04.3B "Reliability analysis > 2D"

In this step, we'll use an advanced reliability analysis tool, called "EXAKT", to process our combined age and condition data sample.

1. Download and install the EXAKT application.
2. Unzip data file onto your desktop.

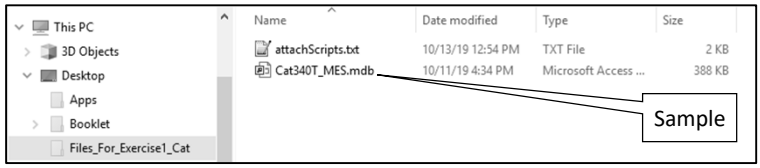
Our sample is in a database file called "**Cat340T_MES.mdb**" in the folder, say, "**\Desktop\Files_For_Exercise1_Cat**".

There is also a text file called "AttachScripts.txt" containing scripts to be used.

1 Download Application and Data file

https://www.livingreliability.com/en/posts/cbm-exercises/

2



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1

Open the EXAKT for Modeling app

1

1. Launch the "EXAKT for Modelling" program.

Slide 2

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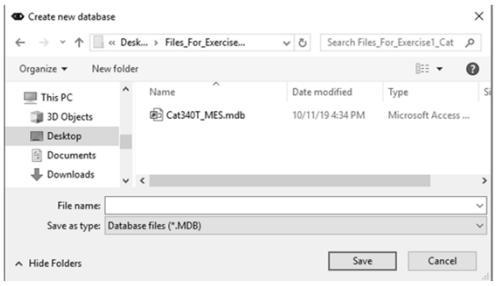
2

Creating a database for building (and maintaining) the model

1

1. Hit **File** and **New**
2. Then navigate to the folder "**\Files_For_Exercise1_Cat**".
3. Enter File name: **Cat340T_WMOD.mdb** and hit **Save**

2



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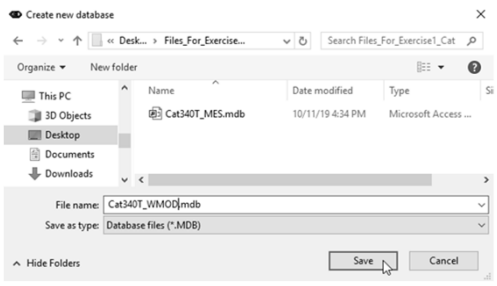
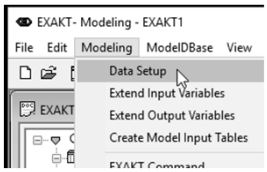


Slide 3

3

Connecting the model to the sample (age and CBM) data

1



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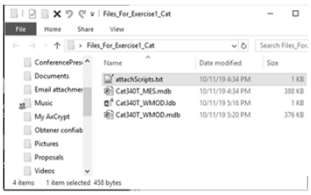

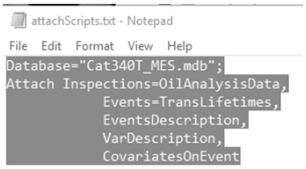

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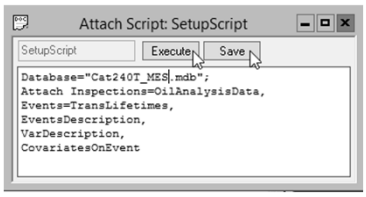


1. Hit Modeling and Data Setup,
2. Copy the first script (from the attachScripts.txt file)
3. Paste it into the Attach Script: SetupScript window. Hit Execute, Save

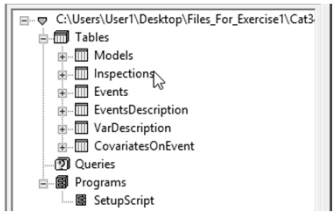
Examine the attachment script.
Note that it links to our "Cat340T_MES.mdb" database containing the sample.
Then in lines 2 to 6 it attaches a number of tables relevant to the sample.

