بازآموزی مدیران فنی و نگهداری و تعمیرات
دومین همایش
2nd International Physical Asset Management Conference

Inspection Decisions including Condition-Based Maintenance

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August 2006

Reliability Improvement through Inspection Decisions

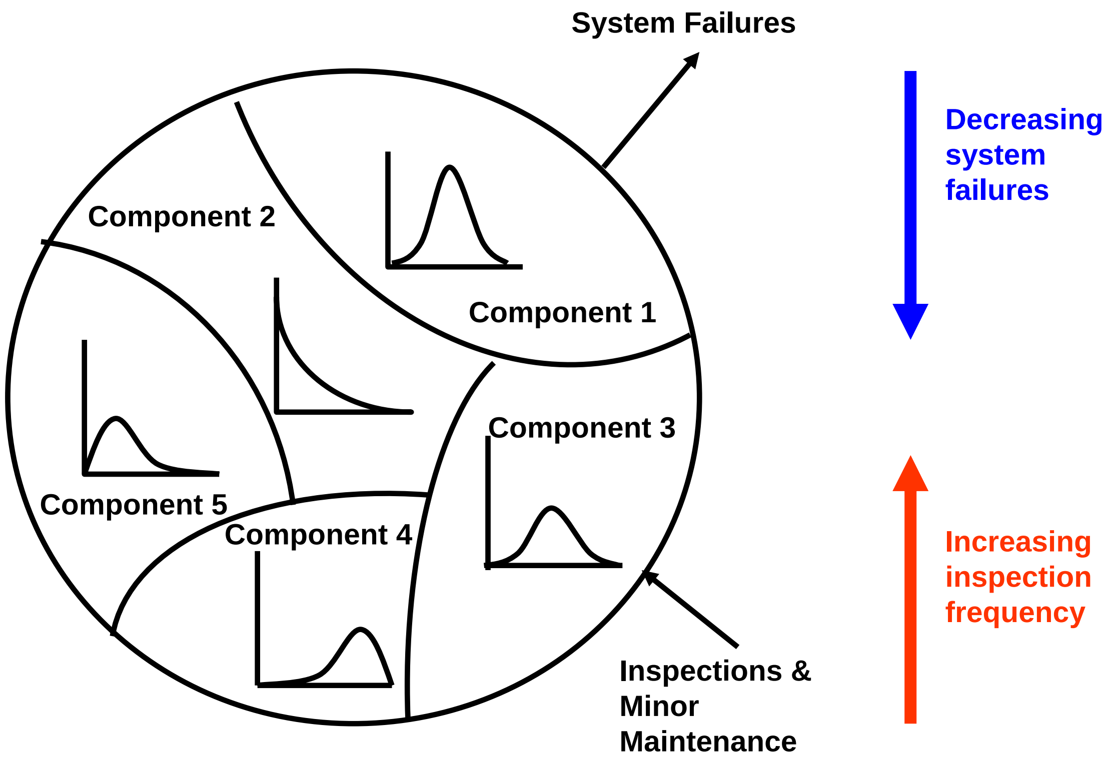
Inspection Problems

1. Inspection frequencies for equipment which is in continuous operation and subject to breakdown.

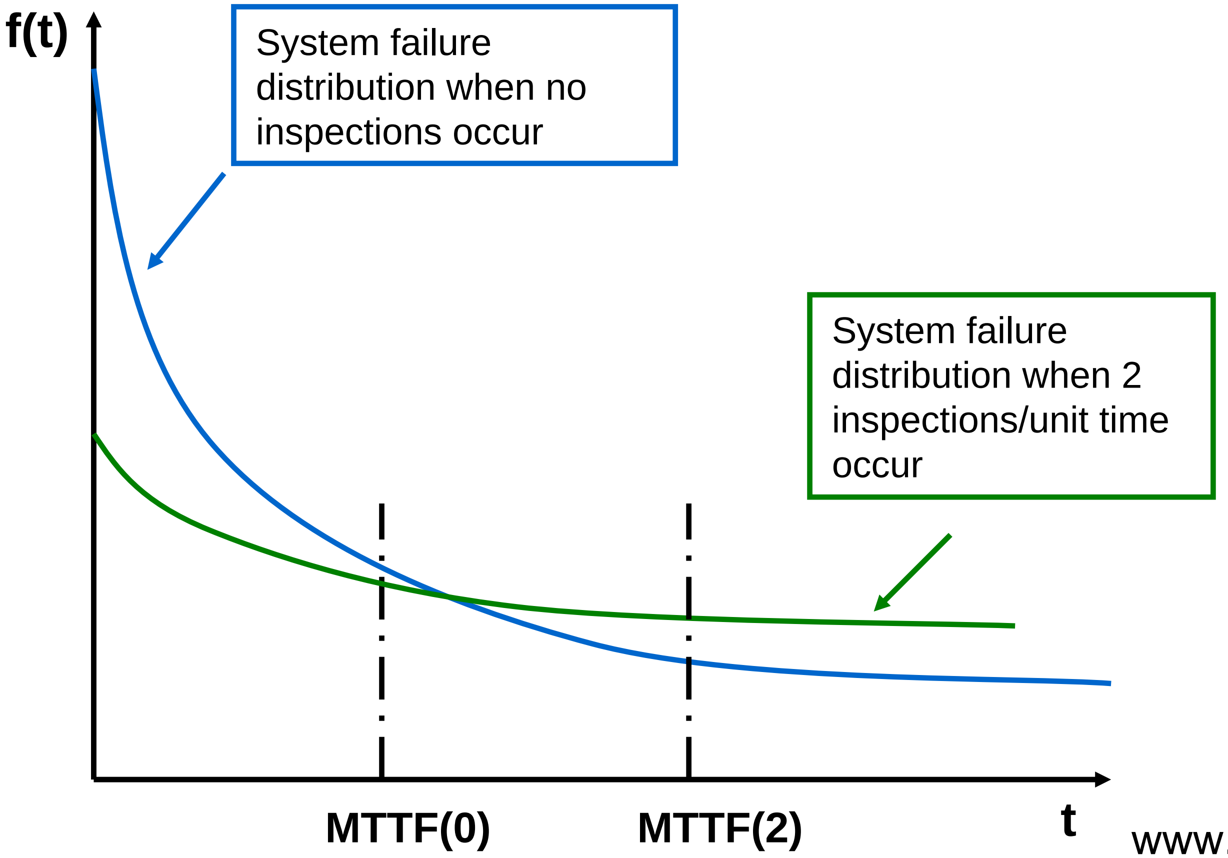
2. Inspection intervals for equipment used only in emergency conditions. (Failure finding intervals)

3. Condition monitoring of equipment: Optimizing condition-based maintenance decisions.

Inspection Problems



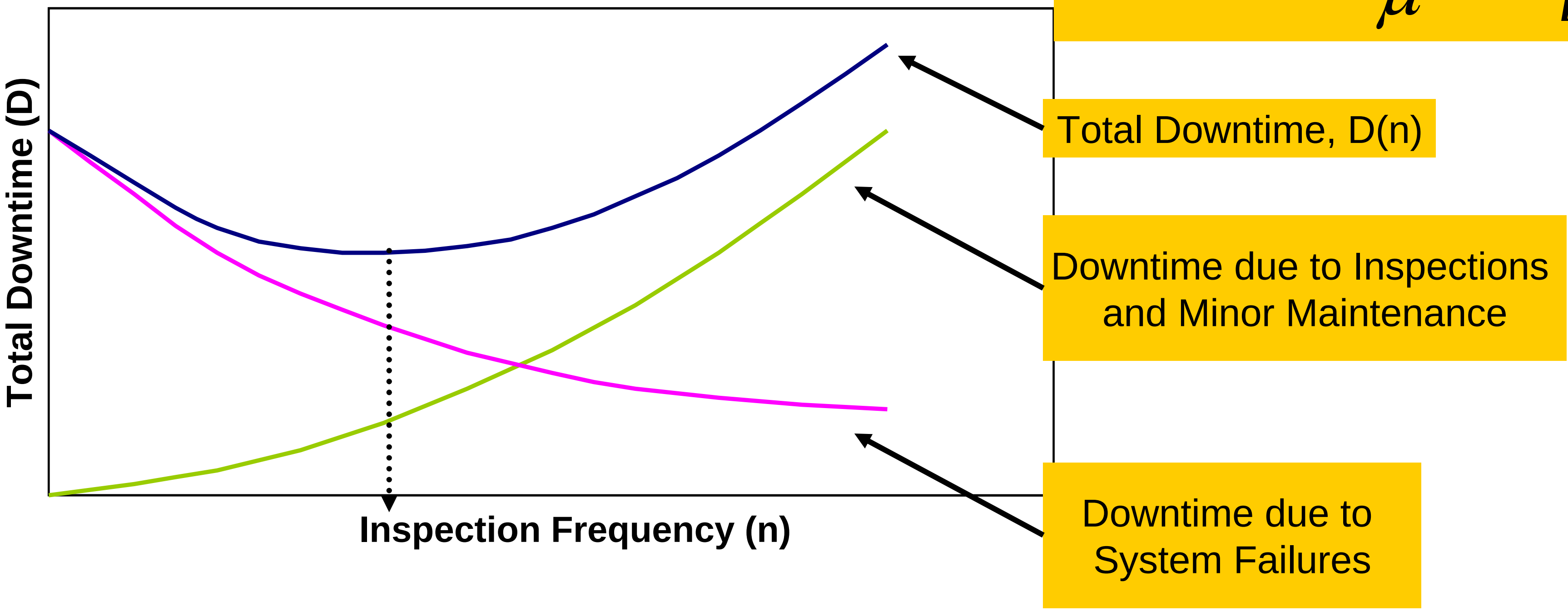
Inspection Frequency versus MTTF



Optimal Inspection Frequency: D(n) Model

$$D(n) = \frac{\lambda(n)}{\mu} + \frac{n}{i}$$

Total Downtime versus Inspection Frequency



Optimal inspection frequency minimizes total downtime, D(n)

Optimal Inspection Frequency: D(n) Model

- In practice, the difficulty is to determine the relationship between system failure rate and inspection policy
- In practice, this may be obtained by:

  1. Experimentation
  2. Co-operation
  3. Simulation

Optimal Inspection Frequency: D(n) Model

D(n) = downtime due to failures + downtime due to inspections

$$D(n) = \frac{\lambda(n)}{\mu} + \frac{n}{i}$$

Where:

- λ***(n)*** is the arrival rate of system failures as a function of inspection policy
- 1/μ is the mean repair time
- ***n*** is the # of inspections per unit time
- ***1/i*** represents the mean downtime due to inspection and associated minor maintenance

D(n) Model: Numerical Example

Assume:

$\lambda(n) = k/n$, and $k=3$, $n \geq 1$

$1/\mu = 0.033$ months (24 hours)

$1/i = 0.011$ months (8 hours)

$D'(n) = 0$ gives:

$$n = \sqrt{\frac{k * i}{\mu}} = \sqrt{\frac{3 * 0.033}{0.011}}$$ = 3 inspections/month

Inspection Frequency to Minimize the Total Downtime per Unit Time of Buses at an Urban Transit Authority

STCUM

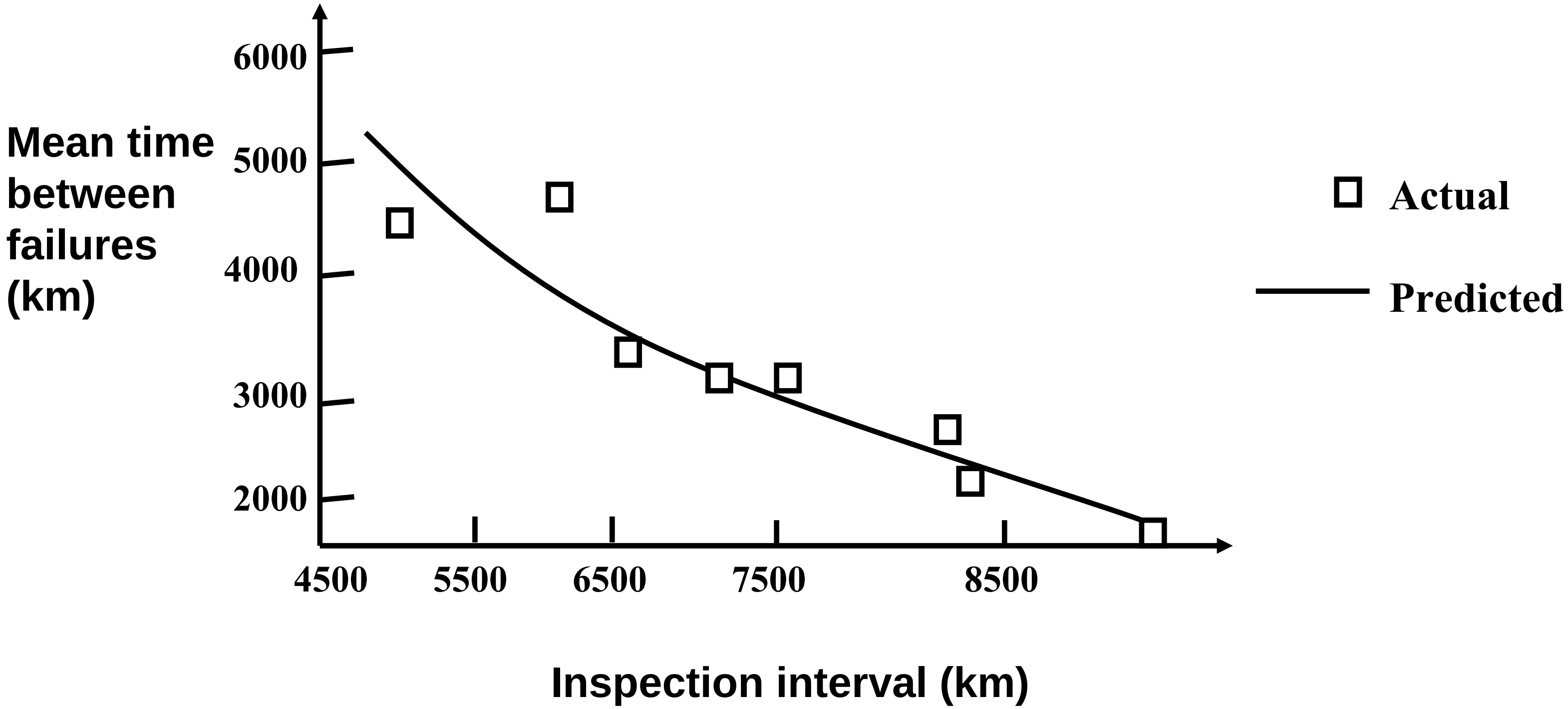
Montreal’s Transit Commission’s Bus Inspection Policy

