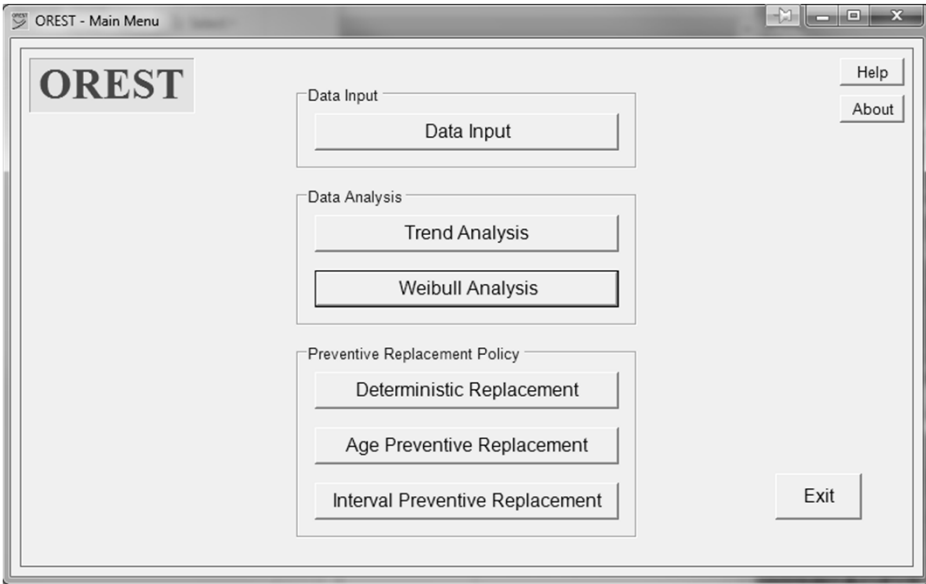
# Clutch failures

For the following truck clutch assembly failure data, use Weibull analysis to determine the parameters of the distribution. Also determine the mean life of the assembly.

Interval 1000 km	Failures
0-5	8
5-10	12
10-15	15
15-20	15
20-25	12
25-70	38

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# Open OREST



10

Start new analysis

1

Data Input

Data Input

2

Add Component...

3

New Component Data Input

Component Name

Clutch

Preventive Replacement Cost

Failure Replacement Cost

Number of Components in Service

Age Unit

1000 km

Cost Unit

Planning Horizon

Is Event Data Grouped?

☐ Yes

☒ No

Component Description

OK

Cancel

4

Components

Event Data

Operating Cost

List of Components

Air Filter

Bearing

Clutch

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Enter event data

Data Analysis

Trend Analysis

Weibull Analysis

OREST - Data Input

Components

Event Data

Operating Cost

Current Component

clutch

Event Data for the Current Component

Record No.	Age	Frequency	Event Type
1	2.5	8	F
2	7.5	12	F
3	12.5	15	F
4	17.5	15	F
5	22.5	12	F
6	47.5	38	F
*			

