GE
Energy

The *business* of PHM :
An “Actuarial Engineering” perspective

Annual Conference of the Prognostics & Health Management Society 2010

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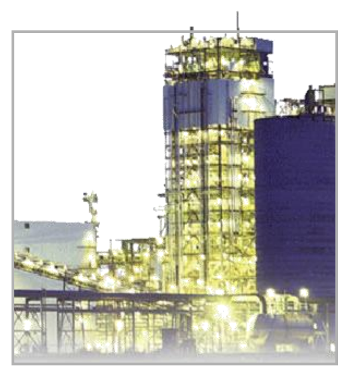
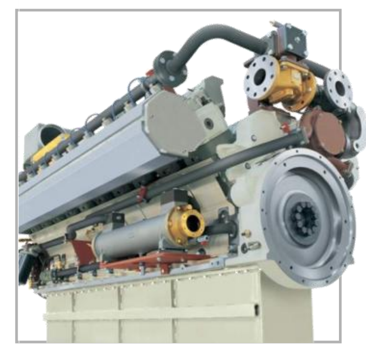
GE Energy – Advanced Technology Operations





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GE Energy

Employees: 82,000 • '09 revenue: $37.1B • Operating in 140 countries

Power & Water

- Power generation
- Renewables
- Gas Engines
- Nuclear
- Gasification
- Water treatment
- Process chemicals

Energy Services

- Contractual agreements
- Smart Grid
- Field services
- Parts and repairs
- Optimization technologies
- Plant management

Oil & Gas

- Drilling/production for … land, offshore, subsea
- LNG and pipelines
- Refining/petrochemical
- Industrial power gen
- Complete lifecycle services

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PHM Serves Diverse Technologies

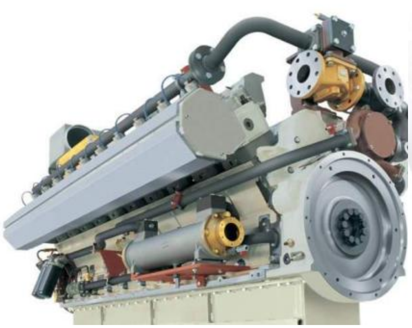
Gas

Wind

Nuclear

Solar

Smart Grid

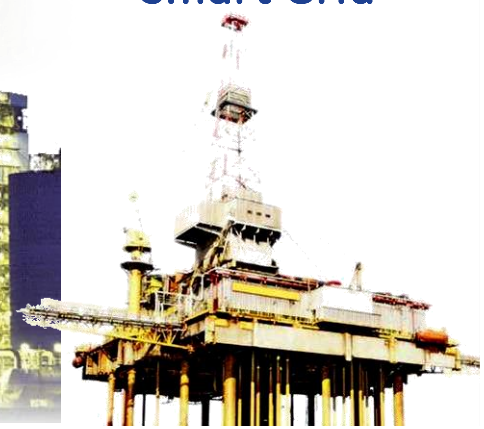


Biomass

Pipeline Integrity

Water Technologies

Cleaner Coal



Oil & Gas

Life Management Evolution

1930-1960

1st Generation
Corrective Maintenance

- Fix when broken
- All life consumed
- High forced outage costs
- Hard to predict
- Poor availability

1960-1985

2nd Generation
Preventive Maintenance

- Very popular
- Scheduled replacement
- Low forced outage costs / risk
- Higher scheduled outage costs
- Wasteful

1985-2000 **2000-2005**

3rd Generation
Predictive Maintenance

Reliability Centered Maintenance (RCM)

- Interval from reliability bathtub curve
- E.g. B1 life
- Useful for unobserved risks

Condition Based Maintenance (CBM)

- Physics/Empirical Damage accumulation
- Update model w/inspection data
- Risk-Based Inspection (RBI)

Prognostics Health Monitoring (PHM)

- Real-time
- M&D data based
- Fault / Anomaly detection & isolation (FDI)
- Prognostics & Diagnostics

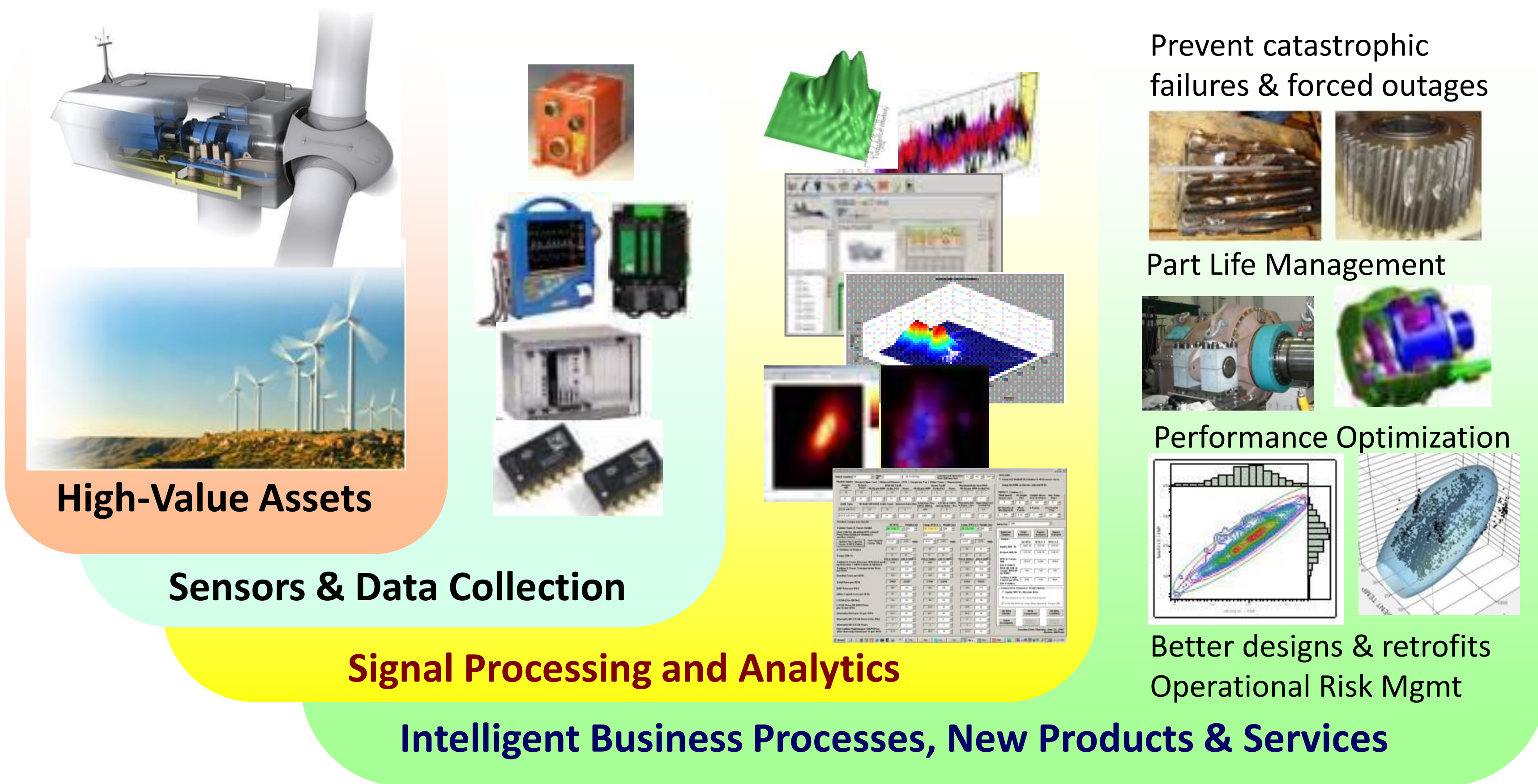
Optimal part life usage, improved reliability, availability maintainability & safety (RAMS), reduced O&M costs