Slide 4

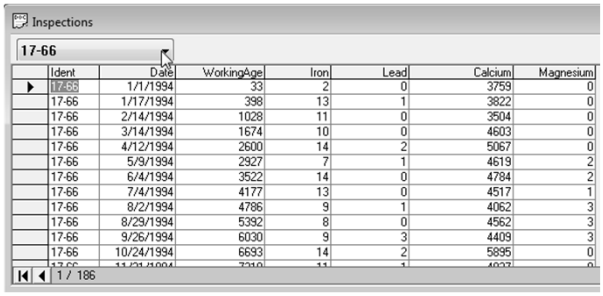
4

Examining the Inspections table

1



2



Ident	Date	WorkingAge	Iron	Lead	Calcium	Magnesium
17-66	1/1/1994	33	2	0	3759	0
17-66	1/17/1994	398	13	1	3822	0
17-66	2/14/1994	1028	11	0	3504	0
17-66	3/14/1994	1674	10	0	4603	0
17-66	4/12/1994	2600	14	2	5067	0
17-66	5/9/1994	2927	7	1	4619	2
17-66	6/4/1994	3522	14	0	4784	2
17-66	7/4/1994	4177	13	0	4517	1
17-66	8/2/1994	4786	9	1	4062	3
17-66	8/29/1994	5392	8	0	4562	3
17-66	9/26/1994	6030	9	3	4409	3
17-66	10/24/1994	6693	14	2	5895	0

1. Double click Inspections in the tree.

Note the column names and content. Ident, Date, and WorkingAge. "Ident" is the unique name of each unit of a specific equipment type to be analyzed.

The "Date" must be in date or in date/time format if multiple readings occur in a 24 hour period.

The WorkingAge is a measure such as hours of operation, fuel consumed, thousands of feet of steel rolled, or any other measurement used by the EAM to measure the accumulated usage or stress on the unit.

Calendar time may be used here if the units operate more or less regularly in time.

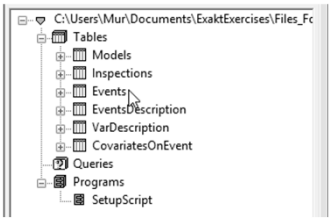
2. Close the Inspections table

Slide 5

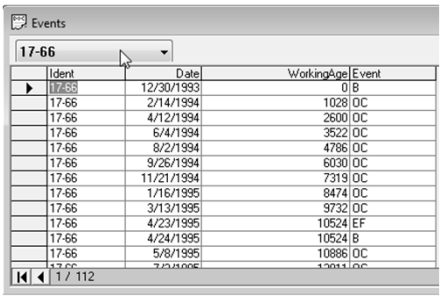
5

Examining the Events table

1



2



Ident	Date	WorkingAge	Event
17-66	12/30/1993	0	B
17-66	2/14/1994	1028	OC
17-66	4/12/1994	2600	OC
17-66	6/4/1994	3522	OC
17-66	8/2/1994	4786	OC
17-66	9/26/1994	6030	OC
17-66	11/21/1994	7319	OC
17-66	1/16/1995	8474	OC
17-66	3/13/1995	9732	OC
17-66	4/23/1995	10524	EF
17-66	4/24/1995	10524	B
17-66	5/8/1995	10886	OC

1. Open the Events table.

Examine the Events table. The Events table holds the age data.
The important Events are:

1. "B" The Beginning of a failure mode life.
2. "EF" The life's Ending by Failure, and
3. "ES" The life's Ending by Suspension. The object part has been taken out of service and replaced for any reason other than failure.

"Non-rejuvenating" events may be included. For example an oil change. "OC" represents an "oil change" event.

If the oil change occurs more ore less at regular intervals it doesn't have to be included since the model will "self-adapt" to a periodic drop in condition monitoring variable.

2. Close the Events table

Slide 6

6

Examining the other tables

1

CovariatesOnEvent

	Event	StartingDate	EndingDate	Iron	Lead	Calcium	Magnesium
▶	B	1/1/1900	1/1/2100	0	0	5000	0
	OC	1/1/1900	1/1/2100	0	0	5000	0
	ES	1/1/1900	1/1/2100	0	0	5000	0
	EF	1/1/1900	1/1/2100	0	0	5000	0
	*ES	1/1/1900	1/1/2100	0	0	5000	0
*							

2

EventsDescription

	EventName	Precedence	Comment
▶	B	1	Oil Change
	EF	2	Failure
	ES	3	Suspension
	B	4	Begin History
*			

3

VarDescription

	VariableName	Comment
▶	Iron	Iron level in oil in ppm
	Lead	Lead level in oil in ppm
	Calcium	Calcium level in oil in pp
	Magnesium	Magnesium level in oil ir
*		

Hit CovariatesOnEvent

1. Open the CovariatesOnEvent table.

It contains condition data "initialization values" for each event. In this case we are initializing wear metals and contaminants in the lube oil to zero and additives to their new-condition levels. We may also establish calendar periods for which these initialized values to be used. (For example, the brand or grade of lubricating oil may change periodically.)

