Modeling the Effects of Prognostics and Health Management

Charles M. Carter
Systems Readiness and Sustainment Technologies
Sandia National Laboratories
Albuquerque, NM USA
cmcarte@sandia.gov

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

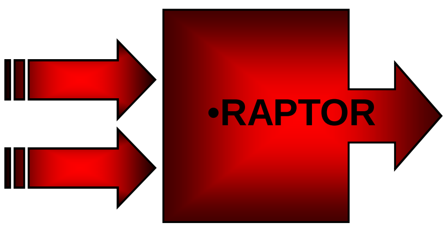
Overview

- Prognostic capabilities are being incorporated into a growing number of systems
- Commercial reliability tools can be used to quantify the benefits of PHM
  - Raptor
- Sandia has developed algorithms to model the impact of prognostic capabilities on enterprise performance
  - Support Enterprise Model (SEM)
- The techniques used in these tools will be discussed along with some results of a notional PHM study

What is Raptor?

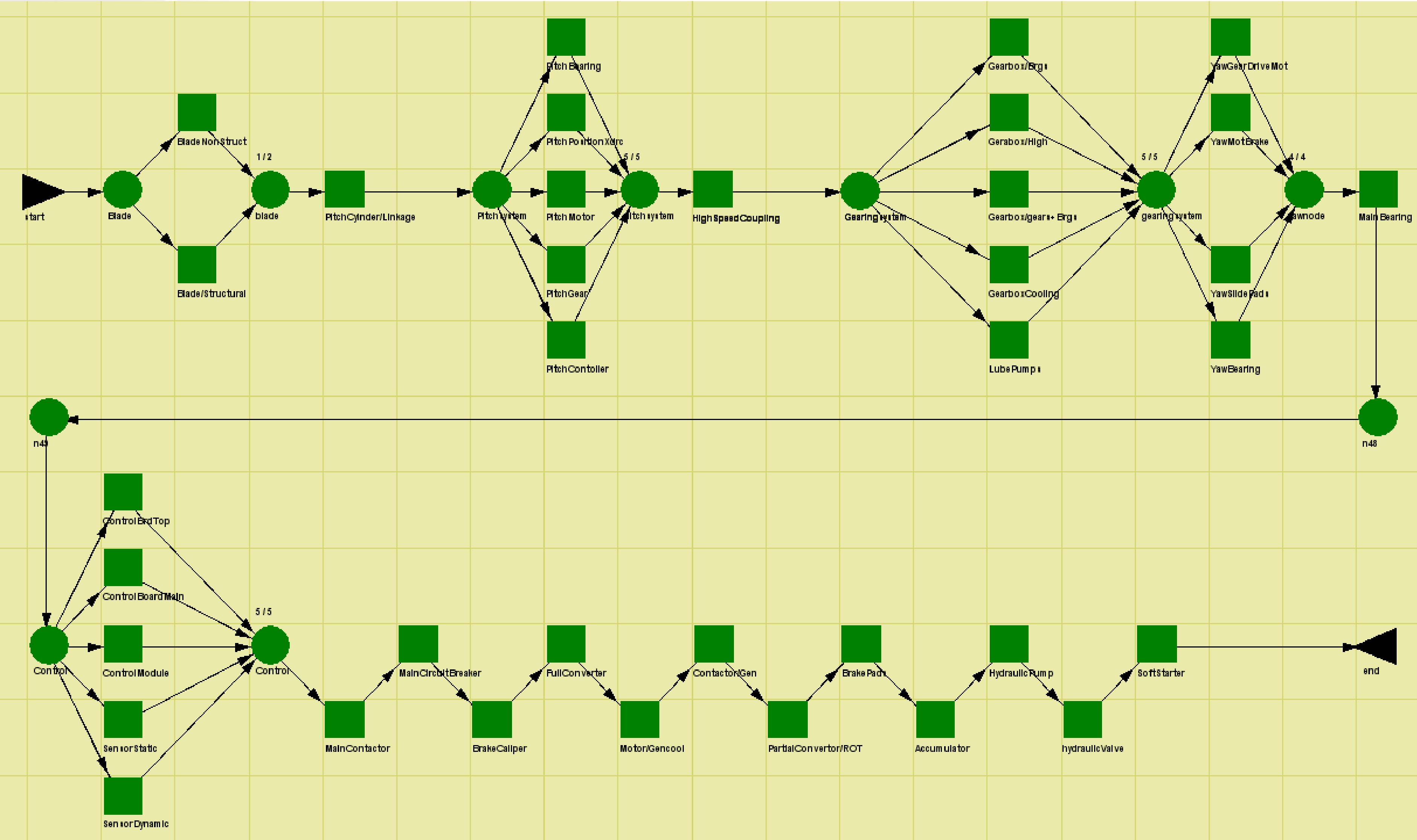
- Raptor is a discrete-event Monte Carlo **simulator**
- Raptor simulates operation of a system using failure, repair, preventive maintenance, sparing, logistics, and cost information