2006+

4th Generation
Intelligent Engine Health Management

- Integrate controls with CBM/PHM
- Optimize asset usage

The *business* of PHM …



Sensors & Analytics provide intelligence and differentiated business processes that allow GE to develop new products & services … and generate value over the life of the asset

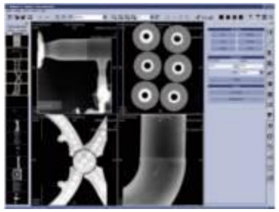
New Roles for PHM & Asset Management

New Business Models, Products

- Extended warranties
- Long term service agreements
- Operation & Maintenance Agreements
- New types of assets .. E.g. Renewable energy

Technology & Reliability, Risk

- Costs of collecting, storing and analyzing data continues to fall .. moving from terabyte to petabyte level databases
- Reliability & Risk Management needs to operate in a real-time 24/7 environment

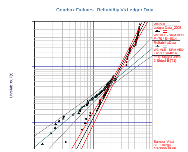



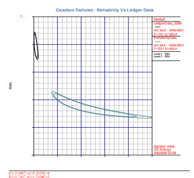
Assessing & Communicating Value in PHM

Business Value & Risk assessed using stochastic risk management processes

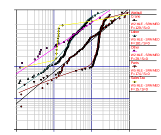
- Value & Risk models help define the product
- Scenario-Based & Probabilistic
- Leverage best practices from actuarial science & energy risk

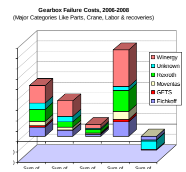
Weibull's & Maintenance Factors





Financials (Parts/Labor/ Logistics)

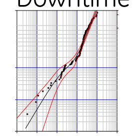




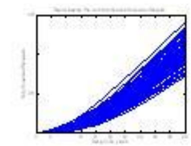
CBM Capability

Detection Probability

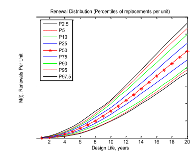
Downtime



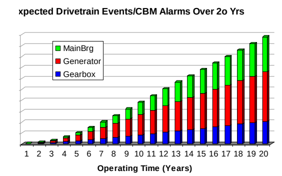
Scenario Simulation

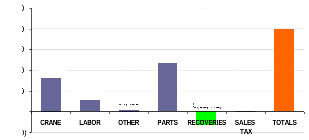


Loss Models

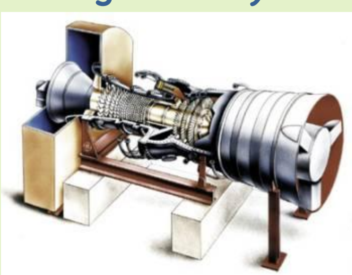


Deal Financials & Portfolio Analytics





Asset Health Usage & Management System



→ Advanced Reporting
→ Anomaly Detection
→ Life Management

Reasoners
Data Fusion
Optimizers

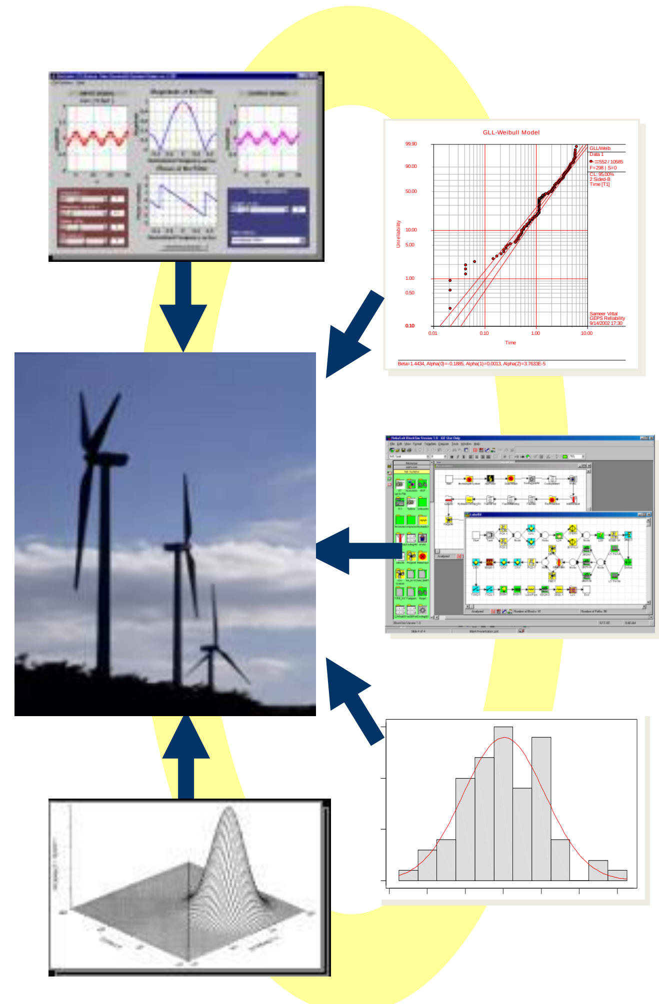
SMART SERVICES

Spare Parts/Pools
Logistics & Supply Chain
Risk-Based Inspection
Maintenance Workscope
Repair Optimization
Availability Guarantees
Performance Guarantees
Business Interruption Risk