Update Database

Import Data

Print Data

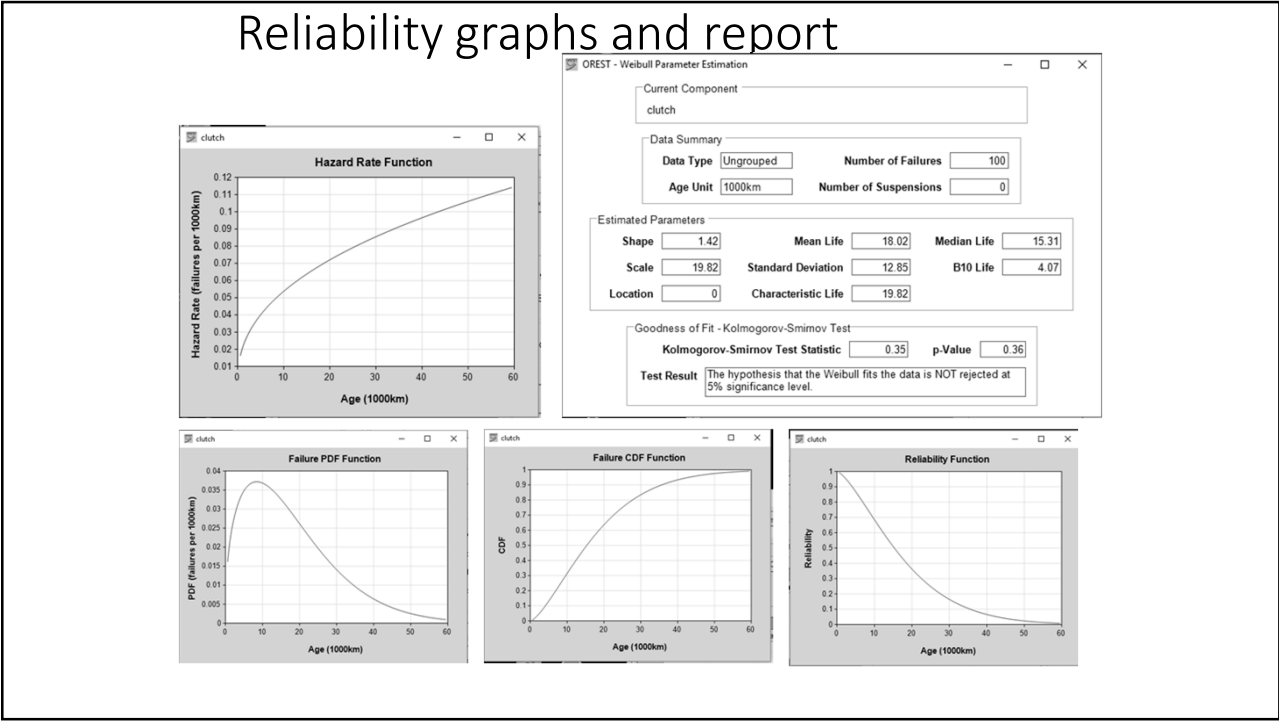
Export Data

Close

NB: Do not perform Trend Analysis. The purpose of Trend Analysis is to determine whether, over time as a result of changes in operating context there has been significant reliability growth or deterioration.

In this example, the data is “grouped”. We do not know the chronological order of the failure events. In the maintenance department data from the EAM will be from individual work orders and will not be grouped in this way.

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Starter motor (includes suspensions)

The following starter motor failure data includes suspensions. Determine the reliability characteristics of the motor.

Interval 1000 km	Failures	Suspensions
0-5	1	0
5-10	0	2
10-15	2	3
15-65	14	37

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Enter general and data

Component Data Edit

Component Name

Starter motor

Preventive Replacement Cost

100

Age Unit

1000km

Failure Replacement Cost

1000

Cost Unit

\$

Number of Components in Service

30

Planning Horizon

8

Is Event Data Grouped?

☐ Yes ☒ No

Component Description

OK

Cancel

OREST - Data Input

Components

Event Data

Operating Cost

Current Component

starter motor

Event Data for the Current Component

Record No.	Age	Frequency	Event Type
1	2.5	1	F
2	7.5	2	S
3	12.5	2	F
4	12.5	3	S
5	40	14	F
6	40	37	S
*			

Update Database

Import Data

Print Data

Export Data

Close

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Perform Weibull analysis

OREST - Weibull Parameter Estimation

Current Component

Starter motor

Data Summary

Data Type

Ungrouped

Number of Failures

17

Age Unit

1000km

Number of Suspensions

42

Estimated Parameters

Shape

1.26

Mean Life

94.39

Median Life

75.94

Scale

101.54

Standard Deviation

75.34

B10 Life

17.05

Location

0

Characteristic Life

101.54

Goodness of Fit - Kolmogorov-Smirnov Test

Kolmogorov-Smirnov Test Statistic

0.22

p-Value

0.99

Test Result

The hypothesis that the Weibull fits the data is NOT rejected at 5% significance level.

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4.2.1 Quiz 1 Reliability Analysis in 2D Workshop

<https://forms.gle/3cwReL6d2oBUmwc87>

1. We should perform trend analysis to verify whether there has been reliability growth or reduction when: \*

1 point

☐ The data sample of lifetimes extends over a long calendar time.

☐ In the sample period a fundamental change in the asset's design has occurred.

☐ There has been a significant shift in operating context over the sample period.

☐ There has been a significant change in the asset's age-reliability behavior pattern.

☐ all of the above

☐ none of the above

2. The following are ways in which we may express or approximate an item's reliability: \*

1 point

reliability: \*

☐ B10 life

☐ MTTF

☐ Characteristic life

☐ Median life

☐ The hazard, reliability, and probability density graphs.

☐ all of the above

☐ none of the above.

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4.2.2 Optimal maintenance strategies

We will include "business factors" to the previous Weibull analyses for PM decision making.

Module 4.2 B

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## Age Preventive Replacement Policy

A policy called "Age Preventive Replacement" applies when the following is true:

1. When a failure occurs, the item is renewed at a fixed cost (called the "failure renewal cost").
2. When the item is renewed preventively the cost of renewal (called the "preventive renewal cost") is smaller than the failure renewal cost.