2. Openthe EventsDescription table.

The column "Precedence" tells EXAKT algorithm in which order to consider separate events that occur at the same date. A CBM inspection event, implicitly has a precedence of 0. An oil change event, therefore must be given a precedence > 0.

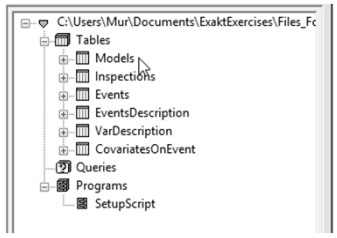
3. Examine the VarDescription table.

The VariableName columns contains the candidate condition Indicators (feature of a time series, Fourier transform, or in this case, oil analysis data). Using the modeling functions of EXAKT we will determine which features influence failure probability. We call these features "condition indicators".

7

Models table

1



Models

Model	SubModel	Default	Description	InspectionInterval	FailureCost	Replaceme
*						

1. Open the Models table.

- It contains no records yet. That is because we have not yet begun building a model.
- This table is populated automatically as we proceed.
- The only time you might access this table manually would be to delete certain trial model that you do not wish to retain.
- In the software, a trial model is called a sub-model.
- It is one of any number of models that we test in the modelling process.
- The sub-model that we retain, will be exported for use by an automated decision agent
- The agent, called "EXAKT for decisions" or EXAKTd will use that model to process new condition data as it arrives in designated data tables.
- The agent will provide optimized decision support, most importantly the Remaining Useful Life Estimite (or RULE) to the maintenance planner, along with a confidence interval.

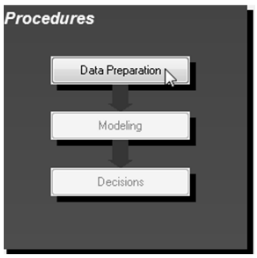
8

The general project data

Now that we have examined the internal and external database tables, we can proceed with the development of a CBM optimization model.

1. Hit Data Preparation
2. Hit the “Enter General Data” button.
3. Now enter the project information as shown. You can copy and paste from the **attachScripts.txt** file as before.

1



2

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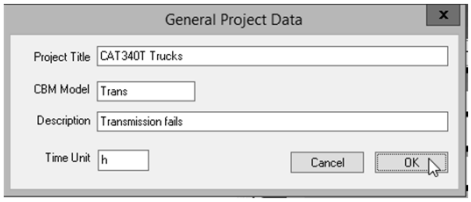


9

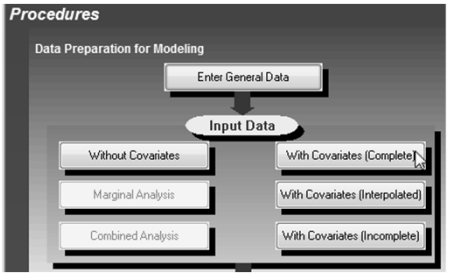
Combining the Events and Inspections tables into a single "virtual" table C_Inspections

1. Hit the button labelled “With Covariates (Complete)”. (
Open and close a table in the tree if the button is not active.

2. Examine the C_Inspections table.
Note that the records of both tables (Events and Inspections) have been combined. And they have been arranged in chronological order.

3. Close C_Inspections

1



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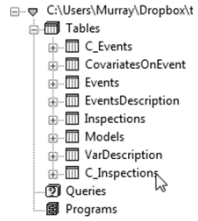
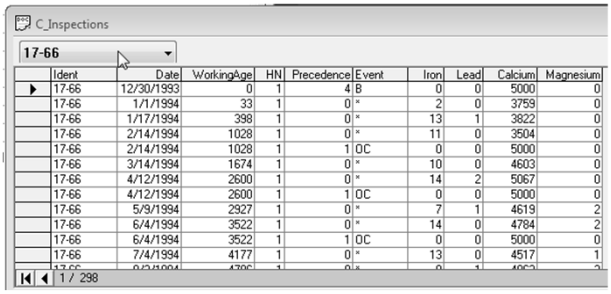


