Cost/Benefit of Advanced Engine Health Monitoring

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Introduction

- Boeing's Propulsion group are interested in performance metrics for Advanced Engine Health Monitoring.
  - On recent airplane programs, we have invested in airplane infrastructure and development costs to facilitate Engine OEMs.
  - For future programs, benefits are not understood.

- There is a distribution of costs and benefits: for each contributor, what is the cost/benefit of Advanced Engine Health Monitoring?
  - To Boeing's airplane product?
  - To the airplane operator?
  - To the Engine OEM?

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Performance Metrics for Advanced Health Monitoring

- SAE sub-committee E-32, “Aerospace Propulsion Systems Health Management” is producing documents:
  - AIR5909 “Prognostic Metrics for Engine Health Management Systems”
  - AIR4985 “A Methodology for Quantifying the Performance of an Engine Monitoring System”
  - **ARP5783 “Health and Usage Monitoring Metrics, Monitoring the Monitor”

- Industry is starting to address the question!

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What is the Benefits vs. *Costs* of AEHM Programs?

Example Benefits and Example Costs

Benefits	Costs
1. Reduced in-flight shut downs (IFSD) events 2. Reduced loss of thrust control (LOTC) events 3. Reduced air turn backs (ATB) and in-flight diversions 4. Reduced dispatch delays and cancellations (D&C) 5. Reduced Unscheduled Engine Removal (UER) 6. Reduced secondary damage → **When successful, good for the OEMs, the owners, and the operators.**	1. Airplane carries additional systems (cost, weight, R&M) 2. Operators invest in ground-infrastructure for data management. 3. Operators perform extra maintenance (line inspections, lower MTBR) 4. Airframers invest in systems development, systems integration and test, and product support. 5. AHM Provider invests in algorithm development, data centers, etc. 6. False positives induce unnecessary costs. → **New money spent by all parties**

Benefit Claim:

Advanced Engine Health Monitoring will predict pending failures to engine components, thus allowing schedulable, preventative maintenance.

Cost claim:

Distributed costs of an advanced health monitoring program.

Question:

Who reaps the rewards and who bares the costs?

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The 2x2 Matrix and Statistics

	Disease / Condition	**No Disease / Condition**
Test Positive	a True Positive	b False Positive
Test Negative	c False Negative	d True Negative

n.b.: SAE-ARP5783 derives these statistics using Bayes' Theorem. Useful, but more difficult than direct derivation!

$$Sensitivity = \frac{a}{a+c}$$

$$Specificity = \frac{d}{b+d}$$

$$PPV = \frac{a}{a+b}$$

$$NPV = \frac{d}{c+d}$$

- ***Sensitivity***: the probability that a test correctly identifies people/machines with the disease/condition.
- ***Specificity***: is the probability that a test does not identify the people/machines without the disease/condition.
- ***Positive Predictive Value***: probability that a positive test result correctly infers that the person/machine has disease/condition.
- ***Negative Predictive Value***: probability that a negative test result correctly infers that the person/machine does not have the disease/condition.

- Sensitivity and Specificity share the same *information* as Positive Predictive Value and Negative Predictive Value
- Sensitivity/Specificity is intuitive, but sometimes PPV/NPV is easier to work with due to available data.
- Working only with PPV can be provident.

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Example of High Specificity

- Example from the Wikipedia entry for Bayes' Theorem (https://en.wikipedia.org/wiki/Bayes%27_theorem)
- A population and a test for a drug have the following properties:
  - Test is 99.0% sensitive
  - Test is 99.0% specific. (hint: in this example, 99% is *low*!)
  - Population size: 1M
  - 0.5% of people are drug users.
- If a randomly selected individual tests positive, what is the probability he or she is a user?

$$P(A|B) = \frac{P(B|A) \cdot P(A)}{P(B)}$$

$$\begin{aligned} P(\text{User} \mid +) &= \frac{P(+ \mid \text{User})P(\text{User})}{P(+ \mid \text{User})P(\text{User}) + P(+ \mid \text{Non-user})P(\text{Non-user})} \\ &= \frac{0.99 \times 0.005}{0.99 \times 0.005 + 0.01 \times 0.995} \\ &\approx 33.2\% \end{aligned}$$

	Disease	**No Disease**	% Correct (PPV)
Test Positive	*4,950*	9,950	33.2%
Test Negative	*50*	*985,050*	

!!! Sensitivity and Specificity fail intuition.

PPV!!!

Why did specificity "fail"? The underlying population has a low probability of the pending failure.

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A Note on IFSD Rates and 'prevalence' of problems

- Actual IFSD rate for 777 (all sub-models, all engines):
  - ***0. 003/1000 EFH*** *(*engine flight hours)
- Required IFSD rate (180-minute ETOPS)
  - ***0.02/1000 EFH***
- 3 events in 1 million flight hours requires a fleet size of at least 142 airplanes (one year, twin-jet aircraft). Thus, any cause of an IFSD, on a "modern" engine fleet, is not prevalent.

→ Any test trying to predict the rare outcome must be very specific to that condition. How specific? Determined by trade study outcome.