The optimal preventive renewal age balances the preventive and failure renewal costs so as to minimize the expected total renewal cost per unit of age.

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**For Perkins engine:** Given that the Failure Renewal Cost is \$1000 and the Preventive Renewal Cost is \$100, use OREST's Age Preventive Replacement Policy calculation to discover:

1. The optimal preventive replacement age that minimizes the average maintenance (failure and PM) cost.
2. The average monthly maintenance (failure and PM) cost.
3. The average PM monthly cost.
4. A plot of the average monthly cost versus the replacement age. Does the minimum on this plot correspond to your answers to questions 1 and 2?
5. If there are 10 engines in service and an engine can be rebuilt in 2 months (the "planning horizon") what is the number of spare engines required?

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# Verify the general data

Information needed for  
spares calculation:

- 1. There are 10 operating engines in service, and
- 2. It takes two months (planning horizon) to rebuild and deliver an engine.

Component Data Edit

Component Name

Perkins2

Preventive Replacement Cost

100

Age Unit

Months

Failure Replacement Cost

1000

Cost Unit

\$

Number of Components in Service

10

Planning Horizon

2

Is Event Data Grouped?

☐ Yes

☒ No

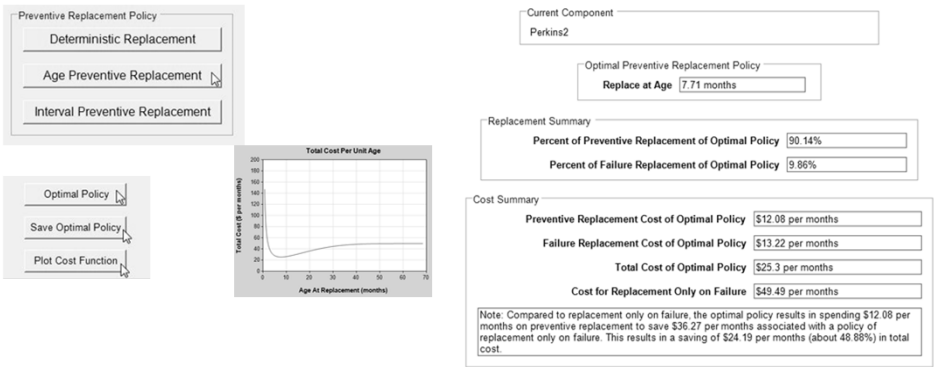
Component Description

OK

Cancel

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# Conduct an Age Preventive Replacement calculation



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### Calculate spares requirement

Spare Parts Requirement

☒ Optimal ☐ User-defined

Spare Parts Requirement

Data Input

Close

Current Component

Perkins2

Parameters

Planning Horizon

2 months

Number of Components in Service

10

Replacement Policy Used

Optimal Replacement: Replace at age 7.71 months

Spare Parts Requirement

Number of Spares Required

2.68

Number of Spares Required for Preventive Replacement

2.42

Number of Spares Required for Failure Replacement

0.26

Number of Spares Required for Replacement Only on Failure

0.99

The optimal policy resulting in lowest (PM and Failure) cost will require a capital investment of 3 spare engines. The organization will weigh that capital investment against the operational monthly savings of \$24.19.

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### Interval Preventive Replacement Policy

Sometimes it is not practical to replace an item based on its individual age. For example, the street lights for an entire block might be replaced all at the same time, given the set up time required.

An "Interval Preventive Replacement" policy is also called "block" or "group" replacement.

The difference (from an age preventive maintenance policy) is that a constant calendar interval rather than an equipment age interval is used for scheduling preventive renewal. This means that an engine will be replaced preventively according to scheduled calendar intervals regardless of its actual “working” age.

So we are required to find the optimal calendar based preventive replacement interval that minimizes monthly (failure plus preventive) renewal costs.

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# Perkins Engine: Interval Preventive Replacement

Assume, due to business factors, that preventive engine replacement can only be done on these engines at fixed calendar intervals.

Using the same data, calculate as in the optimal calendar time replacement interval which will minimize total cost per unit of time?

How does the total cost per unit of time compare with the total cost per unit of age? If the results appear similar, explain why.

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# Perform Interval Preventive Replacement calculation

Preventive Replacement Policy

Deterministic Replacement

Age Preventive Replacement

Interval Preventive Replacement

Optimal Interval Replacement

Optimal Prev Repl Interval

Average Total Cost

Average Prev Repl Cost

Optimal Policy

Save Optimal Policy

Plot Cost Function

Optimal Preventive Replacement Policy

Replace at Time Interval 7.64 months

Replacement Summary

Number of Preventive Replacement of Optimal Policy 1

Number of Failure Replacement of Optimal Policy 0.1

Cost Summary

Preventive Replacement Cost of Optimal Policy \$13.08 per months

Failure Replacement Cost of Optimal Policy \$12.87 per months

Total Cost of Optimal Policy \$25.95 per months

Cost for Replacement Only on Failure \$49.49 per months

Note: Compared to replacement only on failure, the optimal policy results in spending \$13.08 per months on preventive replacement to save \$36.62 per months associated with a policy of replacement only on failure. This results in a saving of \$23.54 per months (about 47.57%) in total cost.