3

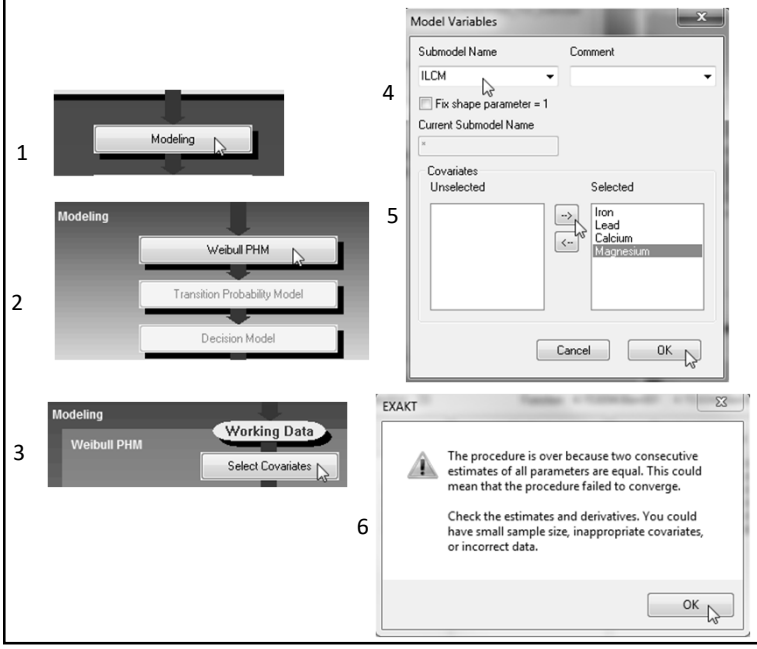


Ident	Date	WorkingAge	HN	Precedence	Event	Iron	Lead	Calcium	Magnesium
17-66	12/30/1993	0	1	4	B	0	0	5000	0
17-66	1/1/1994	33	1	0	"	2	0	3759	0
17-66	1/17/1994	398	1	0	"	13	1	3822	0
17-66	2/14/1994	1028	1	0	"	11	0	3504	0
17-66	2/14/1994	1028	1	1	OC	0	0	5000	0
17-66	3/14/1994	1674	1	0	"	10	0	4603	0
17-66	4/12/1994	2600	1	0	"	14	2	5067	0
17-66	4/12/1994	2600	1	1	OC	0	0	5000	0
17-66	5/9/1994	2927	1	0	"	7	1	4619	2
17-66	6/4/1994	3522	1	0	"	14	0	4784	2
17-66	6/4/1994	3522	1	1	OC	0	0	5000	0
17-66	7/4/1994	4177	1	0	"	13	0	4517	1

1 / 298

10

Building a trial model with all four candidate CBM variables



Now we begin the "modelling" phase of the analysis.

1. Hit the "Modelling" button,
2. Hit the "Weibull PHM" button
3. Next hit "Select Covariates",

We'll start by building a model with all 4 condition variables (iron, lead, calcium, and zinc) present in the CBM data.

4. Enter "ilcm" for Submodel Name.
5. Move all four elements from the left column to the right column.
6. Hit OK twice,

Ignore the convergence warning which is normal for small samples.

11

Examining the proportional hazard model parameter estimation results

Haul Trucks

EXAKT, Condition - Based Maintenance Software 04:58 PM Sat., Sep. 05, 2015

Preventive renewals

Units presently operating

Number of lifecycles in sample

Parameter Estimation

Transmission (IL… (350 T Transmission - Oil Analysi…

Summary of Events and Censored Values

Sample Size	Failed	Censored (Def)	Censored (Temp)	% Censored
13	6	3	4	53.8

Variable is Significant yes /no

Measure of scatter

Summary of Estimated Parameters (based on ML method)

Shape (Age) parameter β

Parameter	Estimate	Sign. (*)	Standard Error	Wald	DF	p - Value	Exp of Estimate	95 % CI Lower	95 % CI Upper
Scale	1.614e+005	-	4.027e+005	-	-	-	-	0	9.506e+005
Shape	4.276	Y	1.668	3.855	1	0.04961	-	1.006	7.545
Iron	0.2433	Y	0.08153	8.905	1	0.002844	1.275	0.08349	0.4031
Lead	1.129	Y	0.3681	9.4	1	0.00217	3.092	0.4072	1.85
Calcium	0.0009996	N	0.001464	0.4661	1	0.4948	1.001	-0.00187	0.00387
Magnesium	0.03502	N	0.06891	0.2583	1	0.6113	1.036	-0.1	0.1701

(-) Not applied

(*) Based on 5% significance level. Shape = 1 tested, Gamma (Cov) = 0 tested

$$(t, \boldsymbol{Z}(t); \beta, \square, \bar{\gamma}) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left(\sum_{i-1}^{m} \gamma_i Z_i(t)\right)$$

1. Examine the Parameter Estimation report

The results of the our first trial PHM calculation are displayed in a Parameter estimation report.