BUSINESS CASE & VALUE PROPOSITION DRIVES PHM SYSTEM ARCHITECTURE

What Is Actuarial Science ? Why is it relevant ?

- Provide commercial, financial and risk management advice on the management of assets & liabilities, especially for long time horizons
- Actuaries are the DNA of the insurance industry
- "..for most actuaries, the role involves making financial sense of the future" (Institute of Actuaries, UK)
- Education is university-based or examination-based. Heavily regulated, global profession with professional standing
- Practice areas are Life, Health, Property & Casualty, Pensions, Benefits and Investments (usually of insurers)
- "Identify and analyze the financial consequences of events involving risk and uncertainty" – historically use past observation and wisdom to construct, validate and apply models



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Actuarial Skills -> Engineering Asset Management

Risk Measurement	Risk Models / Valuation	Risk Control

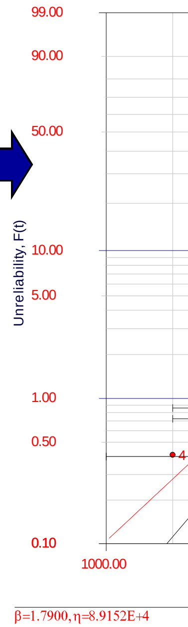
• Modeling **rare events** / extreme value statistics .. Wide range of distributions (100+ used !)
 	
• **Model and parameter uncertainty .. Goodness of fit (LL, BIC, AIC, H-Q)**
 	
• **Understanding correlations (structural, statistical)**
 	
• **Model updating and synthesis** (credibility theory)
 	
• Catastrophe risk analysis (models, methods)
 	
• Ruin theory applied to engineering systems
	• Financial value of risk, Loss Models (Frequency/Severity)
	
	• **Portfolio-based approach** to asset health management
	  • Risk Concentration
	  • Risk Diversification
	  • Correlations .. Copulas
	  • Metrics … VaR, CTE, RAROC
	
	• Regression Vs. simulation, scenario based valuation
	
	• New service products / revenue streams built around the physical asset (from transactional to annuity-type model)
		• **Loss reserving** (methods, tools, standards) and **Pricing** – the risks you assume
		
		• Identify, exclude hazards that cannot be controlled (terms & conditions)
		
		• Integrate asset life management into an **Enterprise Risk Management** framework (operational risk)

Basics …Classical Life Data Analysis

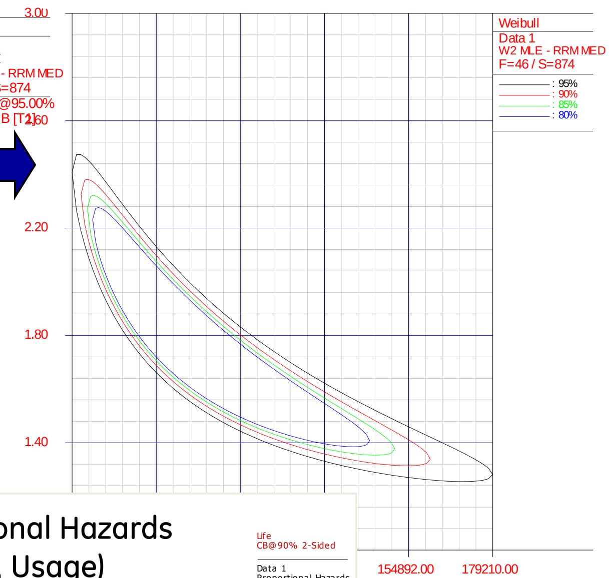
Typical Part Life Data - For illustrative purposes only

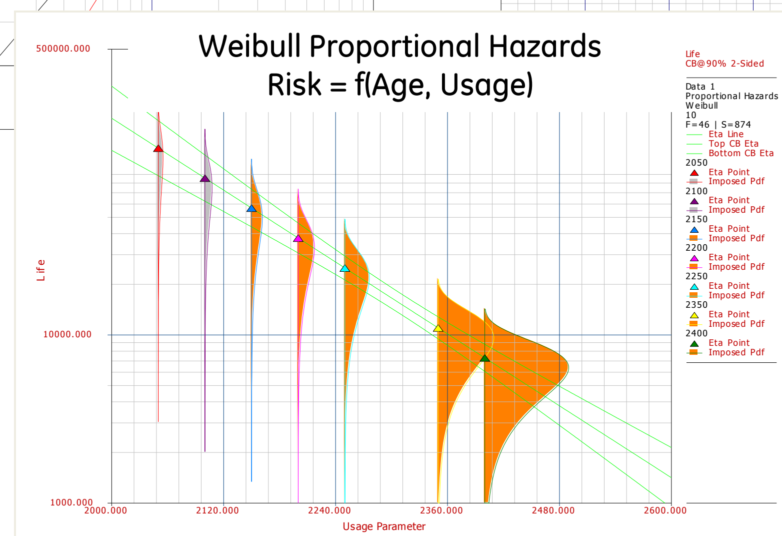
Old Insp. (Hrs)	New Insp. (Hrs)	Usage Factor (X1)	Parts Fail	Parts OK
1000	3000	2400	4	88
2000	4000	2250	3	89
9000	20000	2350	3	89
12000	20000	2100	4	88
15000	25000	2050	7	85
18000	25000	2150	8	84
2000	6000	2200	1	91
3000	12000	2200	2	90
6000	18000	2100	6	86
6000	20000	2150	8	84