Inspection Type

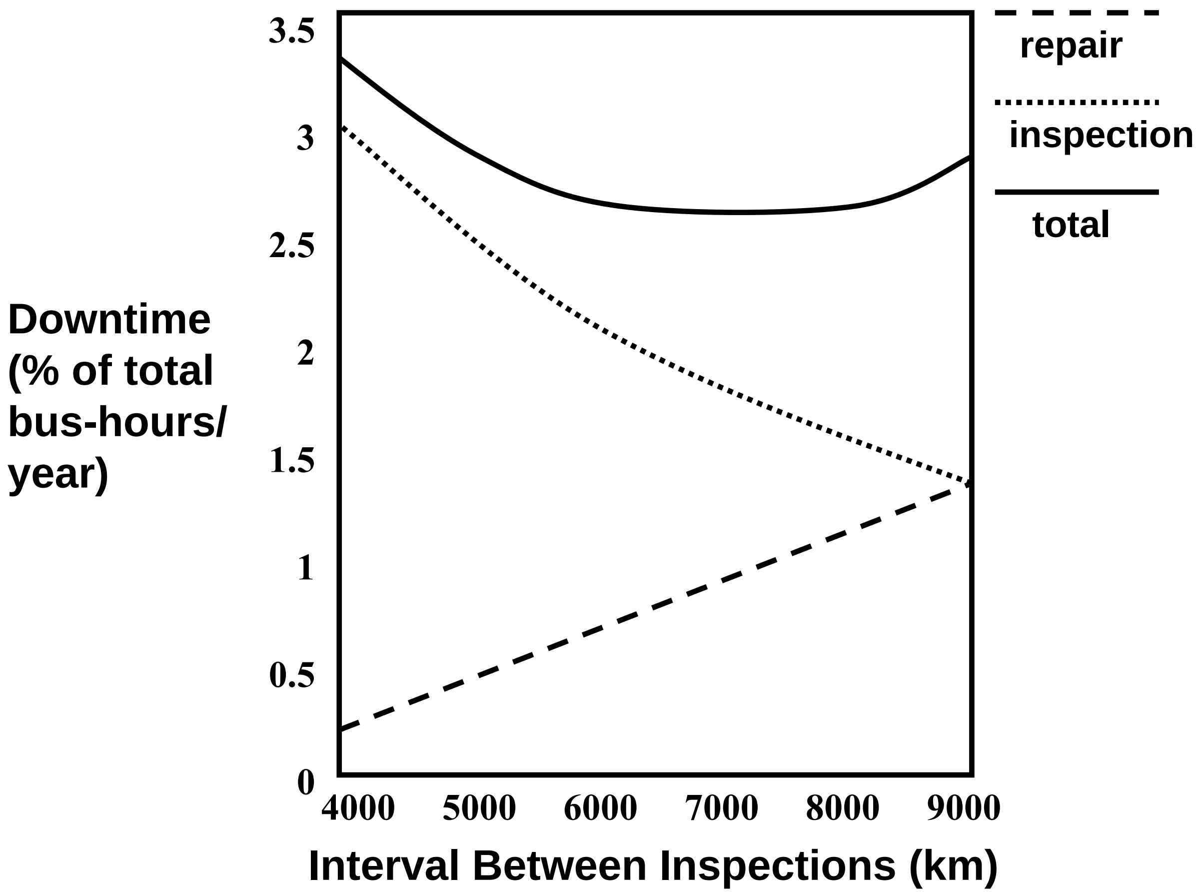
Km (1000)	“A”	“B”	“C”	“D”	
5	X				
10		X			
15	X				
20			X		
25	X				
30		X			
35	X				
40			X		
45	X				
50		X			
55	X				
60			X		
65	X				
70		X			
75	X				
80				X	
Total	8	4	3	1	$\Sigma = 16$
R	0.5	0.25	0.1875	0.0625	$\Sigma = 1.0$

Where:
R_i = No. of type i inspections / Total No. of inspections i = A, B, D, or D

Mean Distance to Failure versus Inspection Interval



Downtime As a Function of the Inspection Frequency



Optimal Inspection Interval

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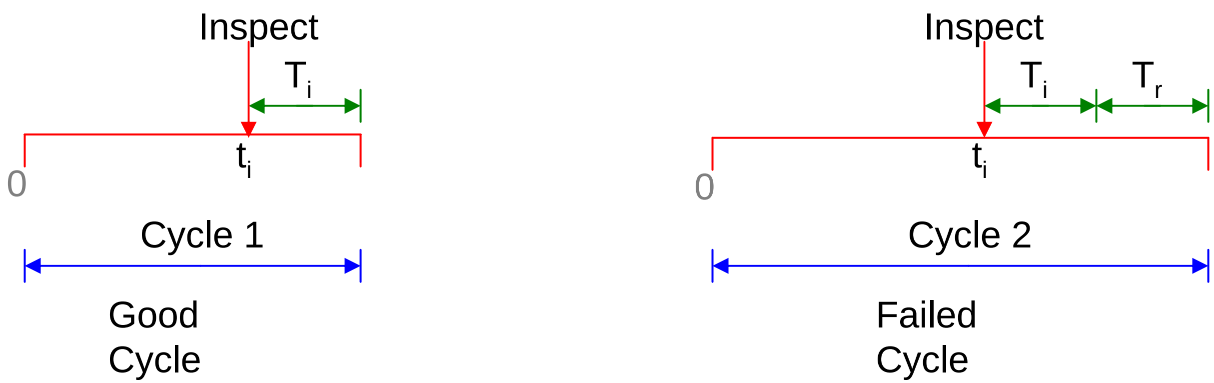
Failure Finding Intervals for Protective Devices

Maximizing Availability

- The problem is to determine the best interval between inspections to maximize the proportion of time that the equipment is in the available state
- Two possible cycles of operation are:



Where: T_i = time required to effect an inspection, T_r = time required to effect a repair or replacement, and t_i = interval between inspections

Numerical Example

Problem: A protective device with a normally distributed MTBF = 5 months (and standard deviation = 1 month) has:

- T_i = 0.25 month
- T_r = 0.5 month

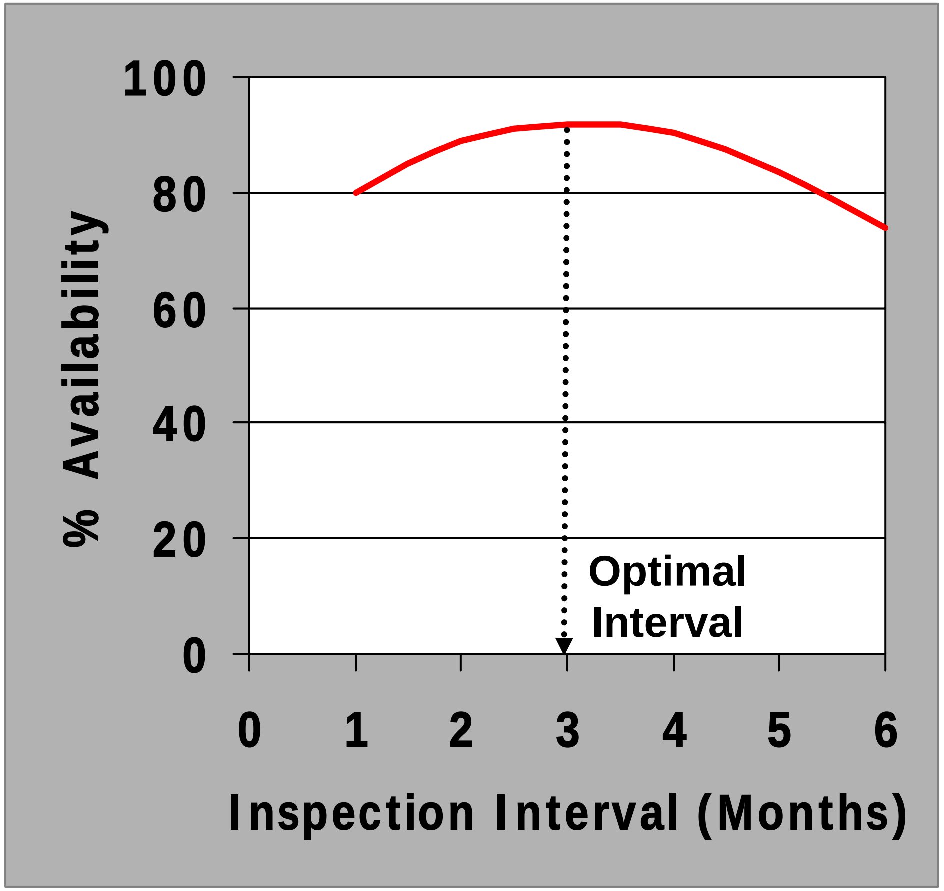
Find the optimal inspection interval, t_i, to maximize availability.

Result:

t_i	1	2	3	4	5	6
$A(t_i)$	0.8000	0.8905	0.9173	0.9047	0.8366	0.7371

Therefore, the optimal inspection interval is 3 months

Inspection Interval vs. Availability



$$A(t_i) = \frac{t_i \times R(t_i) + \int_{-\infty}^{t_i} t \times f(t)\,dt}{t_i + T_i + T_r \times [1 - R(t_i)]}$$

Where:

$A(t_i)$ = availability per unit time

$R(t_i)$ = reliability at an inspection interval of t_i

$f(t)$ = density function of the time to failure of the equipment

T_i , T_r , and t_i have been defined in the previous slide

In this case, T_i = 0.25 month and T_r = 0.5 month

F.F. Interval vs. Availabilty: Moubray (Horton) Model

$$I = 2(1-A)M$$

Where:

A = Availability

M = MTBF

I = Failure Finding Interval

Source: Moubray, *RCM II,* pp. 177

An Example Using the Moubray Model

Problem: Brake lights on motorcycles

- MTBF = 10 years
- FFI = 10% of MTBF of 10 years = 1 year

Result: Availability = 95.0%

Problem source : Moubray, RCM II., 1999, pp. 175-176

Example Using Moubray (Horton) Model

Problem: A protective device has a MTBF = 10 years. Determine the FFI which will yield an Availabilty = 99%.

Answer: FFI = 10 weeks (roughly)

Example for FFI (Failure Finding Interval) for a Protective Device

Pressure safety valve

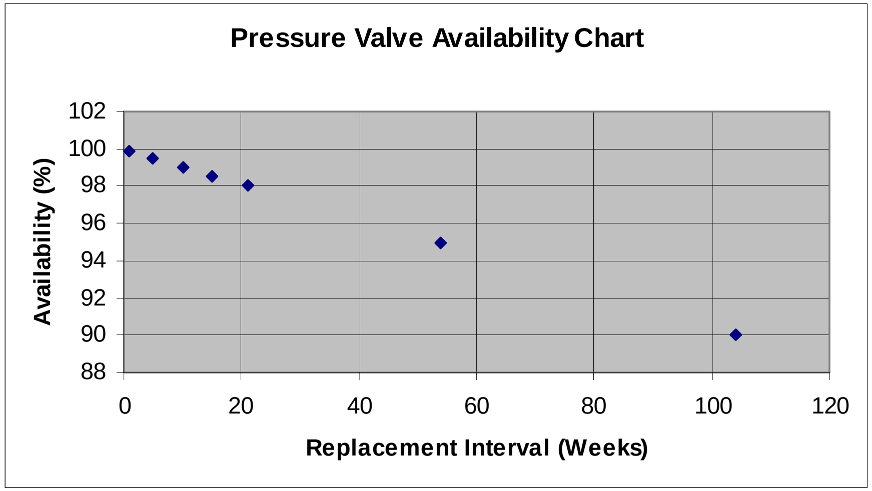
- 1000 valves in service
- Inspection interval = 12 months
- Time to inspect = 1 hour
- Time to repair a defective valve = 1 hour
- 10% of valves found defective at inspection, therefore

  MTTF = (1000x 1) / 100 = 10 years.

What is valve availability for different inspection intervals?