Total Cost Per Unit Time

The interval renewal results are not too different from those of the age renewal since the engines probably work more or less steadily with calendar time.

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# Perform spares calculation

Spare Parts Requirement

☒ Optimal ☐ User-defined

Spare Parts Requirement

Parameters

Planning Horizon

2 months

Number of Components in Service

10

Replacement Policy Used

Optimal Replacement: Replace at interval 7.64 months

Spare Parts Requirement

Number of Spares Required

2.88

Number of Spares Required for Preventive Replacement

2.62

Number of Spares Required for Failure Replacement

0.26

Number of Spares Required for Replacement Only on Failure

0.06

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# Deterministic Replacement Policy

No age (failure and suspension) data available with which to perform reliability (Weibull) analysis)

A "Deterministic Replacement" (as opposed to a probabilistic) policy applies when:

1. The item's operating cost increases with age; (for example it runs less efficiently, requires more repair), and
2. Its renewal (replacement or overhaul) cost is fixed.
3. We do not have age data with which to build a Weibull data.
4. We have, from accounting records, the monthly (or yearly) costs of operating the item(s). The records indicate that the operating cost increases as the item gets older. From this we would surmise that:
  - The real cost (overall to the organization) of replacement (per unit of operational time) *decreases* as the item's service age increases.
  - The optimal replacement age (as a policy) should account for the increasing operating cost and the replacement cost per unit of time so as to minimize the total cost (operating + replacement) per unit time over the life cycle of the item.

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Perkins engine – Deterministic Policy

Assume we do not have age data with which to build a Weibull model. But the operating costs during various age intervals are given below:

	Age Interval	Operating Cost
1	50	10
2	75	12
3	100	15
▶ 4	125	20

Renewal cost: 100

This analysis is independent of the Weibull model developed in the previous section for the Perkins engine. For this problem, we use only the above operating cost data.

Given the PM renewal cost is \$100, find the optimal preventive renewal strategy based on the business data given in the table above.

We can say that for the first 50 weeks the average weekly cost is \$10. For the next 75 weeks the operating cost is \$12 per week. And so on.

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Calculate the optimal renewal age of an engine and related costs.

1

Data Input

2

Operating Cost for the Component Selected

Age Interval No.	Age Interval	Operating Cost
▶ 1	50	10
2	75	12
3	100	15
4	125	20

3

Operating Cost for the Component Selected

Age Interval	Operating Cost	Total Cost
1	50	10
2	75	12
3	100	15
▶ 4	125	22

3a

Age Interval	Operating Cost	Total Cost
1	50	10
2	75	12
3	100	15
▶ 4	125	22

4

Optimal Replacement Age

Compute Total Cost

Compute Optimal Replacement Age

Plot Total Cost

Save Result

Total Cost Per Unit Age

Age At Replacement (Months)	Total Cost (\$ per Month)
50	10
75	12
100	15
125	22

Optimal Replacement Policy

Age Interval	Operating Cost	Total Cost
▶ 1	50	10
2	75	12
3	100	15
4	125	22

Optimal Replacement Age

Compute Total Cost

Compute Optimal Replacement Age

Plot Total Cost

Save Result

Optimal Deterministic Replacement Policy

Replace at Age 75 months

Cost Summary

Replacement Cost of Optimal Policy	\$1.33 per months
Operating Cost of Optimal Policy	\$10.67 per months
Total Cost of Optimal Policy	\$12 per months

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4.2.1 Quiz 2 Reliability Analysis in 2D Workshop

<https://forms.gle/PnL974HSYDmRH6ir9>

1. If a PM policy is based solely on an item's age we might schedule renewal at fixed intervals provided: \*

1 point

☐ The Weibull shape parameter is greater than 1.

☐ Failure probability is age dependent.

☐ The hazard curve increases with age.

☐ The costs associated with a failure exceed the cost of a preventive task.

☐ all of the above

☐ none of the above.

2. The number of spares required to be kept in stock depends on: \*

1 point

☐ The planning horizon.

☐ The number of operating units.

☐ The preventive replacement interval.

☐ all of the above

☐ none of the above.

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