•**Component-level Information**
- •Reliability
- •Logistics
- •Cost
- •Operational use



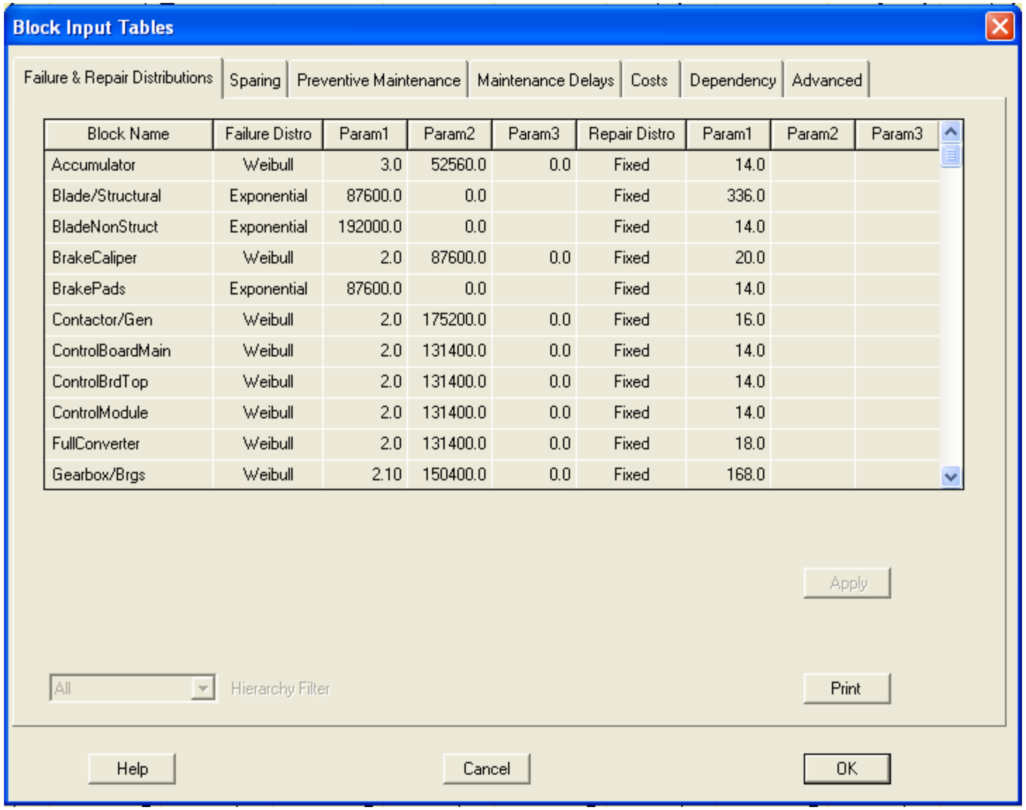
•**System-level Results**
- •Reliability
- •Logistics
- •Availability
- •Cost
- •Capacity
- •Weak Links