Answer

Failure Finding Interval (Weeks)	Pressure Valve Availability (%)
1	99.9
5	99.5
10	99.0
15	98.5
21	98.0
54	95.0
104	90.0



Condition Monitoring Decisions

A Recent Statement

Condition monitoring:

85% visual inspection

15% vibration monitoring, oil analysis etc

Another Statement

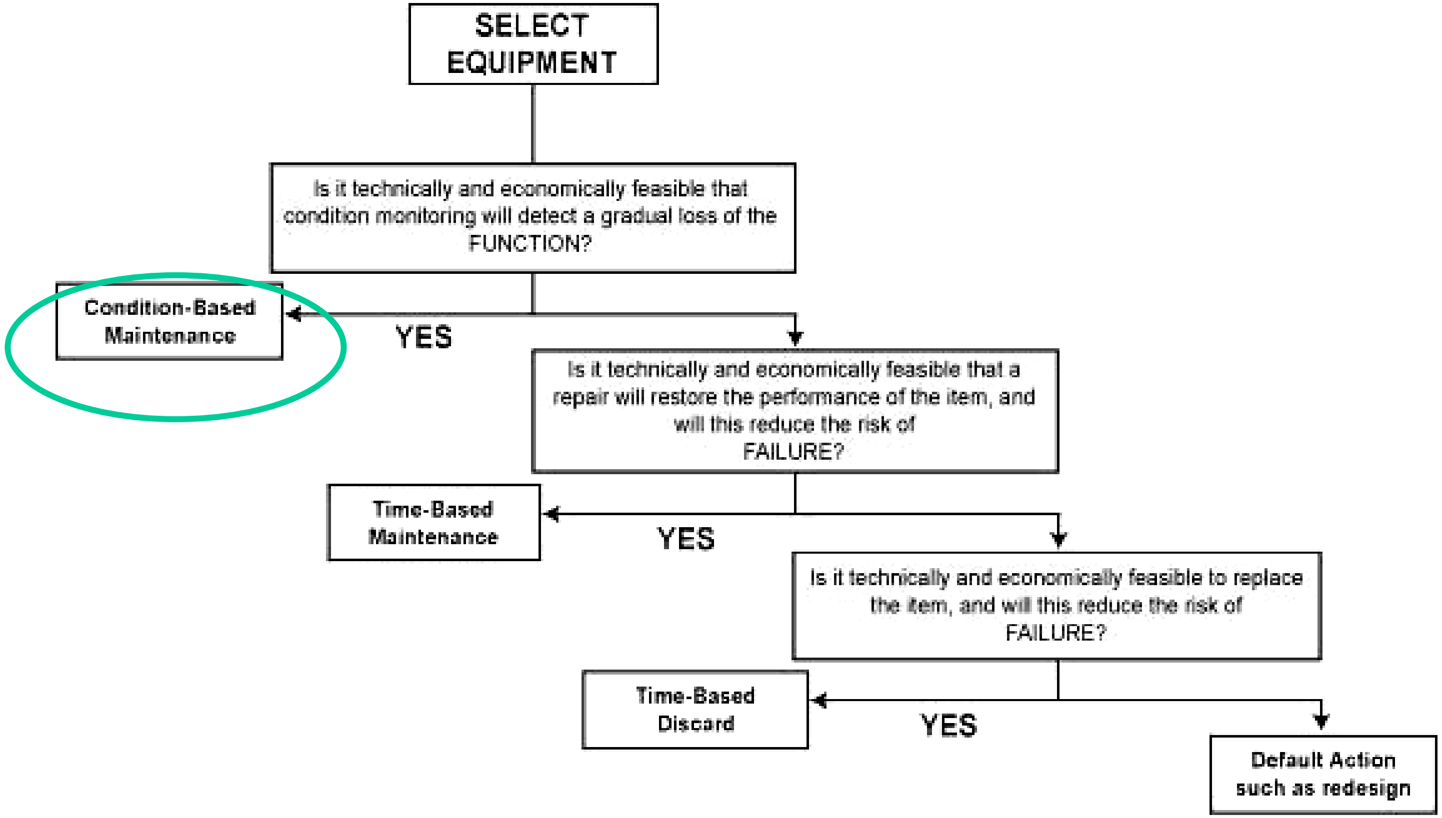
"world class companies often devote up to 50% of their entire maintenance resources to condition based monitoring and the planned work that is required as a result of the findings"

Source: December 2003 issue of Maintenance Technology, page 54, Terrence O'Hanlon

Optimising Condition Based Maintenance (CBM) (Section 3.5)

Objective is to obtain the maximum useful life from each physical asset before taking it out of service for preventive maintenance...

RCM Methodology Logic

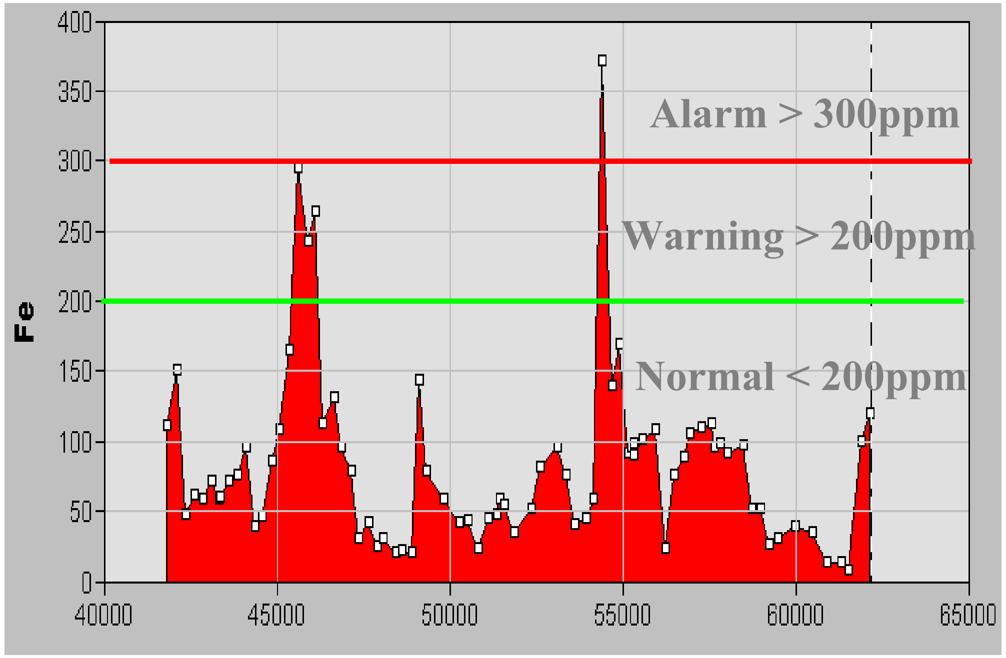


CBM Research

While much research and product development in the area of condition based maintenance focuses on data acquisition and signal processing, the focus of the work at the CBM Lab in Toronto is the third and final step in the CBM process – optimizing the decision making step

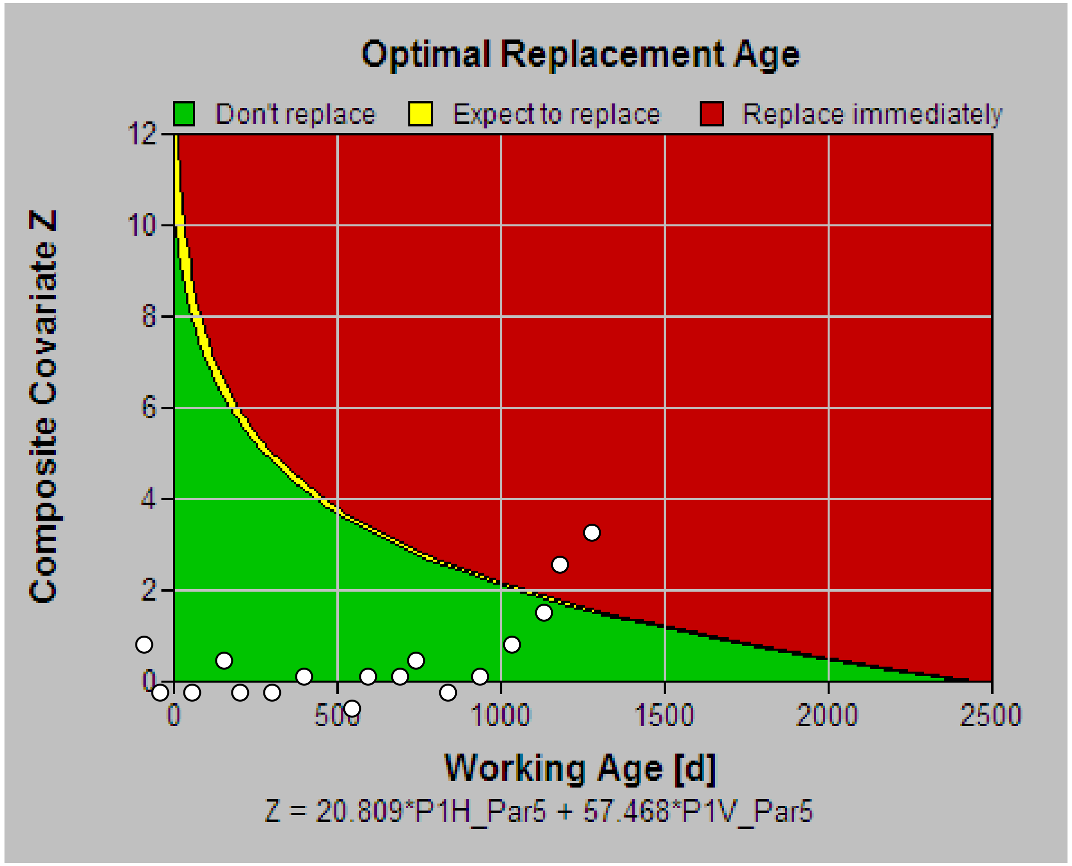
Condition-monitoring via Warning Limits

- Simple to understand
- Limitations:
  - Which measurements?
  - Optimal limits?
  - Effect of Age?
  - Predictions?
- EXAKT extends and enhances the Control Chart technique

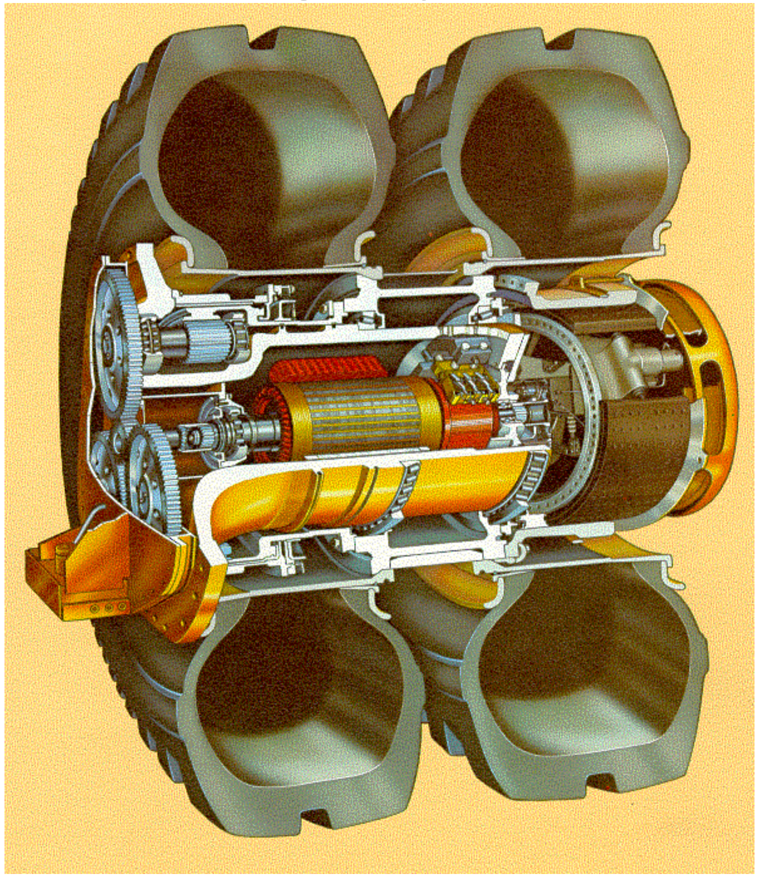


WorkingAge

EXAKT Optimal Decision – A New "Control Chart"



Electric wheel motor: Condition monitoring by oil analysis



Warning Limits in ‘ppm’

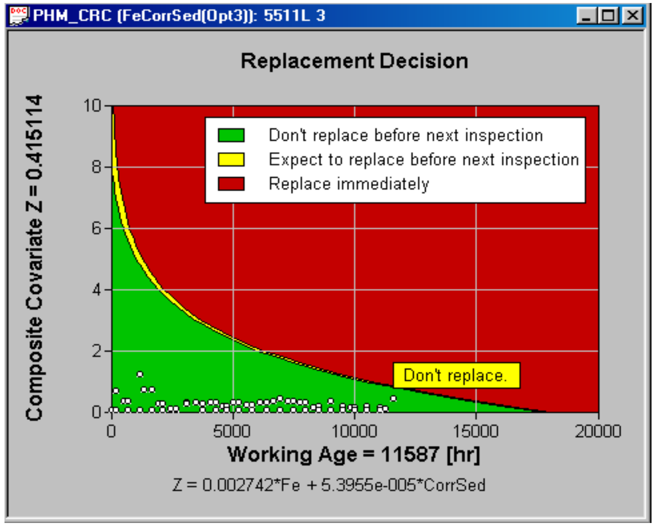
	Normal	Warning	Alarm
Al	< 20	20 - 40	> 40
Cr	<10	10 - 20	>20
Cu	<50	50 - 100	>100
Fe	<200	200 - 300	>300
Si	<15	15 - 25	>25