Standard Weibull Distribution



Weibull Parameters - Joint Confidence Interval





Other analysis types include,

- Non Parametric Methods
- Parametric with Physics-based Aging
- Logistic Regression
- Nonlinear Regression
- Probit Analysis
- Generalized Poisson Process Models, etc

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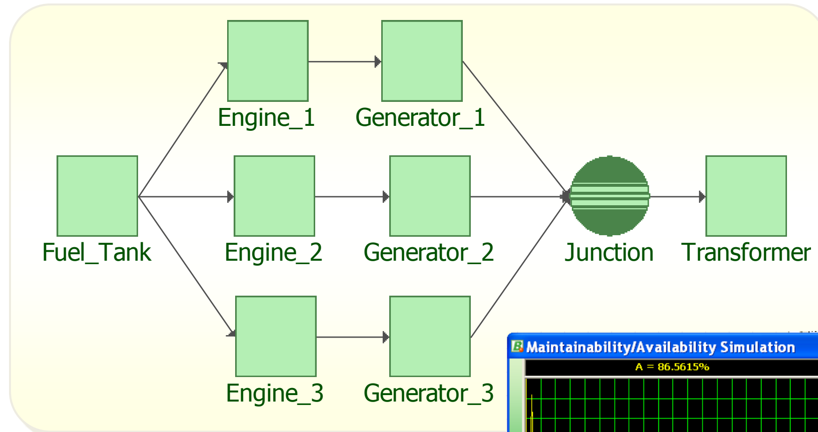
From part to system risk / reliability

Part Failure and Repair Distributions, and other variables as needed (repairs, inspections, logistics, spares, costs, etc)

Component	Failure Distribution		Repair Distribution	
	Eta (hr)	Beta	Mu (hr)	Sigma
FuelTank	200000	1.5	168	20
Engine_1	75000	2.5	336	48
Engine_2	75000	2.5	336	49
Engine_3	75000	2.5	336	50
Generator_1	100000	4.5	250	120
Generator_2	100000	4.5	250	120
Generator_3	100000	4.5	250	120
Transformer	85000	3.0	1000	250
	Weibull		Normal	

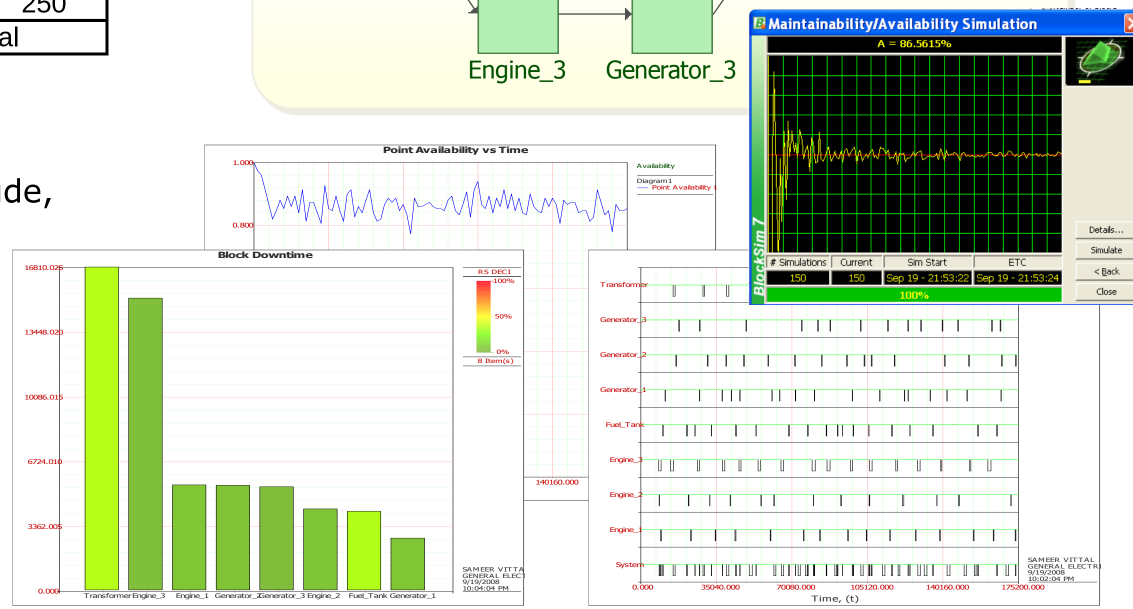
Data for illustrative purposes only

Reliability Block Diagrams are often used to predict component impact on overall system reliability, availability, safety and life cycle costs



Other system reliability methods include,

- General Discrete Event simulation
- Fault Tree Analysis
- Markov & Semi-Markov Models
- Stochastic Petri Nets
- Queuing Models
- Bayesian Networks (Adapted)

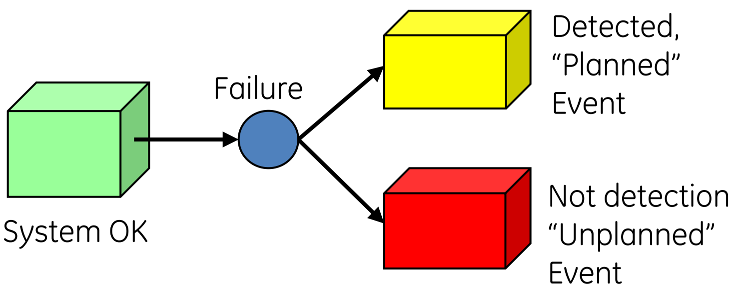


E.g. Component downtime, availability & operational status

Quantifying the Impact of Anomaly Detectors

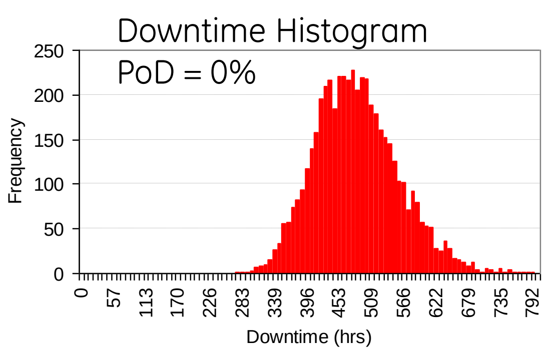
Consider a simple example where we have a system with an onboard sensor / anomaly detection algorithm that detects failures in advance with some probability of detection (PoD). If failure indications are detected early on, associated risks, downtime durations & failure costs are typically much lower