Wind Turbine Reliability Block Diagram in Raptor

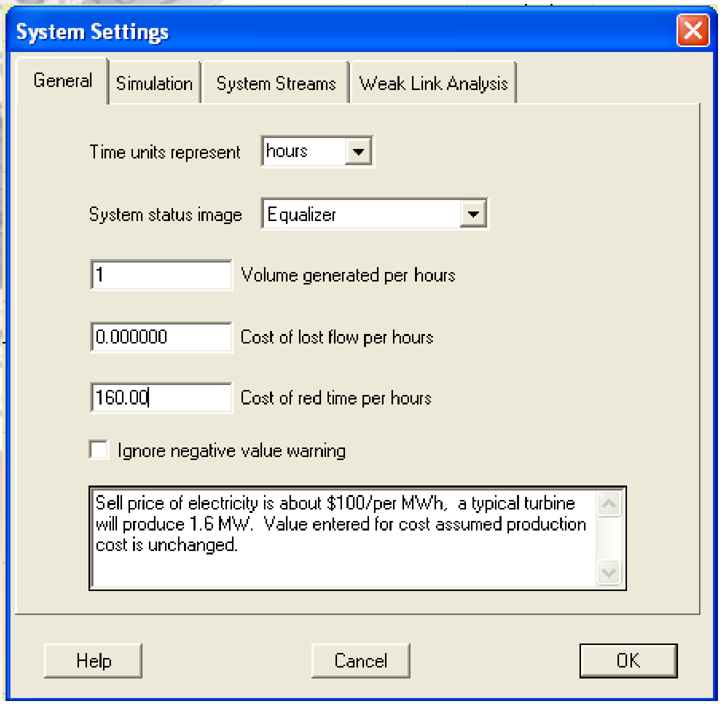


Model Inputs

- **Notional failure and repair data**



Block Name	Failure Distro	Param1	Param2	Param3	Repair Distro	Param1	Param2	Param3
Accumulator	Weibull	3.0	52560.0	0.0	Fixed	14.0		
Blade/Structural	Exponential	87600.0	0.0		Fixed	336.0		
BladeNonStruct	Exponential	192000.0	0.0		Fixed	14.0		
BrakeCaliper	Weibull	2.0	87600.0	0.0	Fixed	20.0		
BrakePads	Exponential	87600.0	0.0		Fixed	14.0		
Contactor/Gen	Weibull	2.0	175200.0	0.0	Fixed	16.0		
ControlBoardMain	Weibull	2.0	131400.0	0.0	Fixed	14.0		
ControlBrdTop	Weibull	2.0	131400.0	0.0	Fixed	14.0		
ControlModule	Weibull	2.0	131400.0	0.0	Fixed	14.0		
FullConverter	Weibull	2.0	131400.0	0.0	Fixed	18.0		
Gearbox/Brgs	Weibull	2.10	150400.0	0.0	Fixed	168.0		



- **"Cost of red time" represents lost revenue due to the system not operating**
- **Assumptions for cost are noted in comment field**

Sandia National Laboratories

Model Inputs (2)

Block Input Tables

Failure & Repair Distributions | Sparing | Preventive Maintenance | Maintenance Delays | Costs | Dependency | Advanced

Block Name	Pre-Logistics	Post-Logistics	Resource	# for Mx	# for PM
Accumulator	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Blade/Structural	Fixd (168.000000)	Fixd (2.000000)	None	N/A	N/A
BladeNonStruct	Fixd (168.000000)	Fixd (2.000000)	None	N/A	N/A
BrakeCaliper	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
BrakePads	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Contactor/Gen	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
ControlBoardMain	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
ControlBrdTop	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
ControlModule	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
FullConverter	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Gearbox/Brgs	Fixd (168.000000)	Fixd (2.000000)	None	N/A	N/A
Gearbox/gears+Brgs	Fixd (168.000000)	Fixd (2.000000)	None	N/A	N/A
GearboxCooling	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Gerabox/High	Fixd (168.000000)	Fixd (2.000000)	None	N/A	N/A
HighSpeedCoupling	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A

All | Hierarchy Filter | Print

Help | Cancel | OK

- **Pre-repair and post-repair logistic delays times are included as input**
- **For some parts the pre-LDT is significant**

Block Input Tables

Failure & Repair Distributions | Sparing | Preventive Maintenance | Maintenance Delays | Costs | Dependency | Advanced