An example: Measurements & Decision

Readings

Al = 2
Cr = 1
Cu = 0
Fe = 151
Ni = 1
Ti = 0
Pb = 0
Si = 7

Sn = 0
Visc40 = 286
Visc100 = 33.17
Sed = 20

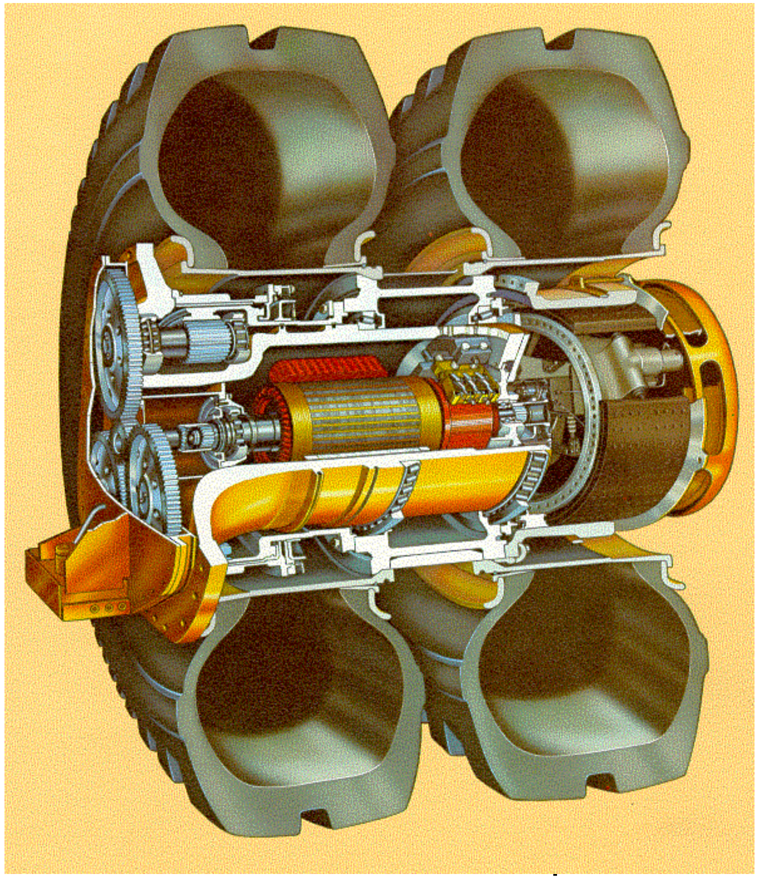


Decision Parameters

Recommendation:	**Don't replace.**
Expect to Replace in [hr]:	**1271.01**
Report Date:	
Current Status:	**In Operation**

Cardinal River Coals

- Oil analysis from 50 wheel motors
  - Twelve covariates measured
  - Covariates used: Iron and sediment
  - Estimated Saving in Maintenance Costs: 22% when the cost consequence of a failure replacement was 3 x cost of preventive replacement.



Optimizing CBM Decisions

Three Keys:

- Hazard
- Transition Probabilities
- Economics

Step 1: Hazard Model

$$HAZARD(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{\gamma_1 z_1(t)+...+\gamma_n z_n(t)}$$

Failures/op.hour
Failure/flying hour
Failures/km.
Failures/tonne
Failures/cycle
Etc…

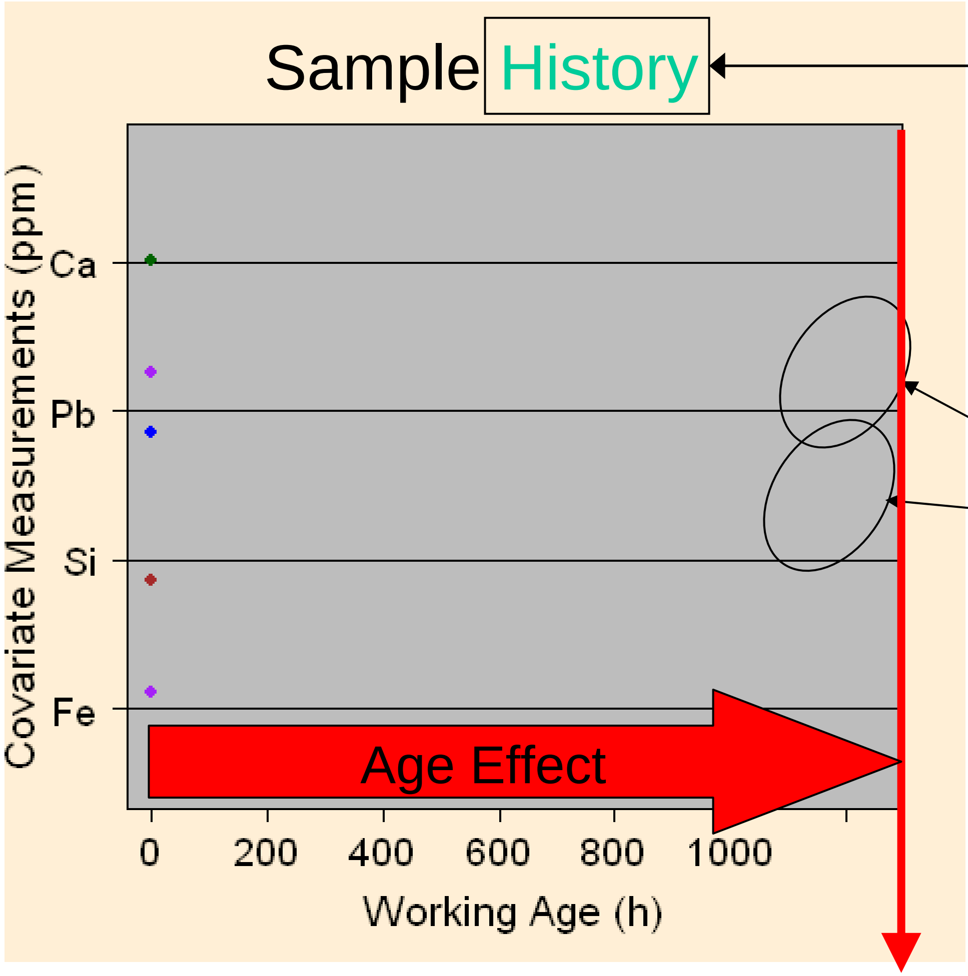
Contribution of age to hazard

Contribution of condition information to hazard

$$= \frac{1.483}{148790}\left(\frac{t}{148790}\right)^{0.483} e^{0.0518Fe+1.867Al+0.01183Mg}$$

Constants estimated from data

How does data model hazard?

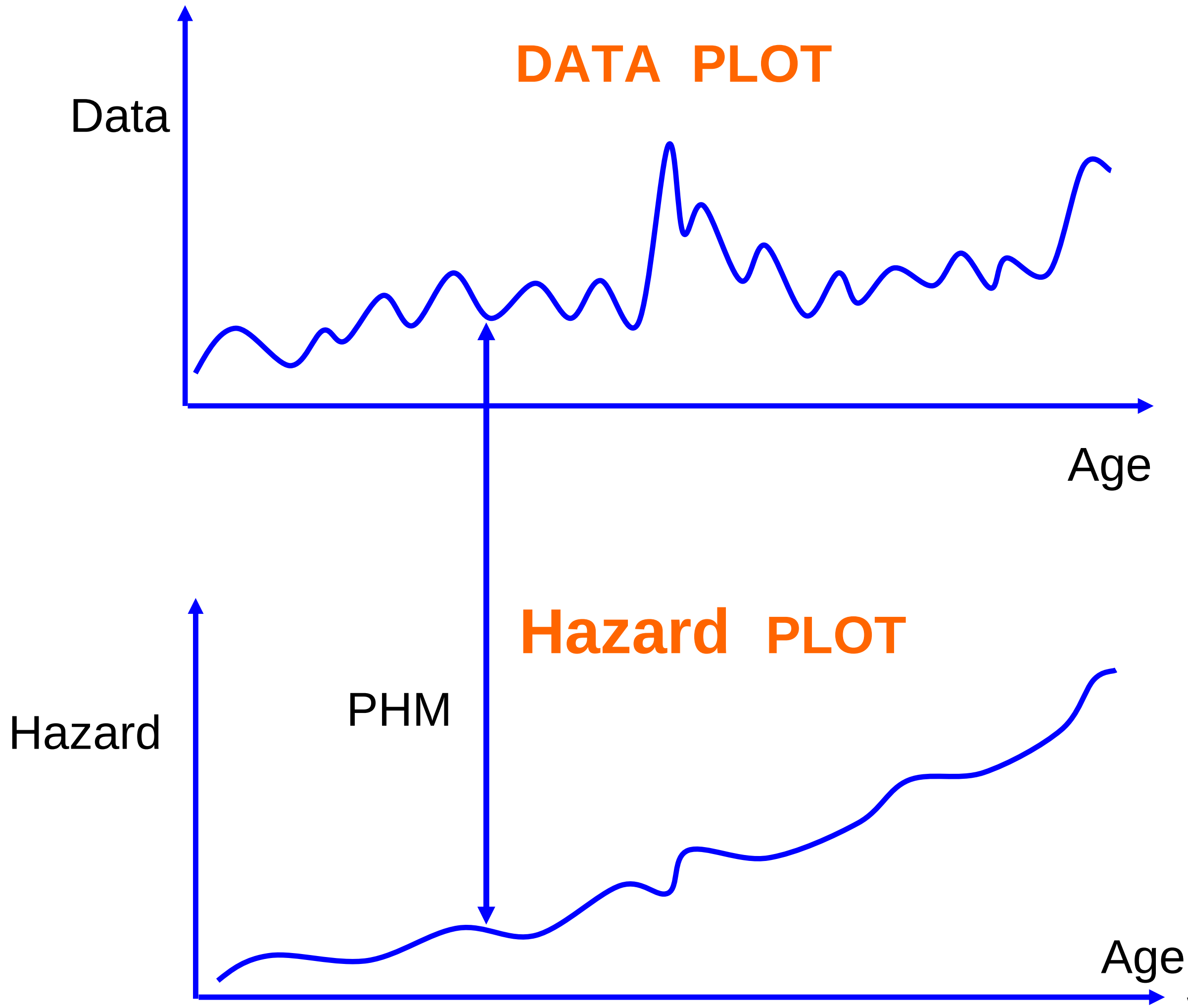


History consists of:
- Beginning time
- Inspection results
- Ending time and reason

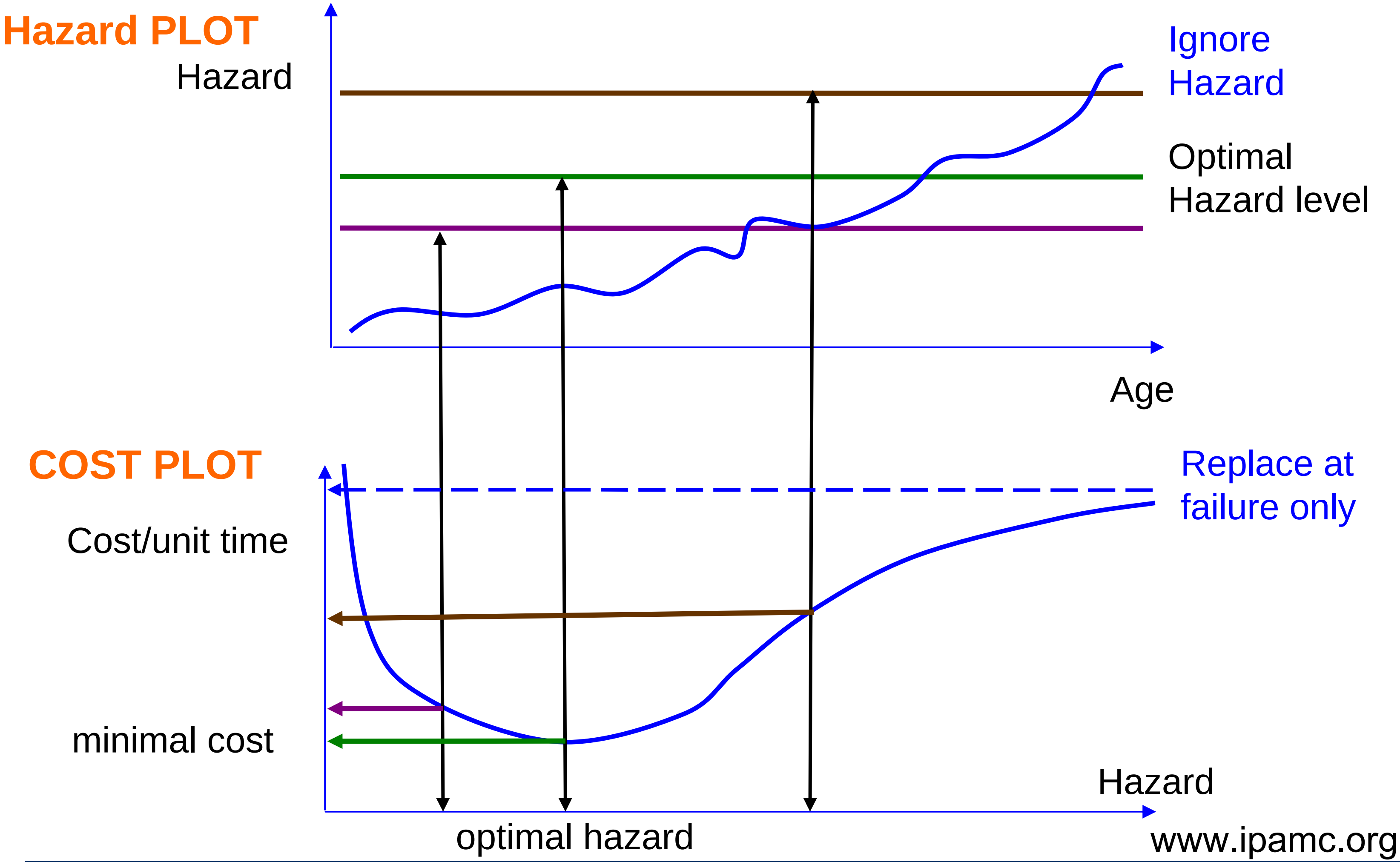
Lead and Silicon are the significant covariates.