Of the 13 histories 6 ended in failure, 3 ended prior to a failure, and 4 units are currently in operation at the moment of this sample. Currently operating units are referred to in EXAKT as "temporary suspensions" and they are identified automatically by the software.

The third column "Sign." indicates significance. If Shape is significant, it means that the item's working age influences the short term failure probability.

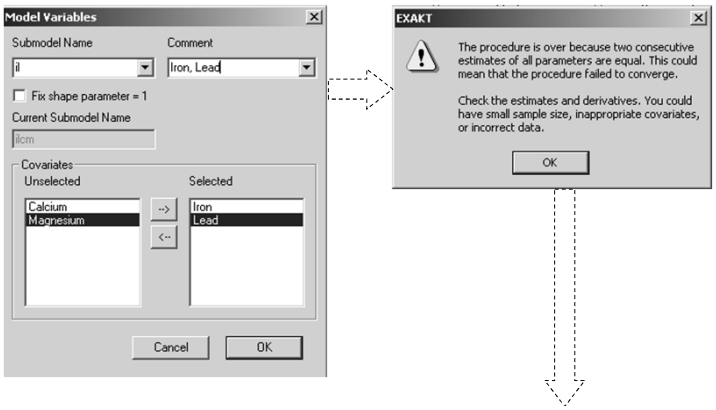
In addition to shape, Iron, and Lead are designated as significant.

Slide 12

12

Eliminating the non-significant variables

5



Summary of Estimated Parameters (based on ML method)

Parameter	Estimate	Sign. (*)	Standard Error	Wald	DF	p - Value	Exp of Estimate	95 % CI	
								Lower	Upper
Scale	3.899e+04	-	1.638e+04	-	-	-	-	6882	7.109e+04
Shape	5.007	Y	1.157	11.99	1	0.0005352	-	2.739	7.276
Iron	0.2626	Y	0.07738	11.52	1	0.000689	1.3	0.111	0.4143
Lead	1.052	Y	0.376	7.83	1	0.005138	2.864	0.3152	1.789

(-) Not applied
(*) Based on 5% significance level. Shape = 1 tested, Gamma (Cov) = 0 tested

The next step is to try a different model by eliminating the variable whose impact on the probability of failure is the least significant, that is, having the highest p-value, – it is magnesium.

1. Close the PHM Parameter Estimation report window and repeat the previous steps to create 2 more sub-models:
2. Name the submodel "ilc", and move Magnesium to the right column.
3. Hit OK twice.
4. Close the report and do the same for calcium, which now has the highest p-value.
5. Name the sub-model "il".

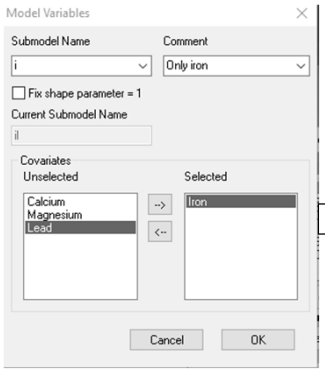
We successively removed covariates with the highest reported p-Value.
The other columns in the "Summary of Estimated Parameters" table contain supporting statistics. They are well-explained in the Exakt Manual. We don't need to go into them in this exercise.

Slide 13

13

Determining if a "simpler" (iron alone) model is good enough

1



At this point we have a candidate sub-model with two covariates. iron and lead, and a shape parameter that are all significant. To be rigorous, we should test one last possible combination – a sub-model with iron alone. Would a model with Iron alone be as good (that is provide the same predictive performance) as a model containing both Lead and Iron.

1. Hit "Select Covariates", move lead to the left column, and rename the model to "I". Hit OK twice.

The report tells us that this is also a potentially good predictive model (i.e. iron alone is still significant). But will it perform as well? In the next step we'll decide which of the two sub-models (i or il) should be retained and deployed for decision support.