Block Name	Pre-Logistics	Post-Logistics	Resource	# for Mx	# for PM
Accumulator	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Blade/Structural	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
BladeNonStruct	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
BrakeCaliper	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
BrakePads	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Contactor/Gen	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
ControlBoardMain	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
ControlBrdTop	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
ControlModule	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
FullConverter	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Gearbox/Brgs	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Gearbox/gears+Brgs	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
GearboxCooling	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
Gerabox/High	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A
HighSpeedCoupling	Fixd (8.000000)	Fixd (2.000000)	None	N/A	N/A

All | Hierarchy Filter | Print

Help | Cancel | OK

- **A second model was created that assumed knowledge of impending failure for certain parts**
- **The Pre-LDT times were reduced to the standard times experienced by other parts**

Results

Output Tables

Summary | Logistics | Sparing | Block Costs

Results from 10 runs of sim time 87600.000000:

Parameter	Minimum	Mean	Maximum	Standard Dev	SEM
Total Cost	$168,640.00	$317,139.96	$514,880.00	$109,971.82	$34,776.14
Availability	0.963264840	0.977373005	0.987968037	0.007846163	0.002481175
MTBDE	3727.739130	5703.305575	9616.222222	1734.061590	548.358423
MDT	71.709225	125.037595	175.600000	35.741562	11.302474
Reliability	0.000000000	0.000000000	0.000000000	0.000000000	0.000000000
Conditional Reliability	0.000000000	0.000000000	0.000000000	0.000000000	0.000000000
System Failures	9	16.100000	23	4.175324	1.320353

Print

Help OK

Output Tables

Summary | Logistics | Sparing | Block Costs

Results from 10 runs of sim time 87600.000000:

Parameter	Minimum	Mean	Maximum	Standard Dev	SEM
Total Cost	$59,840.00	$214,912.00	$416,960.00	$111,694.64	$35,320.95
Availability	0.970251142	0.984666667	0.995730594	0.007969081	0.002520045
MTBDE	3147.925926	5604.169259	9691.777778	1923.312538	608.204827
MDT	36.111111	77.084709	104.900000	26.123937	8.261114
Reliability	0.000000000	0.000000000	0.000000000	0.000000000	0.000000000
Conditional Reliability	0.000000000	0.000000000	0.000000000	0.000000000	0.000000000
System Failures	9	16.900000	27	5.195083	1.642830

Print

Help OK

- **Total Cost values represent the lost revenue over a 10 year period for a single turbine**
  - **PHM Improvement results in additional revenue of $10,222.8/yr**
- **Wind farms with a large number of turbines should see a linear increase in additional revenue**
  - **Cost to implement PHM on a larger scale is likely not linear**

Other Effects of Successful PHM

- Extended life for preventive maintenance items
  - Often components with significant negative consequences associated with failure are replaced on an age basis
  - Condition monitoring could prolong replacement
  - Most commercial block diagram simulators model PM
- Reduced Repair times
  - Orderly shut down and repair may eliminate some tasks associated with an unscheduled failure

Support Enterprise Model (SEM)