EQUIPMENT FAILURE

Data to Hazard



OPTIMAL POLICY - OPTIMAL HAZARD LEVEL



We have created a theory, but in order to make it work in practice we need a tool

Real world research

Managing Risk: A CBM Optimization Tool

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Research Team

Research Students

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Darko Louit (Spare Parts Optimization)

Jean-Paul Haddad (Research Topic TBA)

Andrey Pak (Maintenance & Repair Contracts)

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Principal Investigator

Prof. Andrew K.S. Jardine

Collaborating Researcher

Dr. Xiaoyue Jiang, Assistant Professor
Louisiana State University

Step 2: Transition Probabilities

- Transition probabilities for all significant covariates are calculated from all histories
- Probabilities can change over time
  - e.g. probability of worsening wear can increase with age.

Transition Probabilities

Inspection Interval = 30 days

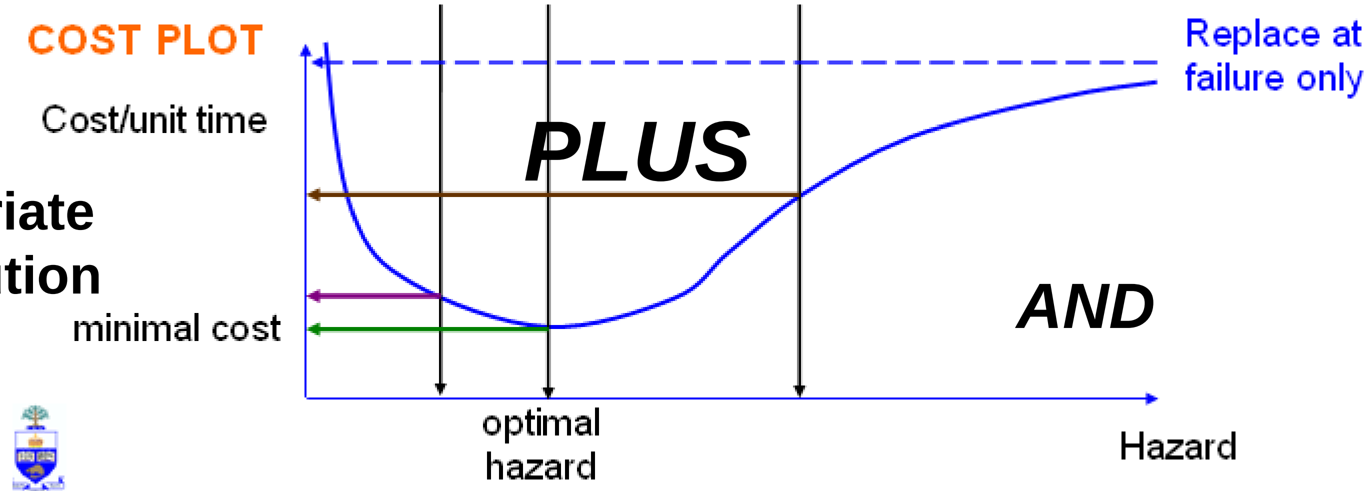
	VEL #1A Age 0 to 180 (Days)	0 to 0.1	0.1 to 0.15	0.15 to 0.22	0.22 to 0.37	Above 0.37
Very Smooth						
Smooth	**0 to 0.1**	0.575373	0.224181	0.145161	0.040554	0.014731
Rough	**0.1 to 0.15**	0.205868	0.249818	0.330898	0.137414	0.076002
Very Rough	**0.15 to 0.22**	0.055426	0.137583	0.37788	0.229398	0.199714
Failure	**0.22 to 0.37**	0.012852	0.047422	0.190398	0.24338	0.50699
	Above 0.37	0.00048	0.002696	0.017039	0.052114	0.927672

Data to Model: Summary

$$\frac{2.523}{3402}\left(\frac{t}{3402}\right)^{1.523} \exp\{0.2293 * Pb + 0.4151 * Si\}$$

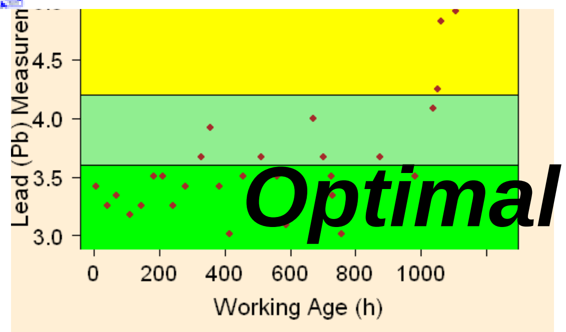
Hazard

PLUS



AND

Covariate Evolution

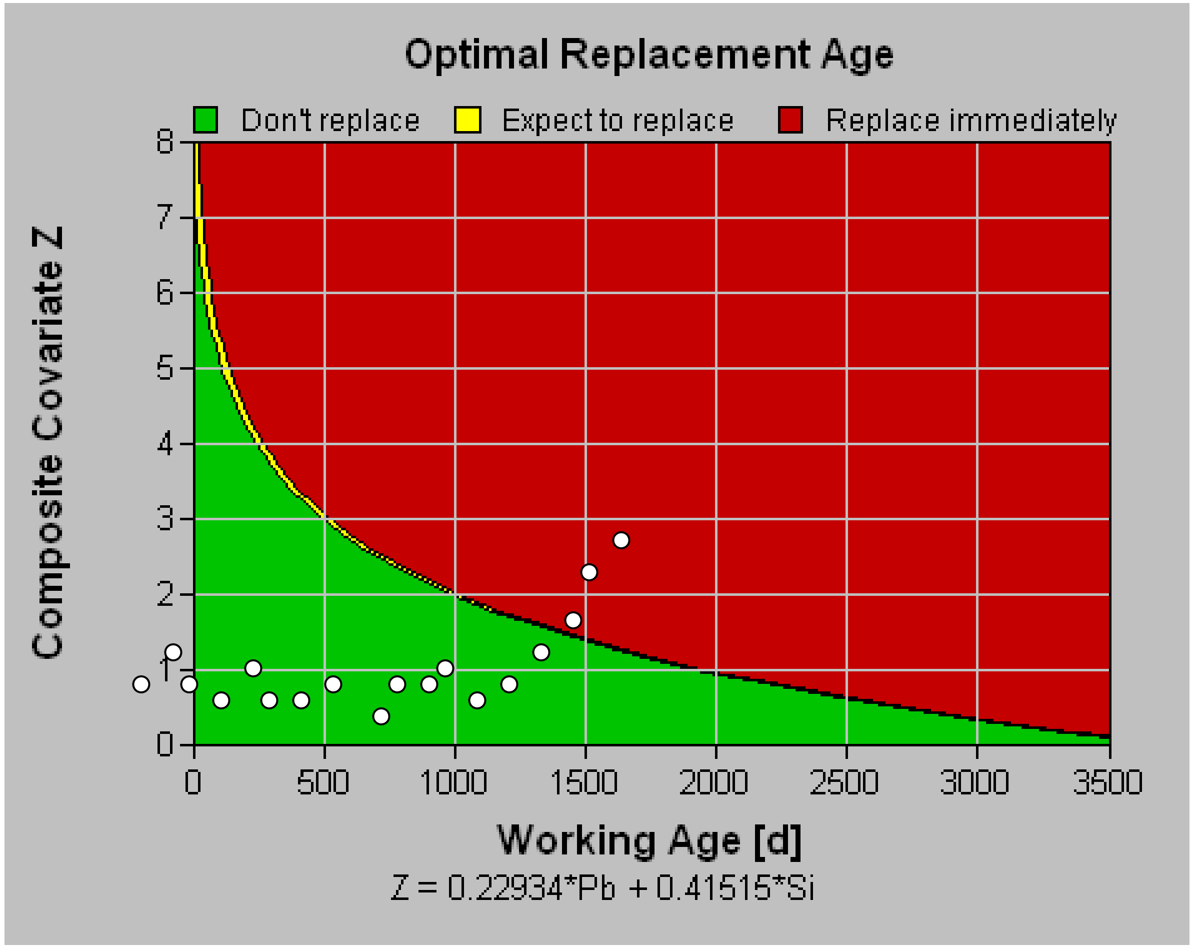


Optimal Hazard Level

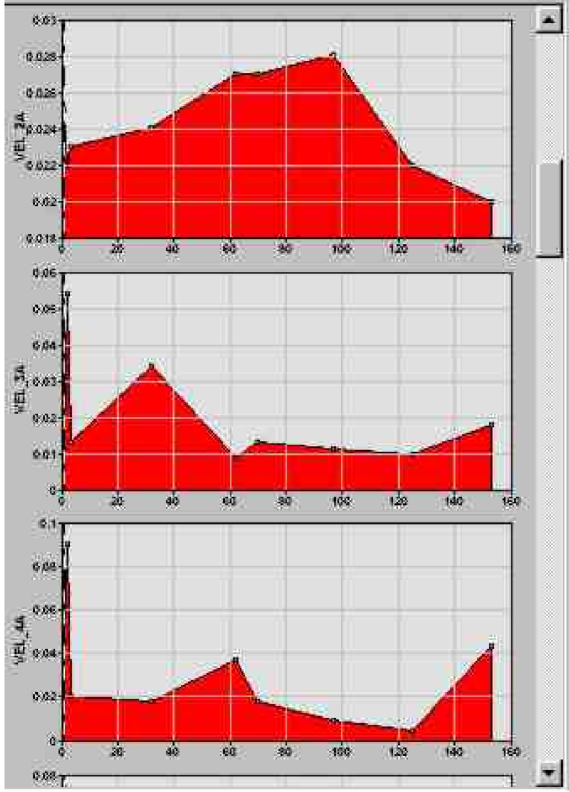
C_f = Total cost of failure replacement

C_p = Total cost of preventive replacement

Optimal Decision Chart



Vibration Monitoring Data



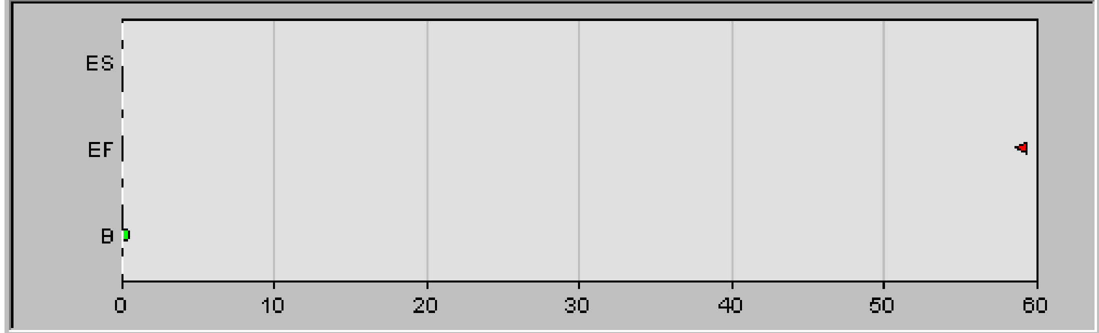
Ident	Date	WorkingAge	OVER_A	VEL_1A	VEL_2A	VEL_3A	VEL_4A
N2	7/21/95	1	0.383	0.37	0.025	0.011	0.046
N2	7/22/95	2	0.422	0.406	0.022	0.054	0.09
N2	7/23/95	3	0.067	0.057	0.023	0.013	0.02
N2	8/21/95	32	0.282	0.275	0.024	0.034	0.018
N2	9/20/95	62	0.15	0.14	0.027	0.0088	0.037
N2	9/28/95	70	0.069	0.059	0.027	0.013	0.018
N2	10/25/95	97	0.074	0.067	0.028	0.011	0.0091
N2	11/22/95	125	0.037	0.027	0.022	0.0098	0.0045
N2	12/20/95	153	0.275	0.269	0.02	0.018	0.043
N3	1/24/96	35	0.224	0.218	0.025	0.0073	0.038
N3	2/12/96	53	0.067	0.056	0.029	0.019	0.0049
N3	2/29/96	70	0.104	0.02	0.014	0.019	0.08
N3	3/04/96	74	0.305	0.161	0.255	0.032	0.0029
N3	5/22/96	152	0.052	0.023	0.041	0.01	0.019
N3	5/31/96	161	0.089	0.085	0.016	0.0052	0.022
N3	6/12/96	173	0.059	0.033	0.013	0.009	0.043
N3	6/24/96	185	0.043	0.019	0.0078	0.0045	0.036
N3	7/17/96	208	0.049	0.0094	0.013	0.034	0.026
N3	8/16/96	238	0.185	0.0091	0.0075	0.0026	0.178
N4	8/26/96	10	0.125	0.015	0.124	0.0091	0.0019
N4	9/20/96	35	0.109	0.008	0.011	0.0031	0.0036
N4	1/30/97	167	0.07	0.0076	0.0034	0.0029	0.0032
N4	5/14/97	271	0.064	0.011	0.026	0.0027	0.0074
N4	5/22/97	279	0.057	0.011	0.0036	0.004	0.0078
N4	6/19/97	307	0.164	0.011	0.0066	0.012	0.045
N4	7/15/97	333	0.104	0.0077	0.0075	0.0067	0.023
N4	9/01/97	380	0.212	0.012	0.023	0.0088	0.047