Summary of Estimated Parameters (based on ML method)

Parameter	Estimate	Sign. (*)	Standard Error	Wald	DF	p - Value	Exp of Estimate	95 % CI	
								Lower	Upper
Scale	1.895e+04	-	3075	-	-	-	-	1.292e+04	2.498e+04
Shape	5.506	Y	1.577	8.167	1	0.004266	-	2.416	8.596
Iron	0.2293	Y	0.05107	20.15	1	0	1.258	0.1292	0.3294

(-) Not applied
(*) Based on 5% significance level. Shape = 1 tested, Gamma (Cov) = 0 tested

Slide 14

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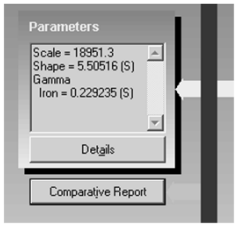
Comparative report

1



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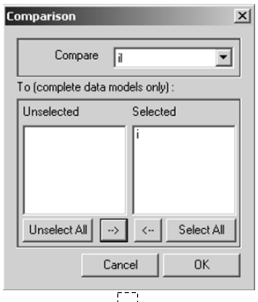


3

4

Submodel	Close to Base (*)	Deviance Change	DF	Proba-bility
Base il		0	0	1
i	N	10.6113	1	0.00112

(*) Based on 5% significance level

1. Hit the "Comparative Report" button.
2. In the compare drop down list, select il,

the more complex of the two models. We always begin the comparison with the model having a greater number of covariates (condition indicators).

3. Transfer the "i" submodel to the right hand column. Hit OK and
4. examine the "PHM Parameter Estimation – Comparison" report

The "N" in the second column is telling us that the sub-model "i" is not close, in terms of a statistic called "deviance" to the base sub-model "il".

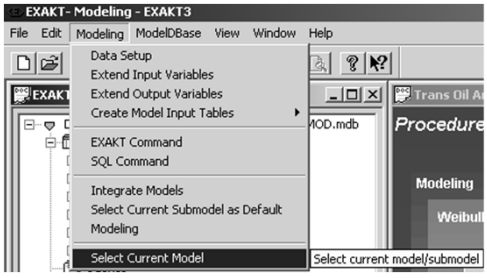
This means that this simpler sub-model will be less performant than the il model. That is, the il model contains significant predictive information that is not present in the i model. We would be losing confidence by using "i" rather than the more complete model "il".

Slide 15

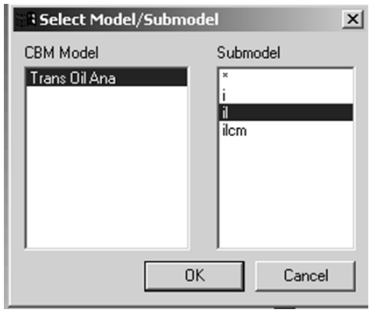
15

Reactivate the model to be retained "il"

1



2



We'll, therefore, reactivate the "il" model.

1. Hit anywhere in the left window pane. Hit "Modeling" on the menu bar, and select "Select Current Model" in the submenu.
2. Select the sub model "il". Hit OK.

Notice that the current Model "Trans (il)" now appears in the title bar of the right hand window pane. It may also appear in the title bar of the EXAKT main window.

Slide 16

16

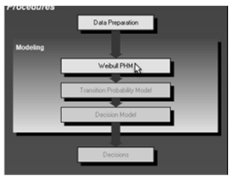
1. Hit the Modeling button (not the Modeling menu item).
2. Hit Weibull PHM.
3. Hit the "Summary Report" button.
4. The table "Summary of Goodness of Fit Test" report tells us that the proportional hazard equation is a good fit to the data we used in its construction.

The test used for this is known as the Kolmogorov Smirnov test, which is reliable with large samples and relatively few suspensions.

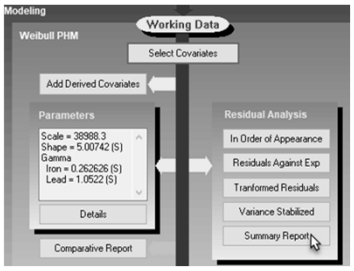
Testing the PHM

1

2



3



4

Haul Trucks

EXAKT, Condition - Based Maintenance Software 01:58 PM Sat., Jun. 04, 2016

PHM Goodness of Fit Test
(Based on Cox - generalized Residuals)

Trans (il) (350 T Transmission)

$$(t, \mathbf{Z}(t); \beta, \eta, \bar{\gamma}) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} exp\left(\sum_{i=1}^{m} \gamma_i Z_i(t)\right)$$

Summary of Events and Censoring Values

Sample Size	Failed	Censored (Def)	Censored (Temp)	% censored
13	6	3	4	53.8

Summary of Estimated Parameters

Scale	Shape	Iron	Lead
38988.3	5.00742	0.262626	1.0522

Summary of Goodness of Fit Test

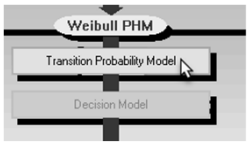
Test	Observed Value	p - Value	PHM Fits Data
Kolmogorov - Smirnov	0.288432	0.191072	Not rejected (*)