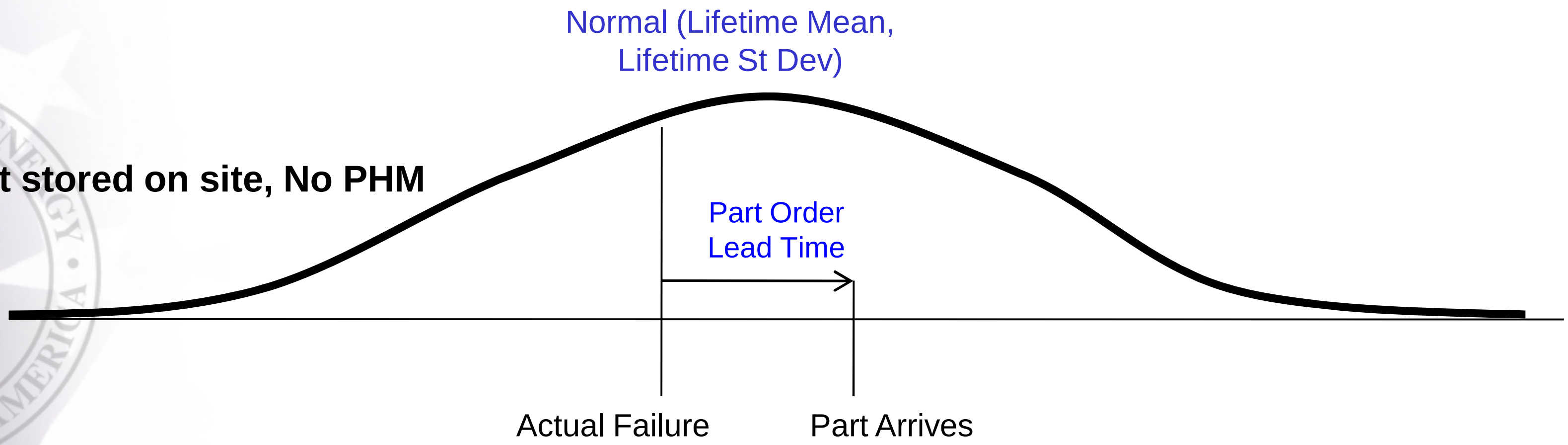
- **What is SEM?**
  - A flexible approach to modeling logistics support systems
  - An Enterprise-level, multi-echelon, end-to-end logistics model
  - Integrated modeling of supply and repair chain activities for a worldwide support system
  - A discrete event logistics simulation
- **Time-based and event-based results from SEM provide analysts with the ability to:**
  - Determine site performance based upon maintenance and supply down times
  - Calculate equipment and support system performance and cost metrics accounting for uncertainty (multiple trials)
  - Identify most significant cost drivers at each site (inventory, consumables, etc.)
  - Characterize the impact of changes in:
    - Support system architecture
    - Processes & business rules
    - Equipment R&M characteristics
    - Equipment usage
  - Support critical business decisions for a large scale problem

PHM Modeling in SEM

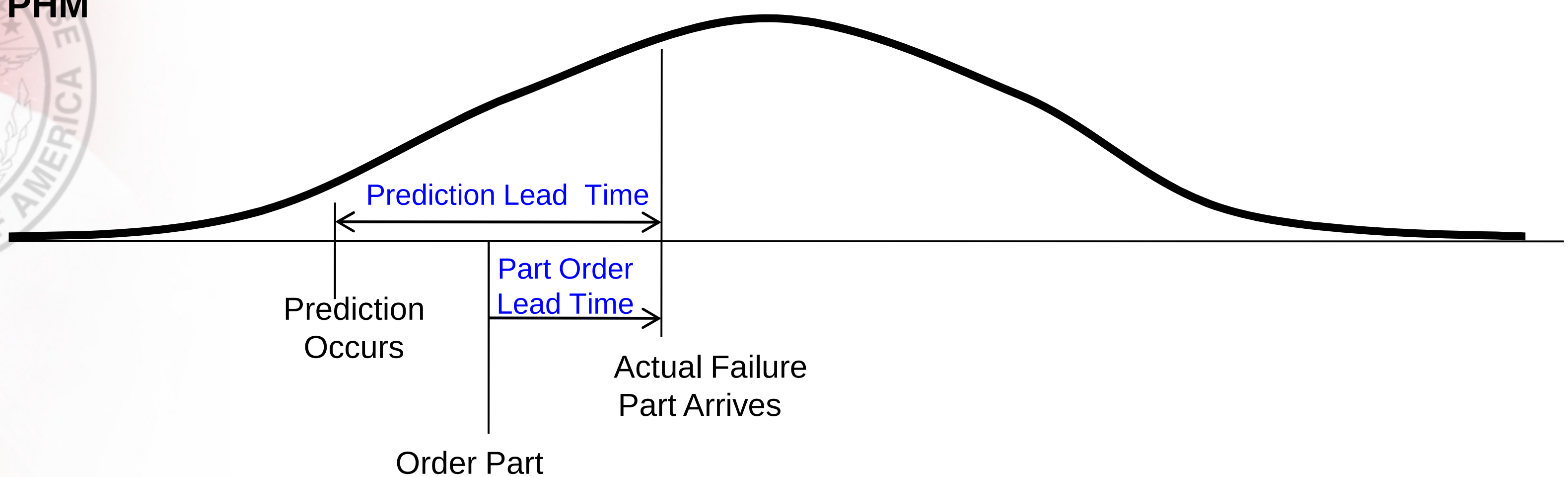
- SEM models part failures
  - Random failures (Exponential)
  - Wear-out failures (Normal)
  - Time Change failures (constant)
- Wear-out failures in SEM are failures based upon a Normal distribution
  - Represent wear-out or fatigue failures on parts
  - PHM is modeled only for parts with a wear-out distribution
- PHM Wear-out
  - Used to model prediction and diagnostics of actual failure
  - Used to model the logistics response
  - Expected to impact the NMCS (Non Mission Capable due to Supply)