95 / 165

Vibration Analysis Events Data

Events (B1)

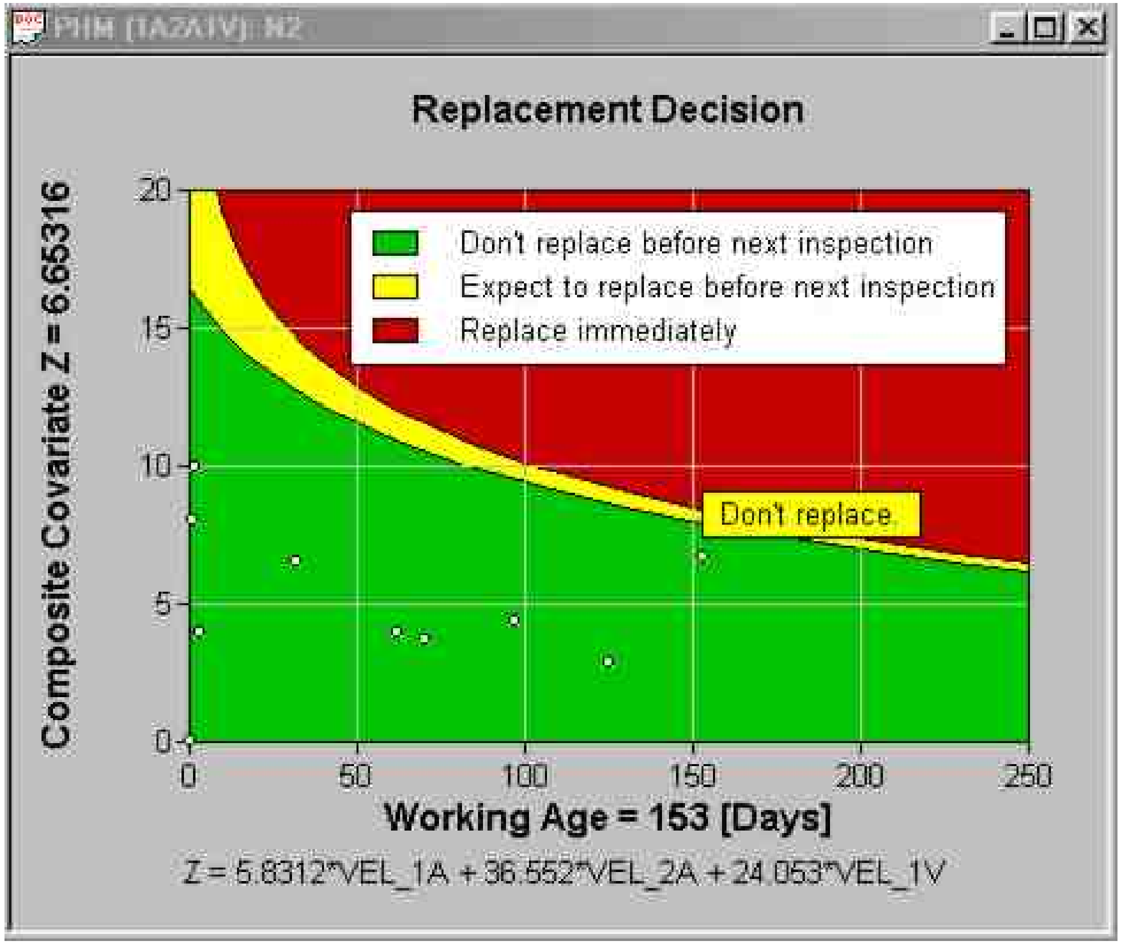
B1



Ident	Date	WorkingAge	Event
B1	9/28/94	0	B
B1	11/26/94	59	EF
B2	11/26/94	0	B
B2	1/12/95	47	EF
B3	1/12/95	0	B
B3	7/20/95	189	EF
B4	7/20/95	0	B
B4	8/21/95	33	EF
B5	8/21/95	0	B
B5	12/20/95	121	EF
B6	12/20/95	0	B
B6	3/04/96	75	EF
B7	3/04/96	0	B

1 / 55

Vibration Monitoring Decision



Campbell Soup Company

Analysis of Shear Pump Bearings Vibration Data

– 21 vibration measurements provided by accelerometer

Using <EXAKT>:

– 3 measurements significant

A Check:

– Had <EXAKT> model been applied to previous histories

– Savings obtained = 35 %

EXAKT V 4.0 Released in December 2005

EXAKT™

The CBM Optimizer

Recent Developments in CBM Optimization

- Marginal Analysis: addressing individual system failure modes
- Remaining Useful Life (RUL): Reporting RUL and standard deviation for selected state of covariates and working age
- Probability of failure in a short interval as a part of decision report

#1. Marginal Analysis: Modeling of Diesel Engines employed on T23 Frigates

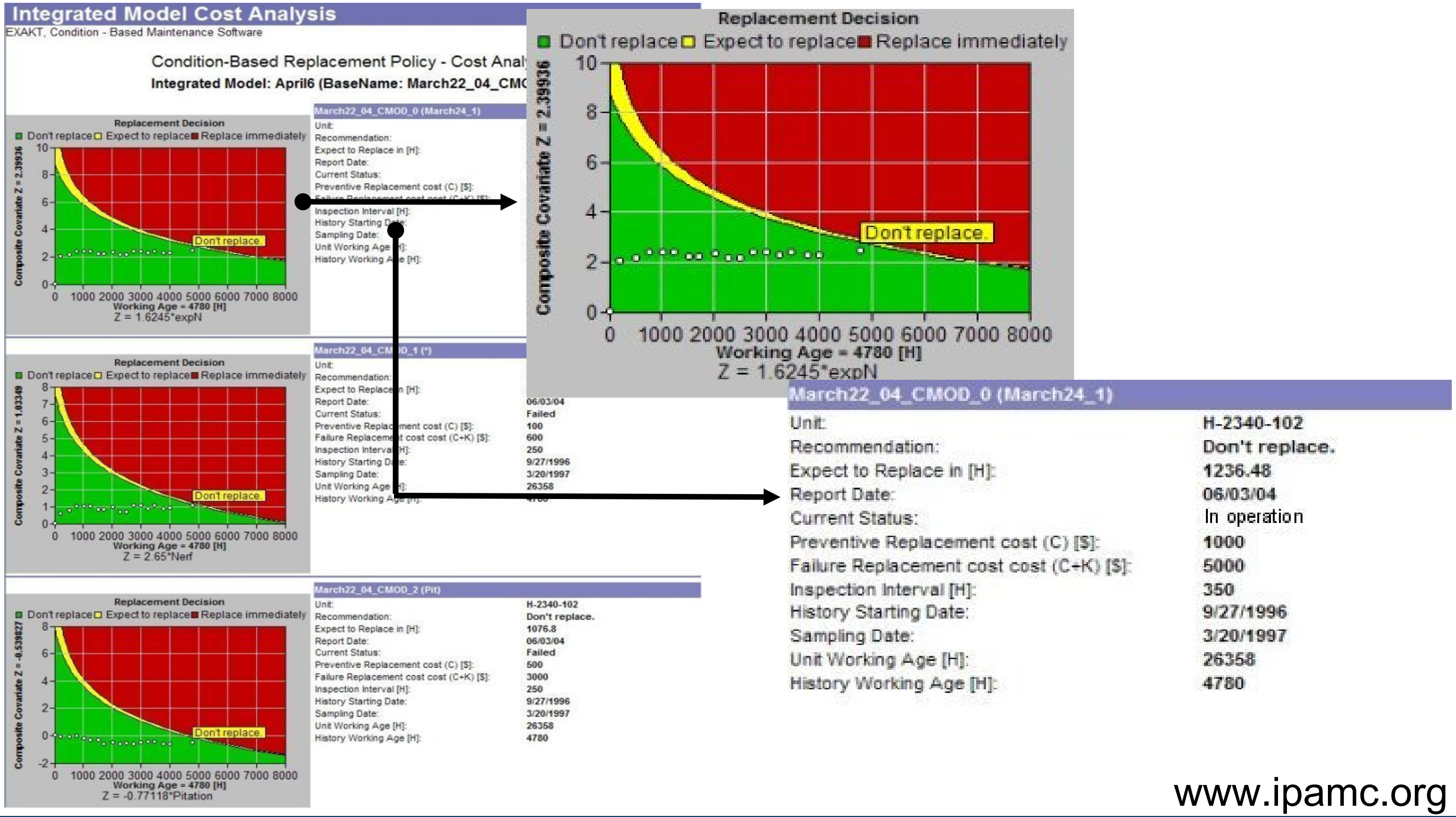
Diesel Engines: Failure Modes

	Type of Failure	Count
0	Not Known	3
1	Cooling System	13
2	Fuel System	6
3	Generator	9
4	Accessories	9
5	Cylinder Liners and Rings	24
6	Valves and Running Gear	20
7	Pistons, Articulations and Bearings	15
8	Cylinder Heads	14
9	Misc, including cylinder block failures	12

Unrelated to oil readings (rows 0–4)

Possibly related to oil readings (rows 5–9)

Simultaneous decisions for each failure mode of a repairable system



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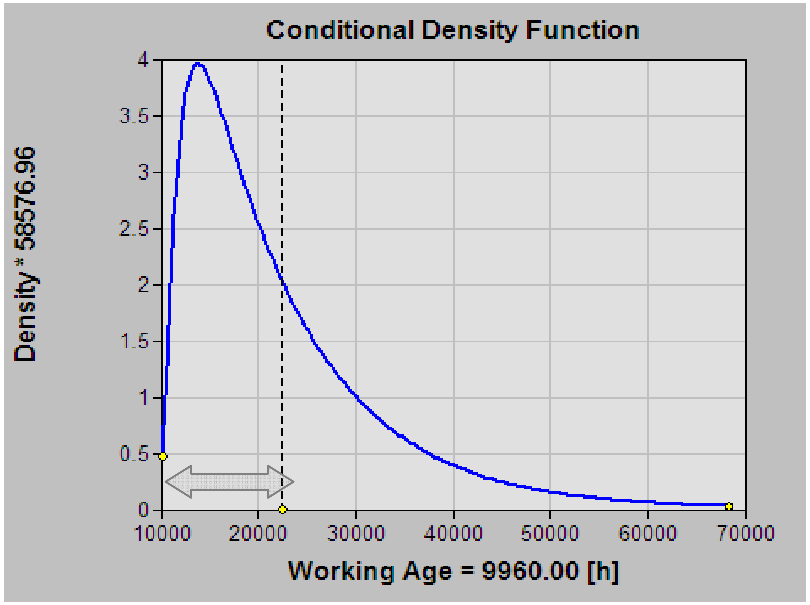
#2. Conditional Density Function & Remaining Useful Life

- Shows the shape of the distribution of the time to failure given current conditions
- Expected time to failure (Remaining Useful Life, or RUL)
- Standard deviation