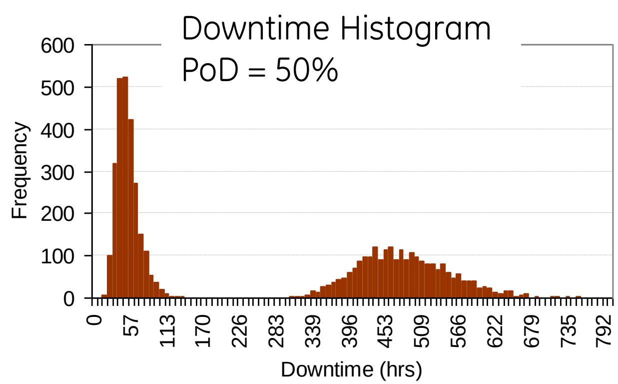
Simulation-based trade studies can be used to optimize the sensor suite (PoD, false alarm rate, time to detect, etc) with the asset being monitored. This significantly improves reliability, reduces outage durations and reduces overall system operational risk.

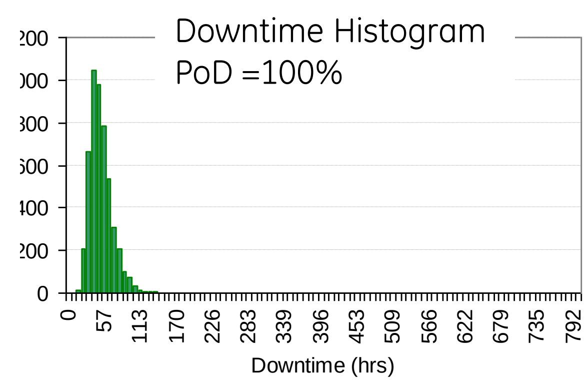


Assumptions / Input		Key Statistics	
Event Type	**Distribution**	**Mean**	**StDev**
Time to Failure (hr)	Weibull	22181.6	9491.7
Planned Downtime (hr)	Lognormal	48	18
Unplanned Downtime (hr)	Lognormal	480	75

Data & results for illustrative purposes only







Case Study 1 : From Weibull's to Loss Models

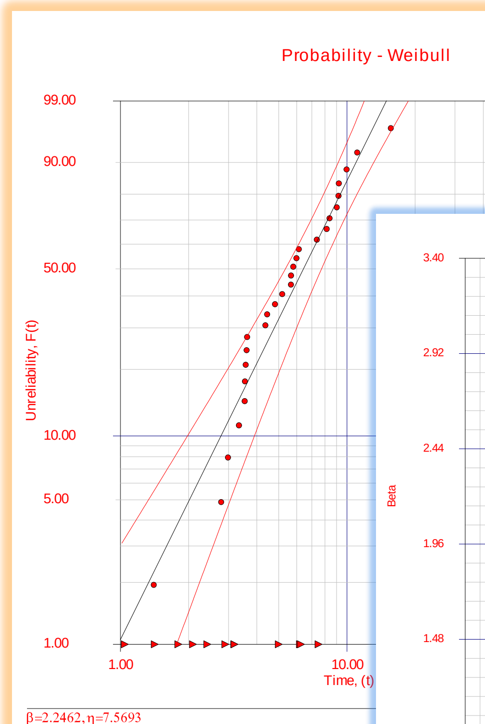
- We show how life data analysis can be combined with a PHM metric (E.g. Probability of Detection) to estimate a distribution of losses (costs)
- Impact of model parameter uncertainty on "tail" risks .. Concept of VaR, TVaR, etc.

Step 1 : Collect failure ("F") & suspensions / right-censored "S" data

Type	Failure Time
S	0.824
S	1.046
S	1.416
F	1.428
S	1.801
S	2.091
S	2.419
F	2.835
S	2.905
F	3.038
S	3.182
S	3.188
F	3.394
F	3.602
F	3.607
F	3.635
F	3.670
F	3.689
F	4.441
F	4.523

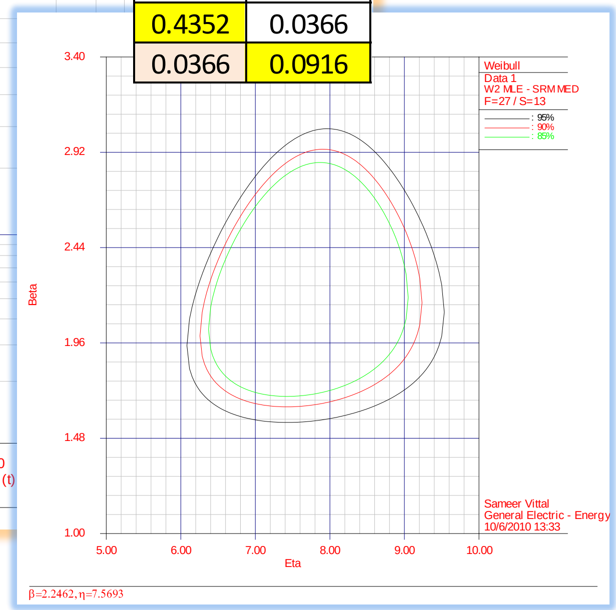
Type	Failure Time
F	4.900
S	4.999
F	5.271
F	5.760
F	5.772
F	5.896
F	6.093
S	6.201
F	6.242
S	6.271
F	7.495
S	7.495
F	8.282
F	8.527
F	9.181
F	9.349
F	9.379
F	10.142
F	11.303
F	15.904

Step 2 : Fit a standard survival model (E.g. Weibull) and estimate parameter uncertainties



	Value	Lower 95% CI	Upper 95% CI
Eta =	7.5693	6.3807	8.9793
Beta =	2.2462	1.7248	2.9252