Ideal PHM

- **Part not stored on site, No PHM**

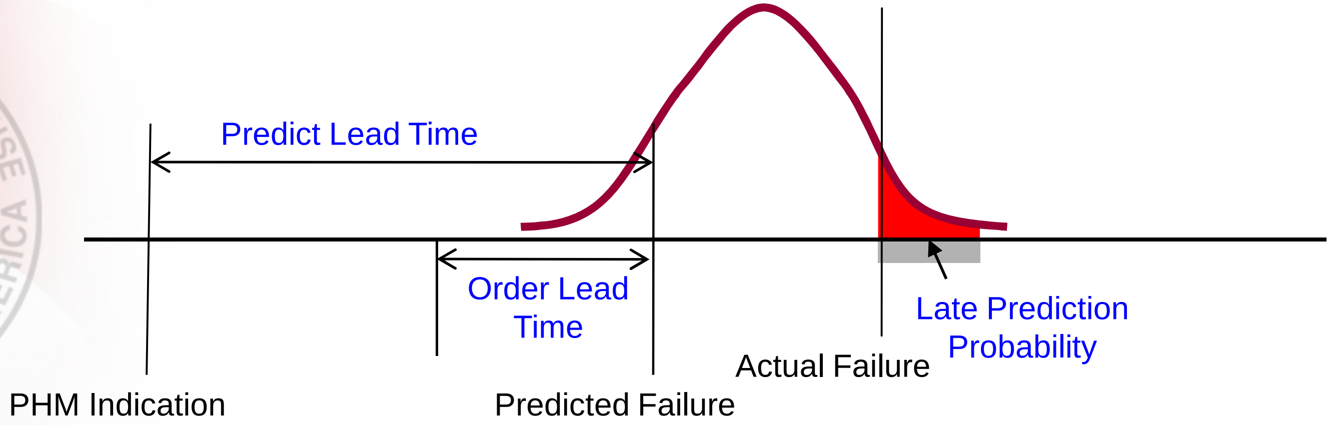


- **Perfect PHM**



PHM Model in SEM

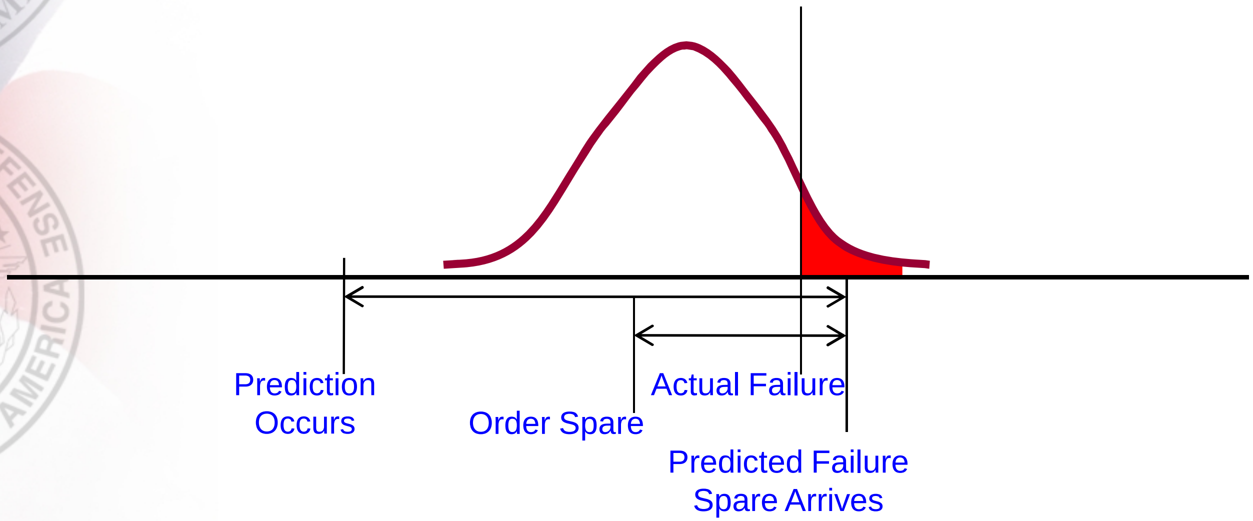
- **Uses the standard deviation of prediction time variability (Predict Time SD) and creates a Normal curve that is offset from the Actual failure time**
  - **Offset is positioned to account for the late prediction probability**
- **A random draw from this normal curve determines the time of the PHM indication and the predicted failure time**