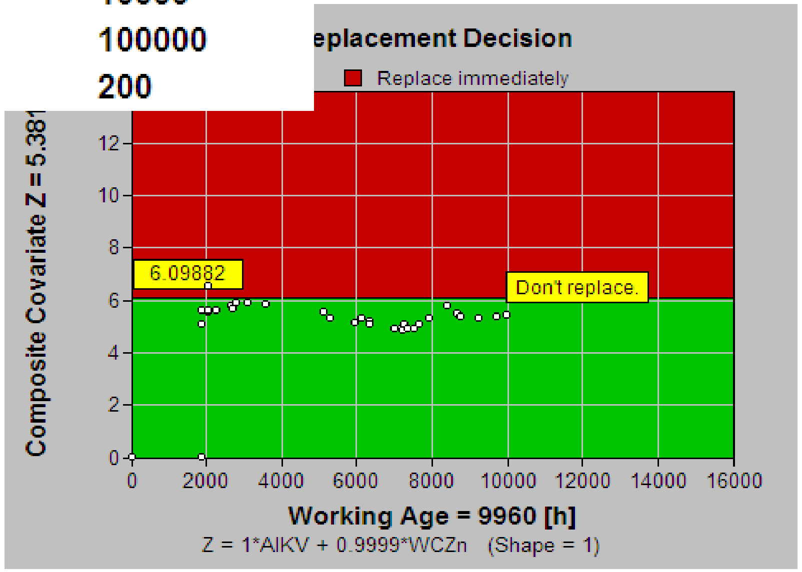


Probability Intervals

RUL=12425.554043,	StdDev=10724.113435

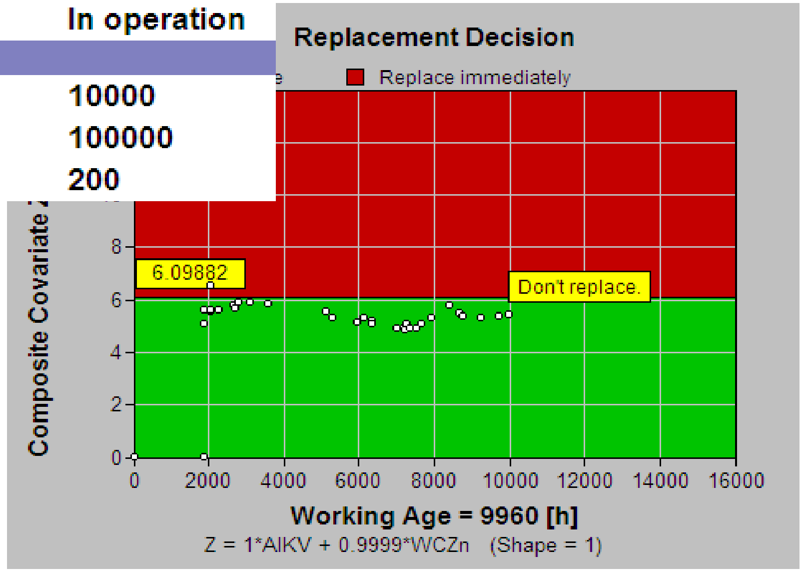
#3. Pre-2006

Decision Parameters	
Recommendation:	**Don't replace.**
Expect to Replace in [h]:	**2454.92**
Report Date:	**04/20/06**
Current Status:	**In operation**
Input Parameters	
Preventive Replacement cost (C) [GBP]:	**10000**
Failure Replacement cost (C+K) [GBP]:	**100000**
Inspection Interval [h]:	**200**

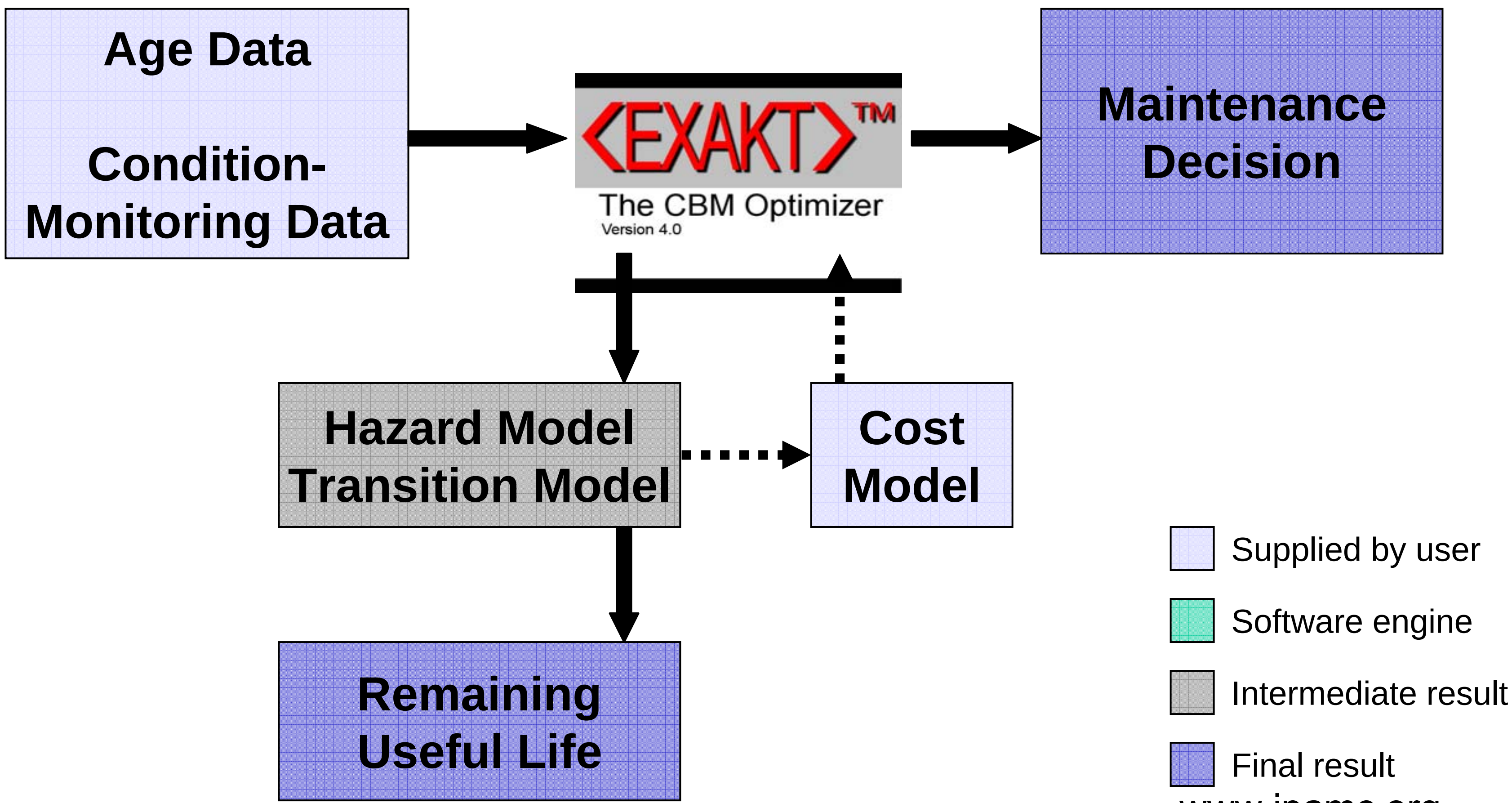


2006-

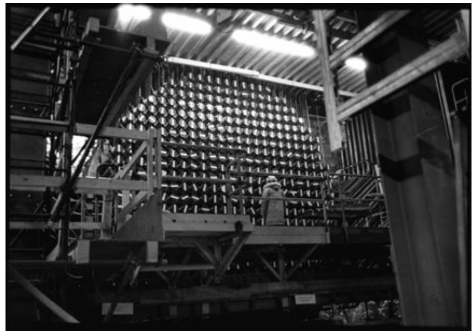
Decision Parameters	
Recommendation:	**Don't replace.**
Expect to Replace in [h]:	**2454.92**
Probability of Failure in (200) [h]:	**0.0051522**
Probability of Failure in (400) [h]:	**0.0102779**
Report Date:	**04/20/06**
Current Status:	**In operation**
Input Parameters	
Preventive Replacement cost (C) [GBP]:	**10000**
Failure Replacement cost (C+K) [GBP]:	**100000**
Inspection Interval [h]:	**200**

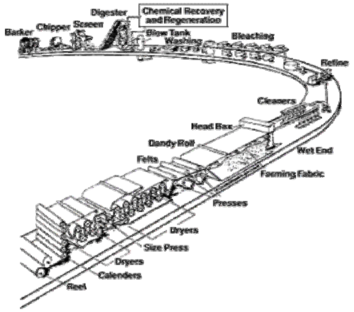


Principle of CBM Optimization using EXAKT



Other CBM Optimization Studies





Condition Monitoring – An Analogy

EQUIPMENT FAILURE

Hazard or Risk = *f* (Age) + *f* (Risk factors)

Risk factors:

- Oil Analysis (Fe, Cu, Al, Cr, Pb.....etc.)
- Vibration (Velocity and Acceleration)
- Thermography
- Visual Inspection

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Hong Kong Mass Transit Railway Corporation

- Had excessive traction motor ball bearing failures
- CBM to monitor bearing grease colour
- Changed inspections from every 3.5 years to annual
- Reduced failures/yr.. From 9 to 1
- Reduced total costs by 55%

The reality:

Failures reduced to 2/yr.

Sasol Plant

Analysis of Warman-Pump

Bearings Vibration Data

- Total 8 pumps each with two bearings (16 bearings) analyzed
- 12 vibration covariates identified

Using <EXAKT>:

- 2 covariates significant
- Annual replacement cost savings= 42 %

Feedback:

- Model results found realistic by Sasol plant
- Significant vibration covariates identified by <EXAKT> are agreed as a major problem

Vlok, et al, "Optimal Component Replacement Decisions using Vibration Monitoring and the PHM", JORS, 2002.

Open Pit Mining Operation

CAT 793B Transmissions Oil data analyzed

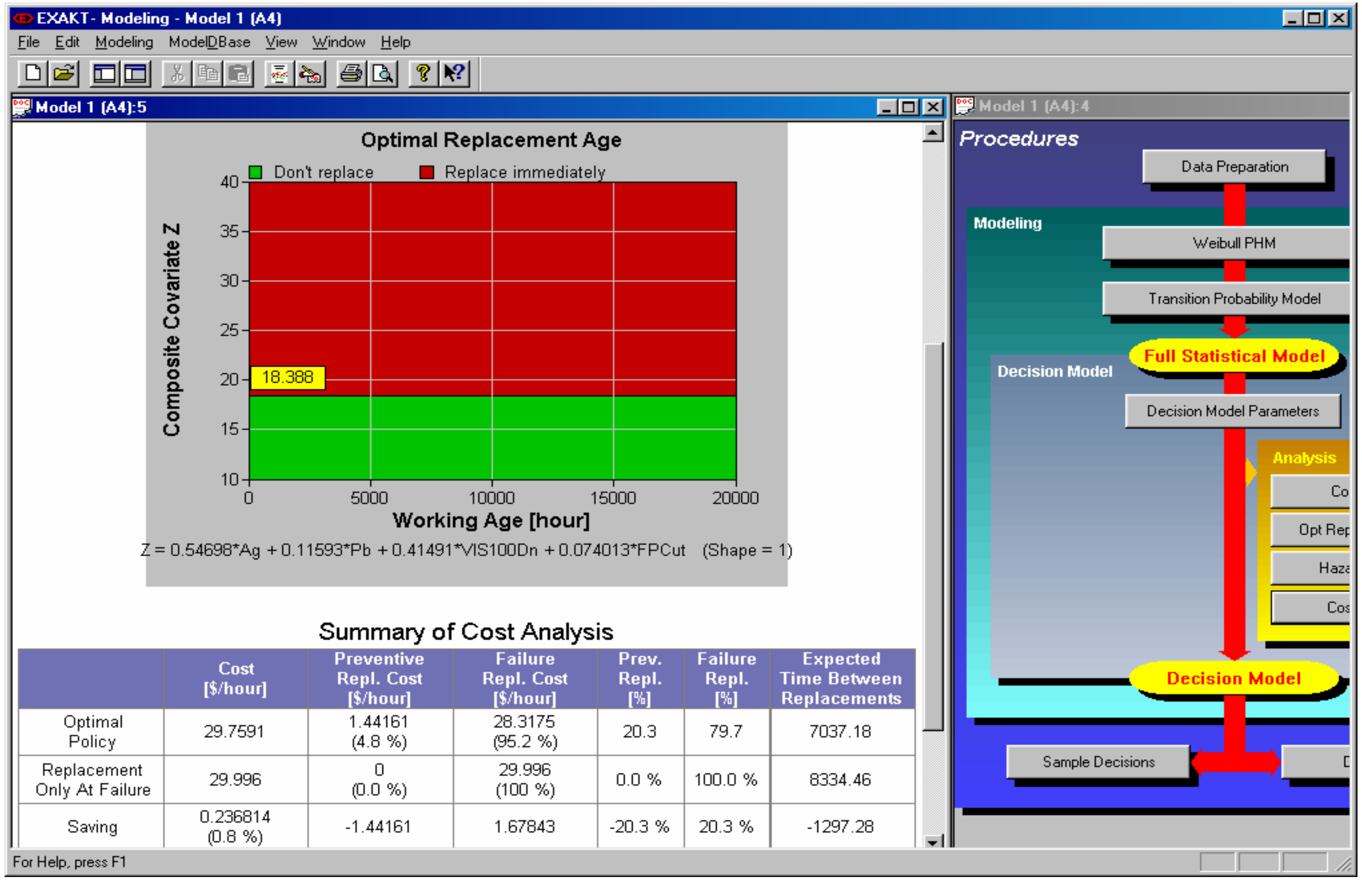
- Covariates used: Iron, Aluminum, Magnesium
- Saving in Maintenance Costs: 25%
- Average replacement time increase: 13%
- Warranty limit could be increased

Maintenance and Diagnostic Data

EXAKT Modeling with MWM Diesel Engine

employed on Halifax Class ships.