Var-Eta	Var-Beta
0.4352	0.0366
0.0366	0.0916



Note: This example is for illustrative purposes only

Case Study 1 : From Weibull's to Loss Models

Step 3 : A simple simulation model in Excel (for demo purpose only)

- Simple portfolio of 5 units ..
- All have identical Weibull life distributions (same eta/beta)
- **No parameter uncertainty**
- Probability of Detection assumed to be 65%
- If event is detected, lower costs …if missed, substantially higher cost distributions
- Costs distributions (detected, missed) are lognormal
- 20-Yr warranty assumed
- Run Monte Carlo trials .. use any tool / VBA script

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Eta (yr)	7.57	7.57	7.57	7.57	7.57
Beta	2.25	2.25	2.25	2.25	2.25
Simulated Failure Time (Yrs)					
TTF 1	8.7	4.9	5.7	9.5	4.4
TTF 2	12.4	13.4	11.1	11.9	15.9
TTF 3	18.5	19.7	16.9	20.8	22.5
TTF 4	26.7	20.4	20.3	27.7	28.2
TTF 5	44.2	36.5	27.0	32.3	34.0

Cost/Event	Detect	Miss
Dist	LOGN	LOGN
Mean	$ 2,500	$ 25,000
StDev	$ 1,000	$ 10,000
CoV	0.4	0.4
Mu	7.244	9.547
Sigma	1.077	1.077

PoD	65%

Avg-STD $ 1,576

Table that tracks events

Year	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	detect	0	0	miss
6	0	0	miss	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	detect	0	0	0	0
10	0	0	0	detect	0
11	0	0	0	0	0
12	0	0	detect	miss	0
13	detect	0	0	0	0
14	0	detect	0	0	0
15	0	0	0	0	0
16	0	0	0	0	detect
17	0	0	miss	0	0
18	0	0	0	0	0
19	detect	0	0	0	0
20	0	miss	0	0	0

Year	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
1					
2					
3					
4					
5		$ 2,629			$ 25,543
6			$ 878		
7					
8					
9	$ 1,630				
10				$ 10,489	
11					
12			$ 242	$ 7,916	
13	$ 1,164				
14		$ 1,740			
15					
16					$ 2,093
17			$ 31,682		
18					
19	$ 1,753				
20		$ 69,889			
TOTAL	$ 4,547	$ 74,258	$ 32,802	$ 18,405	$ 27,636
$/Yr	$ 227	$ 3,713	$ 1,640	$ 920	$ 1,382

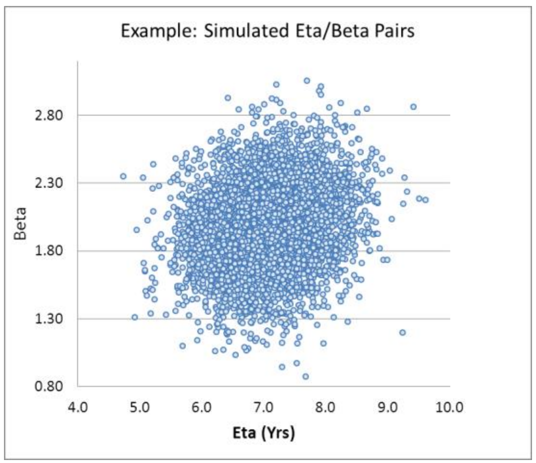
Screenshot of a typical MC trial

Note: This example is for illustrative purposes only

Case Study 1 : From Weibull's to Loss Models

Step 4 : A simple simulation model in Excel (for demo purpose only)

- Same portfolio of 5 units ..
- Unit Weibull's are not the same
- Eta/Beta pairs obtained from Weibull covariance matrix .. Assume they are bivariate normal
- **This scenario includes parameter uncertainty**



- Rest is same ..
- Run Monte Carlo trials ..

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
Eta (yr)	6.78	6.65	6.73	5.40	6.34
Beta	2.42	2.15	2.12	2.25	1.62
Simulated Failure Time (Yrs)					
TTF 1	5.5	3.3	9.4	3.9	5.7
TTF 2	8.5	11.5	15.7	6.2	13.5
TTF 3	13.8	14.9	18.4	11.7	20.8
TTF 4	20.5	17.0	27.3	16.7	22.7
TTF 5	26.6	21.8	32.4	19.1	27.3

Cost/Event	Detect	Miss
Dist	LOGN	LOGN
Mean	$ 2,500	$ 25,000
StDev	$ 1,000	$ 10,000
CoV	0.400	0.400
Mu	7.244	9.547
Sigma	1.077	1.077

PoD	65%

Avg/Yr/Unit **$ 1,282**

Table that tracks events

Year	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	miss	0	miss	0
5	0	0	0	0	0
6	detect	0	0	0	detect
7	0	0	0	detect	0
8	0	0	0	0	0
9	detect	0	0	0	0
10	0	0	miss	0	0
11	0	0	0	0	0
12	0	detect	0	detect	0
13	0	0	0	0	0
14	detect	0	0	0	detect
15	0	detect	0	0	0
16	0	0	detect	0	0
17	0	0	0	detect	0
18	0	miss	0	0	0
19	0	0	detect	0	0
20	0	0	0	detect	0

Year	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5
1					
2					
3					
4		$ 27,043		$ 15,805	
5					
6	$ 4,966				$ 2,280
7				$ 10,975	
8					
9	$ 2,353				
10			$ 5,934		
11					
12		$ 376		$ 15,296	
13					
14	$ 620				$ 2,817
15		$ 1,402			
16			$ 7,075		
17				$ 4,365	
18		$ 22,257			
19			$ 3,727		
20				$ 950	
TOTAL	$ 7,939	$ 51,078	$ 16,736	$ 47,391	$ 5,097
$/Yr	$ 397	$ 2,554	$ 837	$ 2,370	$ 255