(*) based on 5% significance level

17

Predicting Condition Indicator values

1



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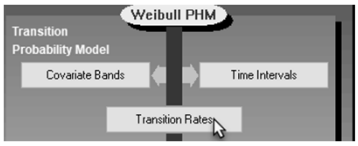

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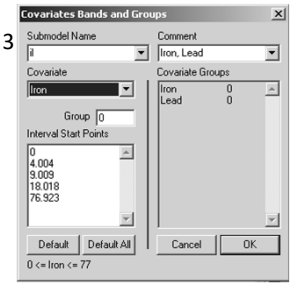

4

We've constructed an equation that gives us reliability as a function of age and condition indicators found to be significant. For predictive maintenance, we will also need the probable trajectory in time of those condition indicators. We do this by defining condition data states. The condition data changes (transitions) from one state to another.

1. Hit the "Transition Probability Model" button.
2. Hit "Transition Rates button".
3. Examine the Lead bands, and then the Iron bands (using the drop down list box "Covariate".

EXAKT has created a set of bands or states. These are "transition" states for Lead and Iron. These divisions or bands are used by the software to build a "transition probability model". The transition probability model calculates the probability of jumping to another state at the next inspection. To create the transition bands EXAKT has examined all previous condition data in the CBM database and determined reasonable boundaries to define the states, e.g. normal, good, poor, marginal, critical. This will add predictive capability to our model.

4. Hit OK.

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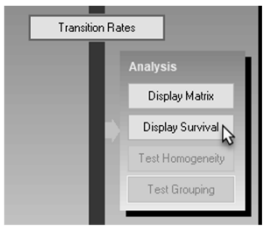
1



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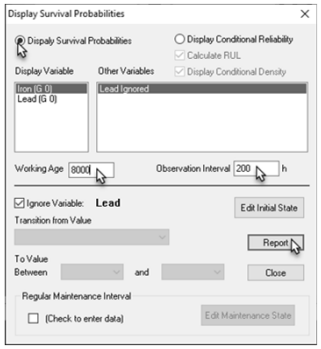

3

Transition Probabilities

Iron	State At Age: 8200.00 [Hrs.]					
State At Age: 8000.00 [Hrs.]	0 to 4.004	4.004 to 9.009	9.009 to 18.018	18.018 to 76.923	Above 76.923	Failed
0 to 4.004	0.651472	0.301615	0.042711	0.000892	0.000006	0.003304
[illegible]	[illegible]	[illegible]	0.175604	0.004214	0.000024	0.040572
9.009 to 18.018	0.001157	0.071115	0.796861	0.022628	0.000174	0.108065
18.018 to 76.923	0.000001	0.000117	0.001068	0.000024	0.000000	0.998790
Above 76.923	*	*	*	*	*	*

* The case is not applicable

Transition probability matrix

1. Hit "Display Survival". (Hit "Transition Rates" (if the display Matrix Survival button is inactive).)
2. For "Working Age" enter 8000. For "Observation Interval" enter 200. Select "Display Survival" and hit the "Report" button.

The "Survival Probability matrix" is displayed. The probabilities of Iron values jumping to another state and the probability of failure in the upcoming interval are displayed in a tabular format.

3. Note, for example, that if we are currently in state "0- 4.004" there is a 30.1615% probability that iron will move to the next state in 200 hours.

This report provides the probabilities of being in any state at some future time. These transition probabilities will be used in the prediction and decision model to be developed next.

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Setting the decision (business) model parameters

1

2

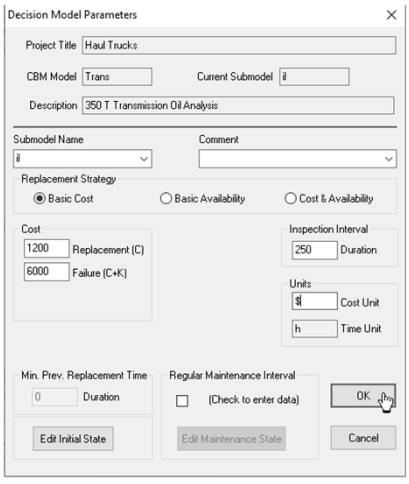
1. Hit Decision Model.
2. Then hit Decision Model Parameters.
3. Select Basic Cost

We choose cost minimization as our optimizing objective.