	Disease / Condition	**No Disease / Condition**
Test Positive	*a* True Positive	*b* False Positive
Test Negative	*c* False Negative	*d* True Negative

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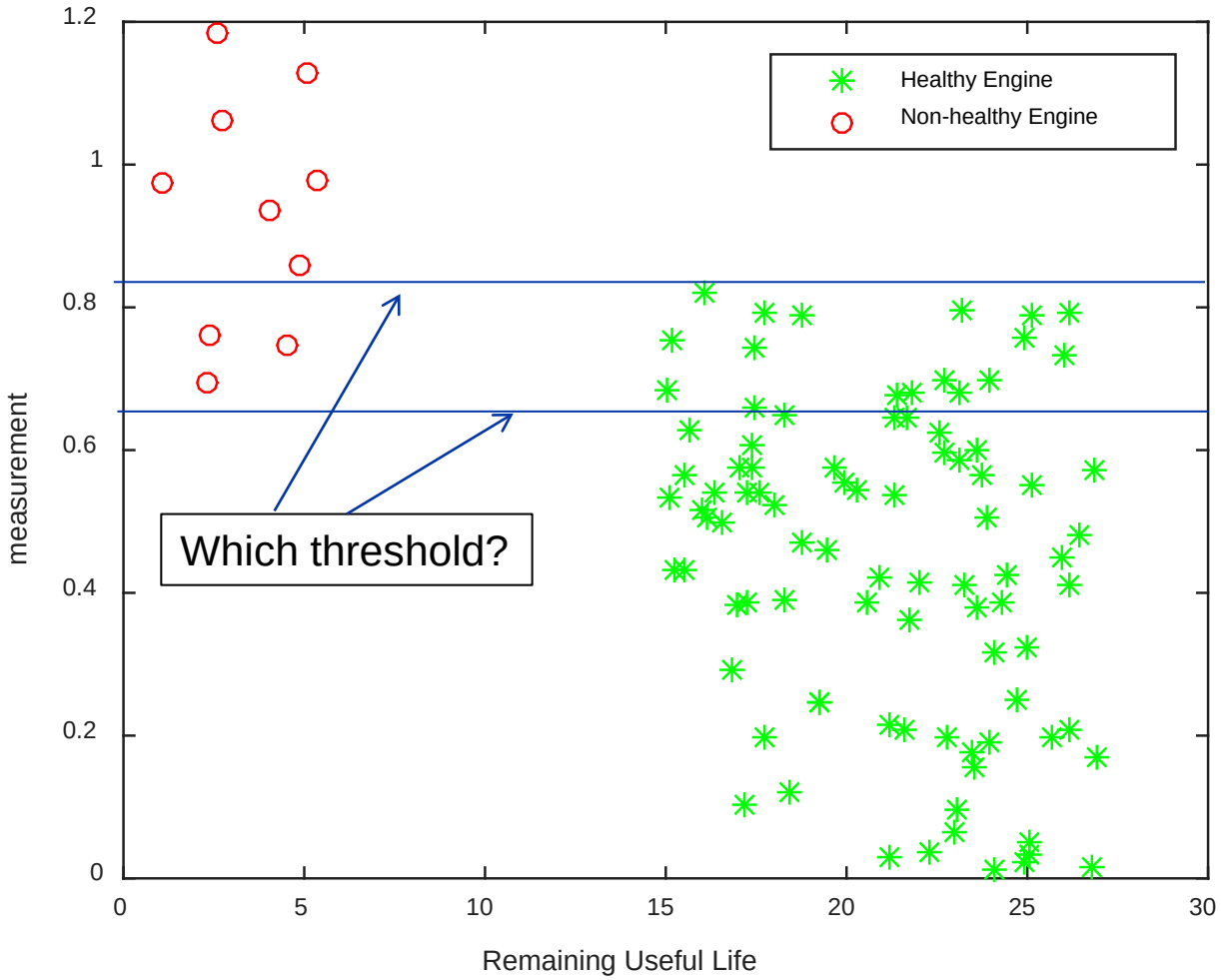
Threshold Tuning and Effect on Statistics

- Do you maximize the open circles above the line?
- Do you minimize the solid circles above the line?
- Is there an optimal threshold to be found?



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Required Data and Data Collection Methods

- Data wanted (expected or actual):
  - Target number of events per million flight hours (e.g., IFSD)
  - True Positive Rate: number of events per million flight hours are prevented
  - False positive rate: number of components causing unnecessary maintenance.
  - Total Trip rate for algorithm (trip rate = true positive rate + false positive rate)

- Data available (generally available, with caveats)
  - Cost of events (airlines know their cost/route, Boeing use a fleet average for study)
  - Cost of maintenance / inspections / spares
  - Cost of infrastructure

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A Balance Sheet

Example: Balance Sheet for Airplane-Level of AEHM

Benefits	Costs

1. Prevented in-flight shut downs (IFSD/FH)
2. Prevented in-flight diversions (IFD/FH)
3. Prevented departure delays and cancellations (D&C/FH)
4. Prevented Unscheduled Engine Removals (UER/FH)
	1. False Positives per FH (to derive costs per FH)
	  1. inspections with null results
	  2. Part R&R with no fault found
	  3. Engine removal
	2. Cost of ownership for PHM-specific infrastructure
	3. Cost of infrastructure development

→ With benefits per FH data collected, stake holders can calculate costs and derive a total benefit, based on the reduced operational costs ($/hour of FH)

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Wrap Up

- AHM Performance Metrics are of interest because:
  - The prevalence of any cause of an event type (e.g., IFSD) is low.
  - Preventing events is always favorable, but the cost/benefit of preventing those events needs to be understood.
  - Preventing *one* IFSD comes at a cost of *fleet-wide* increased maintenance, increased false positives rate, decreased MTBR, and new costs for data retrieval and storage. ***What is the total cost/benefit?***
- The 2x2 matrix is powerfully simple.
  - Sensitivity and Specificity are intuitive, but intuition may fail. (How is “high” or “low” rate defined?)
  - Positive Predictive Value (PPV) is good – directly measures true positive rate vs. false positive rate!
- Data describing true and false positive rates are required.
  - How can this be estimated prior to implementation?
  - How can this be monitored in the fleet after implementation?
- False positive rates and cost/benefit analyses should be part of the algorithm development.
- The balance sheet is a simple, effective, communication tool once cost/benefit data is collected.

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