Condition-based Optimal Replacement Policy



Summary of Cost Analysis

	Cost [$/hour]	Preventive Repl. Cost [$/hour]	Failure Repl. Cost [$/hour]	Prev. Repl. [%]	Failure Repl. [%]	Expected Time Between Replacements
Optimal Policy	29.7591	1.44161 (4.8 %)	28.3175 (95.2 %)	20.3	79.7	7037.18
Replacement Only At Failure	29.996	0 (0.0 %)	29.996 (100 %)	0.0 %	100.0 %	8334.46
Saving	0.236814 (0.8 %)	-1.44161	1.67843	-20.3 %	20.3 %	-1297.28

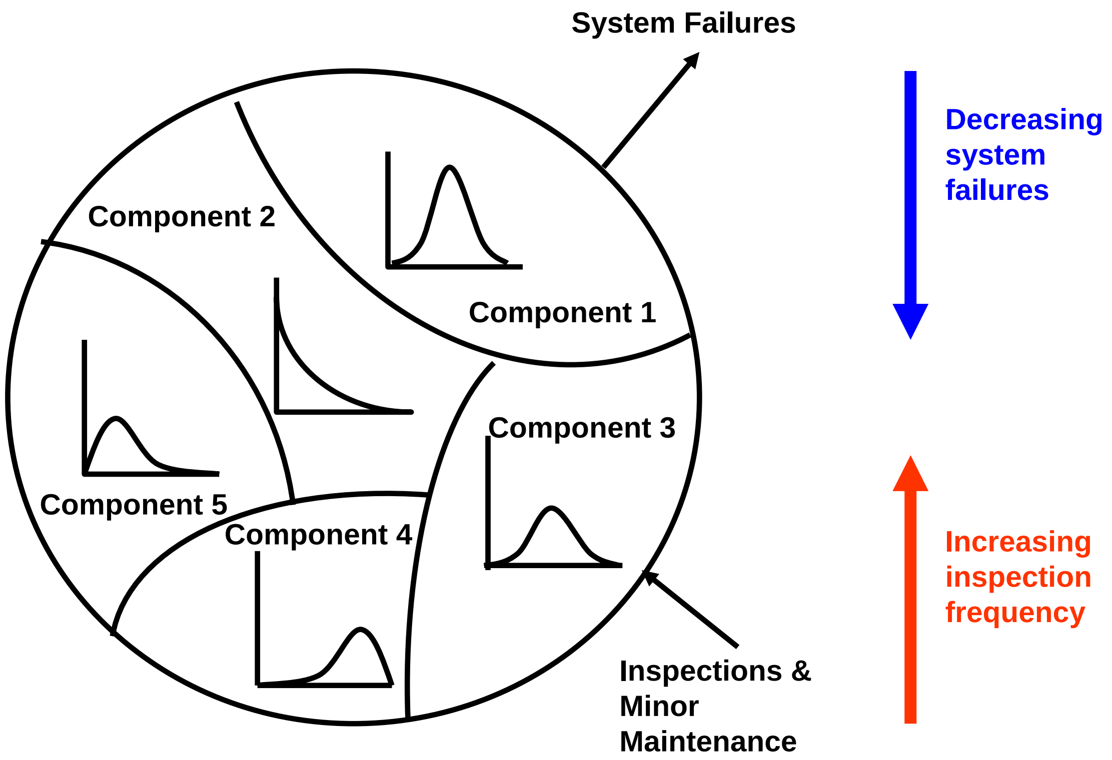
Review

Inspection Decisions

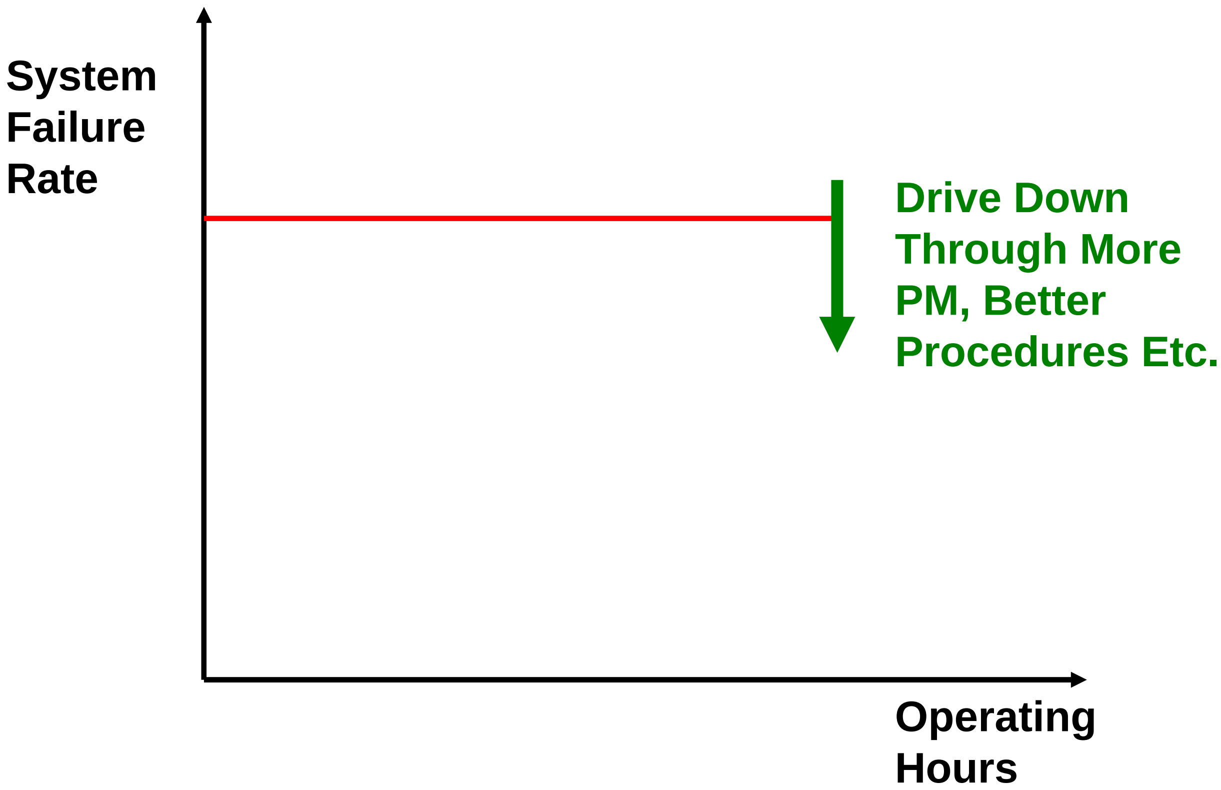
SYSTEM FAILURES

- Expect Failure Rate to be Constant
- Can Drive Down System Failure Rate By Preventive Maintenance (E.g. Inspections and Minor Maintenance)

Inspection Decisions



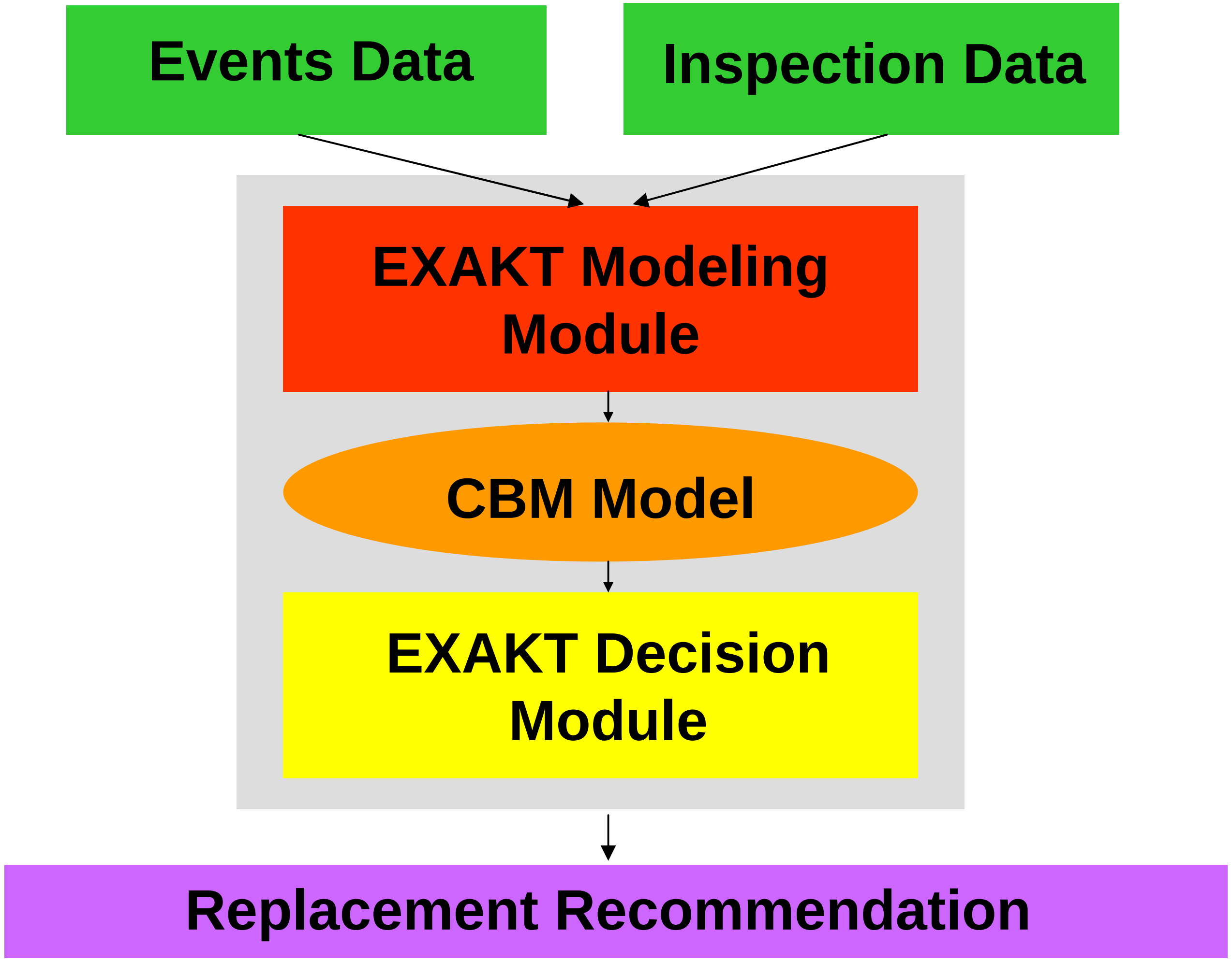
System Failure Rate



Failure Finding Intervals

- Availability Maximization
- Moubray (Horton) model for a single protective device

An Overview of EXAKT



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Additional CBM References

1. **www.mie.utoronto.ca/cbm** (For information about the CBM research activities at the University of Toronto)

2. **www.omdec.com** (For information about the EXAKT: CBM Optimization software)

EXAKT Tutorials

Learn the fundamentals of EXAKT by going through the EXAKT tutorial for single items, i.e.,components or systems as a whole:

www.omdec.com/articles/p_exaktTutorial.html

Link to advanced EXAKT tutorial for complex items, e.g., systems consisting of components with different failure modes:

www.omdec.com/articles/p_ExaktTutorialComplexItems.html

Note: Just follow the instructions on the web pages.

Problems

1) The current maintenance policy being adopted for a complex transfer machine in continuous operation is that inspections are made once every 4 weeks. Any potential defects that are detected during this inspection and that may cause breakdown of the machine are rectified at the same time. In between these inspections, the machine can break down, and if it does so, it is repaired immediately. As a result of the current inspection policy, the mean time between breakdowns is 8 weeks.

It is known that that breakdown rate of the machine can be influenced by the weekly inspection frequency, n, and associated minor maintenance undertaken after the inspection, and is of the form $\lambda(n) = K/n$, where $\lambda(n)$ is the mean rate of breakdowns per week for an inspection frequency of n per week.

Each breakdown takes an average of 1/4 week to rectify, while the time required to inspect and make minor changes is 1/8 week.

Problems

a. Construct a mathematical model that could be used to determine the optimal inspection frequency to maximize the availability of the transfer machine.

b. Using the model constructed in (a) along with the data given in the problem statement, determine the optimal inspection frequency. Also give the availability associated with this frequency.

Problems

2) A company monitors the gearboxes on vehicles by attaching a wireless sensor to each gearbox to take vibration readings. The vibration signals are then analyzed by a digital signal processing toolbox. Two condition indicators showing the health of the gearbox, CI1 and CI2 are extracted from each vibration signal. After running the above condition monitoring on a fleet of vehicles, the company has accumulated a certain amount of data. Now the company manager asks you to apply EXAKT to the data.

Problems

a. The first step for you would be to collect and prepare the data. What are the two main sources of data required by EXAKT?

b. Now you have obtained the right data and have properly prepared it. You want to establish a PHM for the gearboxes. The usual way for the modeling is to include both indicators in the PHM.

i. If you find one of them, CI1, is significant and the other, CI2, is not, how would you proceed with the modeling? What would you do if both CI1 and CI2 are not significant?

ii. If you find that the shape parameter is not significant (i.e., $\beta = 1$), how would you proceed? What does it really mean when you say the shape parameter is *not significant*?

Problems

c. Assume that the final PHM you get is

<insert equation>

where $h(t$, CI2) is the hazard rate and t is the operation hours.

Given the following data from the three gearboxes, estimate the hazard rate of each gearbox (Table 1).

Table 1: Data from Three Gearboxes

Gearbox No.	Operation Hours	CI1	CI2
1	8550	2	5.5
2	3215	10	2.1
3	9460	12	1.4

d. You are asked to submit a report regarding the hazard rate of gearbox 1. How might you explain the value you have obtained and what maintenance action would you recommend within the next 48 hours?