➢ **Predicted Failure Time = Actual Failure Time + Normal(Alpha*Predict Time SD, Predict Time SD), where Alpha = -erf $^{-1}$(2* Late Prediction Probability – 1)**

Late PHM Indication

- **Occasionally, the PHM Predicted Failure Time is later than the Actual Failure**
  - **In this case system down time is incurred waiting for a spare**



Sandia National Laboratories

PHM Model in SEM: Inputs

PHM

	Part	Prognostics	Order Lead Time	Prediction Lead Time (Flight Hrs)	Predict Time SD (Flight Hrs)	Late Prediction Probability	Run To Failure	Predict Time St Dev Growth
1	1	☐	.00	.00	.00		☐	
2	2	☑	24.00	6.00	.75	5.00%	☐	

Configuration Parts

	Configuration	Part	WUC/LCN	LCN Description	Mean Flight Hours Between	Lifetime Mean	Lifetime St Dev	Fault Isolation Probability	Critica
1	R&R Repair	1	1		1.00	.00	.00	.00%	
2	R&R Repair	2	2		1.00	80.00	5.00	.00%	
3	RIP with	1	1		1.00	.00	.00	.00%	
4	RIP with	2	2		1.00	175.00	6.00	.00%	
5	RIP with	1	1		1.00	.00	.00	.00%	
6	RIP with	2	2		1.00	133.00	7.00	.00%	

- **Prognostics Flag:** Indicates prognostics are available
- **Lifetime Mean:** The mean of the **Actual Failure** normal distribution
- **Lifetime St Dev:** The standard deviation of the **Actual Failure** distribution
- **Predict Lead Time:** The mean time (flight hours) ahead of the **Predicted Failure** the support network will know of the failure
- **Predict Lead Time SD:** The standard deviation of the time the **Predicted Failure** is known ahead of the failure. This can change over time.
- **Late Prediction Probability:** The proportion (0-100%) of the predictions that will be late (past the **Actual Failure** time)
- **Run to Failure:** If yes, then the failed part is replaced the first opportunity after the failure occurs. If no, the failed part is replaced the first opportunity after the ordered part arrives.
- **Order Lead Time:** earliest time (simulation hours) prior to failure at which a part can be preordered

SEM PHM Modeling Notional Results

- SEM model typically runs multiple years of operations
  - Expected impact of PHM increases over longer periods of time
  - In a model with 52 sites, 4 parts, 240 aircraft over a 2 year period, the results for the Mission Capable Rate and Non-Mission Capable Supply rate are as follows:
    - Baseline (no PHM on 2 wear-out parts) – 77% MCR, 17% NMCS
    - Enhanced (PHM on 2 wear-out parts) – 82% MCR, 12% NMCS

Conclusions

- Capabilities exist to model the benefits of PHM
  - Indirectly by focusing on PHM effects
  - Directly with built in PHM variables
- Additional considerations
  - Which parts can be monitored (technology exists)?
  - Which parts will have the most impact on system performance?
  - What other costs are involved in a PHM program?
    - Off system monitoring equipment
    - Personnel
- Is PHM cost effective?