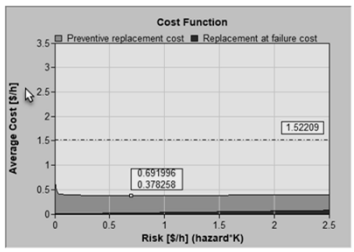
4. In the Replacement (C) box enter 1200,
5. In the Failure (C+K) boxe enter 6000,

6. For Cost Unit enter a $ sign.
7. And for Inspection Interval enter 250.
8. Hit OK.
9. When the cost function graph appears, it the Full Report Icon.

3



4 5 6 7 8



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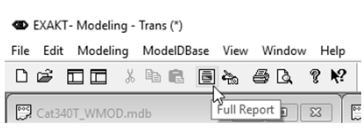

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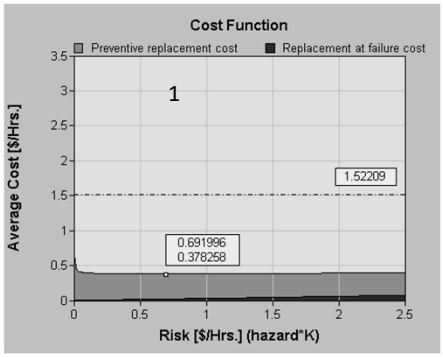
Examining the optimal decision policy cost analysis



Summary of Cost Analysis

	Cost [$/Hrs.]	Preventive Repl. Cost [$/Hrs.]	Failure Repl. Cost [$/Hrs.]	Prev. Repl. [%]	Failure Repl. [%]	Expected Time Between Replacements
Optimal Policy	0.378258	0.356373 (94.2 %)	0.0218851 (5.8 %)	98.8	1.2	3326.4
Replacement Only At Failure	1.52209	0 (0.0 %)	1.52209 (100 %)	0.0	100.0	3941.95
Saving	1.14383 (75.1 %)	-0.356373	1.5002	-98.8	98.8	-615.548

1 2

The "Condition Based Replacement Policy – Cost Analysis" report appears.

1. Examine the "Summary of Cost Analysis" table. It says that by adhering to the interpretive decisions of our model, we'll achieve a cost savings of 75.1% over a replacement-only-at-failure policy. (We will look at the actual decision model in the next step.)
2. Since "optimal" implies a balance or a compromise, note, in this example that the expected frequency of intervention is slightly higher. In other words we are buying low cost and paying for it with slightly higher preventive activity.

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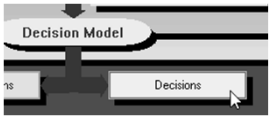
Decision model testing

1



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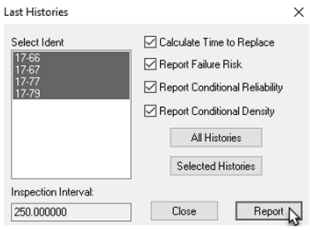

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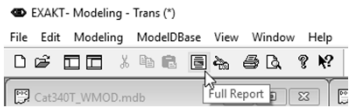

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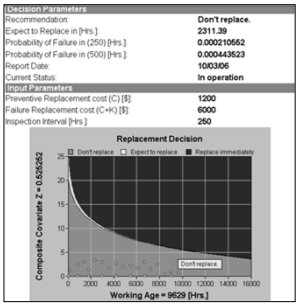

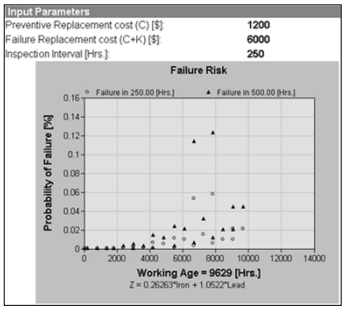

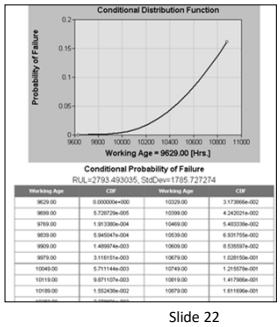

1. Hit "Decisions".
2. Select all four units in the fleet. Hit Report.
3. Hit the Full Report Icon.
4. Hit PgDn to see the results of the model applied to the selected equipment.

Successively hitting PgDn, four sets of prediction graphs are shown – one for each of the four units in the fleet.

In the next step we'll put the model to work.

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