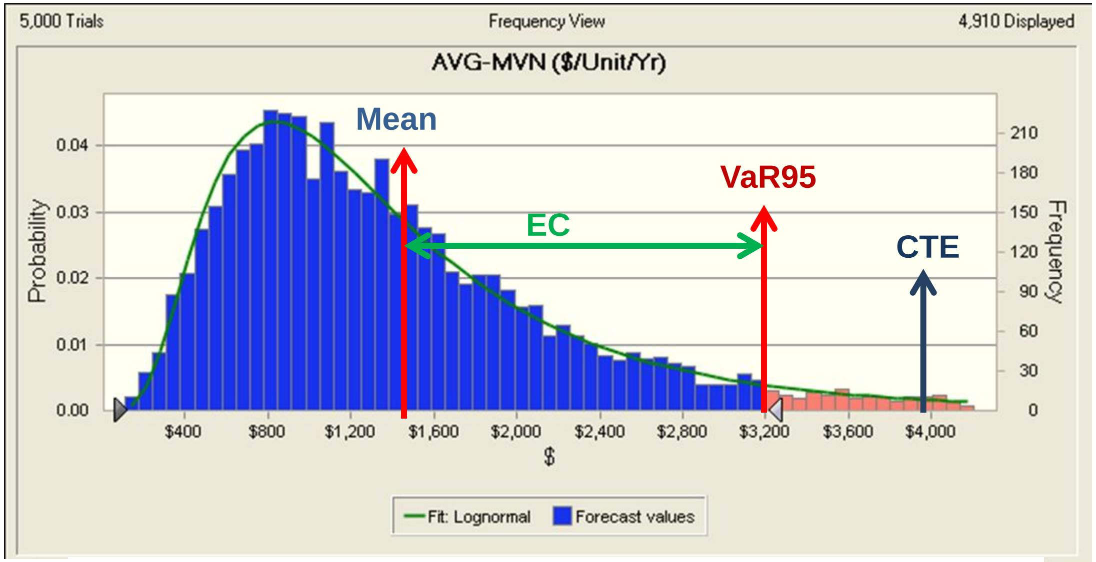
Screenshot of a typical MC trial

Note: This example is for illustrative purposes only

Case Study 1 : From Weibull's to Loss Models

Statistic	Weibull with Parameter Uncertainty	Weibull Parameters Only
Trials	5000	5000
Mean	$1,451	$1,350
Median	$1,228	$1,139
Std Deviation	$983	$898
Variance	$967,219	$806,465
Skewness	3.20	2.58
Kurtosis	29.99	18.82
CoV	0.6777	0.6653
Minimum	$110	$94
Maximum	$16,957	$12,962
Range Width	$16,847	$12,868

Percentiles	Weibull with Parameter Uncertainty	Weibull Parameters Only
P0	$110	$94
P10	$554	$502
P20	$735	$676
P30	$886	$824
P40	$1,052	$973
P50	$1,228	$1,139
P60	$1,429	$1,334
P70	$1,658	$1,553
P80	$1,998	$1,881
P90	$2,604	$2,420
P100	$16,957	$12,962



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Typical Metrics :

Value At Risk (VaR)

- Percentile of interest (P95/P99) from loss model
- Depends on business risk appetite

Conditional Tail Expectation (CTE) or TVaR

- "Expected" value of losses in tail (usually beyond the VaR limit)

Risk-Adjusted Return On Capital (RAROC)

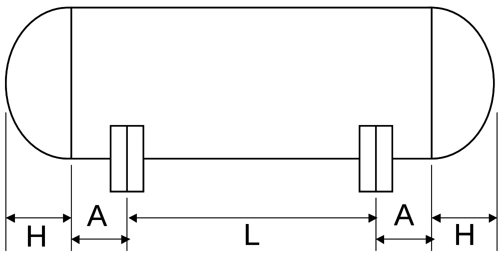
- RAROC = Expected Return / VaR or EC
- Multiple uses in risk mgmt.

Case Study 1 : Observations

- Actuarial Methods .. Frequency/Severity or Discrete Event Simulation-based … ARE applicable to engineering asset management
- Uncertainty matters !! (We all know this in PHM) .. But very critical for risk as models get larger, more realistic .. Include economic variables, shocks .. plus a lot of things that are hard to measure !!
- "Expected" values and "traditional" metrics .. RoI, NPV, IRR, are helpful, but not enough.. The tail risk alone can wipe out a badly designed contract / portfolio
- Communicate the value of PHM using the **vocabulary of financial risk management** : VaR, CTE, RAROC, EC, etc. ..

- This is an EXTREMELY SIMPLE "made-up" example .. real projects require both model & parameter uncertainties, asset correlations (E.g. Copulas), systemic risk .. Contagion risk .. Risk attractors / diversifiers … beyond the scope of this presentation

Case Study 2 : Probabilistic Design & PHM



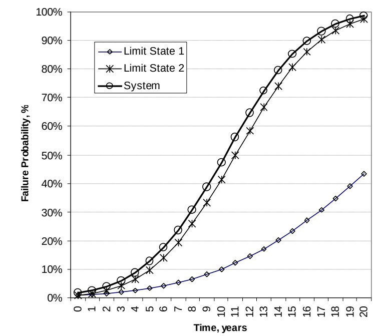
Pressure Tank
2 Limit States (ASME)
Design Variable : Shell Thickness

Time-based FORM, SORM, MF-FOSM, etc

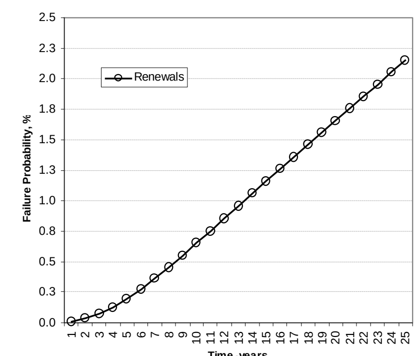
$$Pf = \int \dots \int_{g()<0} f_X(x_1, x_2, \dots, x_n)\, dx_1 dx_2 \dots dx_n$$

$$\beta(t) = \frac{\bar{g}(t)}{\sqrt{\sum_{i=1}^{k} \left(\frac{\partial g(t)}{\partial y_i} \right)^2 \sigma_{y_i}^2}}$$

Equivalent Weibull

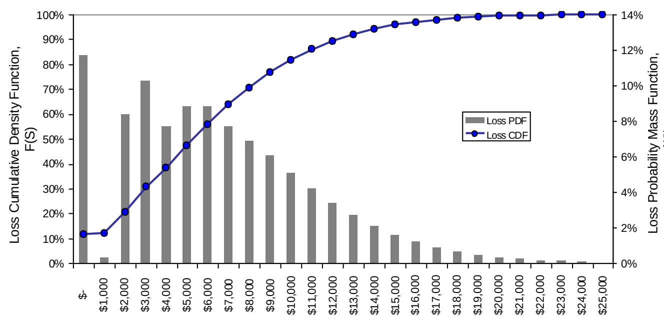


Renewal Model



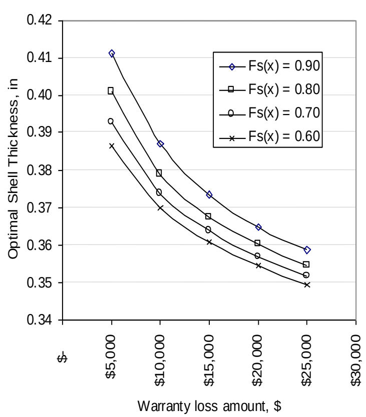
$$M(t) = F(t) + \int_{u=0}^{u=t} M(t-u)\, dF(u)$$

Actuarial Loss Model



$$F_S(x) = \sum_{n=0}^{n=\infty} \left[p_n \int_{k=0}^{k=n} F_X^{(k-1)}(x-y)\, dF_X(y) \right]$$

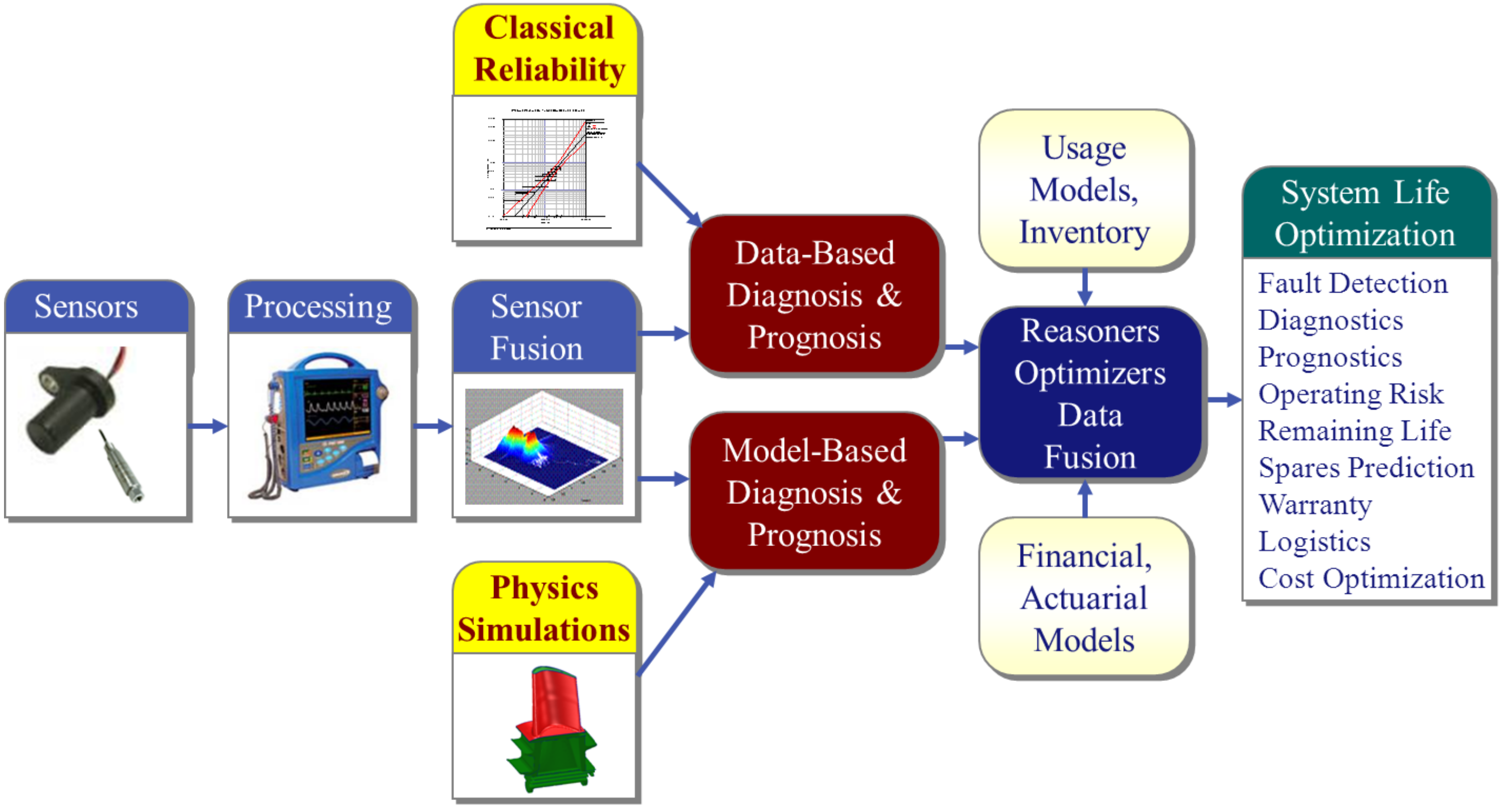
Optimization



Reference : Vittal S. & Phillips, R., "Modeling and Optimization of Extended Warranties Using Probabilistic Design", RAMS2007, Orlando, FL (2007)

PHM As Part of Risk Management

- PHM + Life-Extending Controls provide the "vital knobs" to manage operational risk in portfolio's of monitored assets
- It's an "early warning system" .. For emerging/ systemic issues
- Effective risk transfer mechanism .. From unplanned to planned maintenance



Summary .. "Actuarial Engineering"

- ✓ An "engineering only" approach cannot unlock PHM's full value .. the associated financial service & business process is just as important
- ✓ "**Actuarial Engineers**" .. Engineers with skills in Operations Research, PHM, Reliability & Actuarial Science ... are the people who can run the ***business*** of PHM
- ✓ This field requires collaboration between the engineering and actuarial communities .. need to learn the other person's language ..
- ✓ Exciting area for research !!

Thank You !