Prognostics and Health Management: the Second Decade

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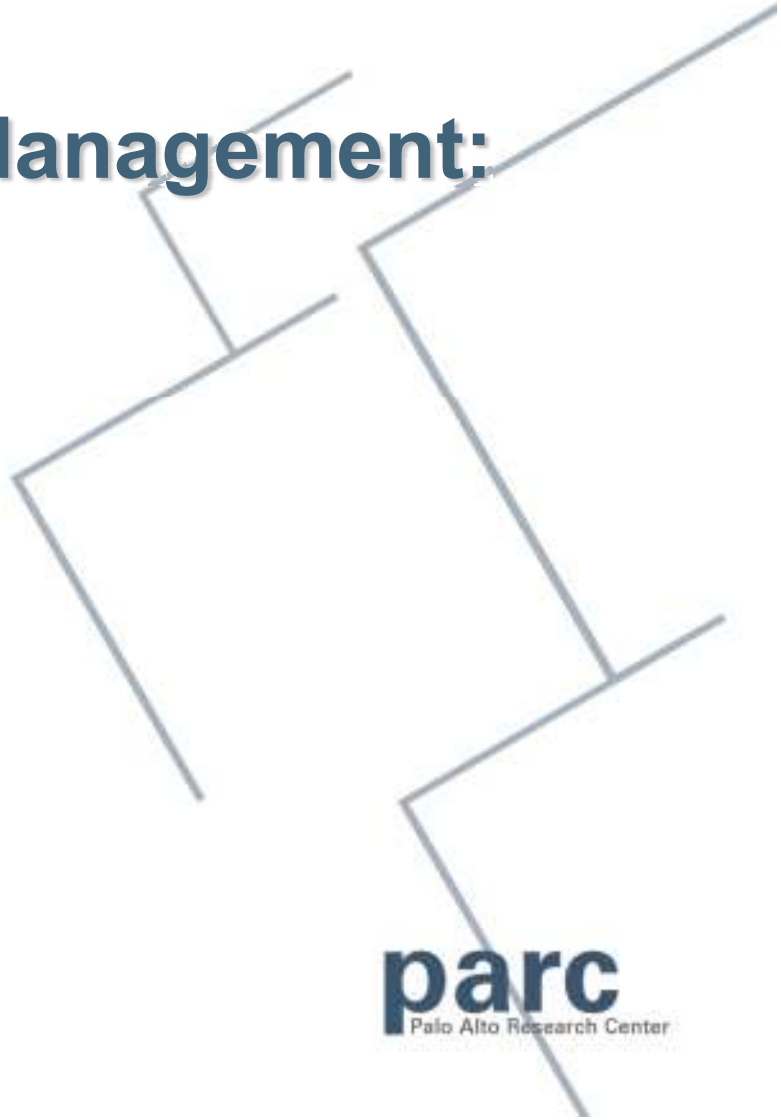

Agenda

- Introduction
- Challenges in prognostics
  - Reliable RUL estimates
  - Measurable business value
- Research methods in PHM vs medicine
- Methods to achieve reliable RUL estimates
- Using prognostics for business impact
- Recommendations

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Core Concepts

- All electromechanical systems age.
- Component aging and damage accumulation is an irreversible physical (or chemical) process.
- Signs of aging are detectable prior to overt failure of the component.
- It is possible to correlate signs of aging with a model of component aging and thereby estimate ***remaining useful life*** (RUL) of individual components.
- It is possible to use RUL estimates for measurable business impact.

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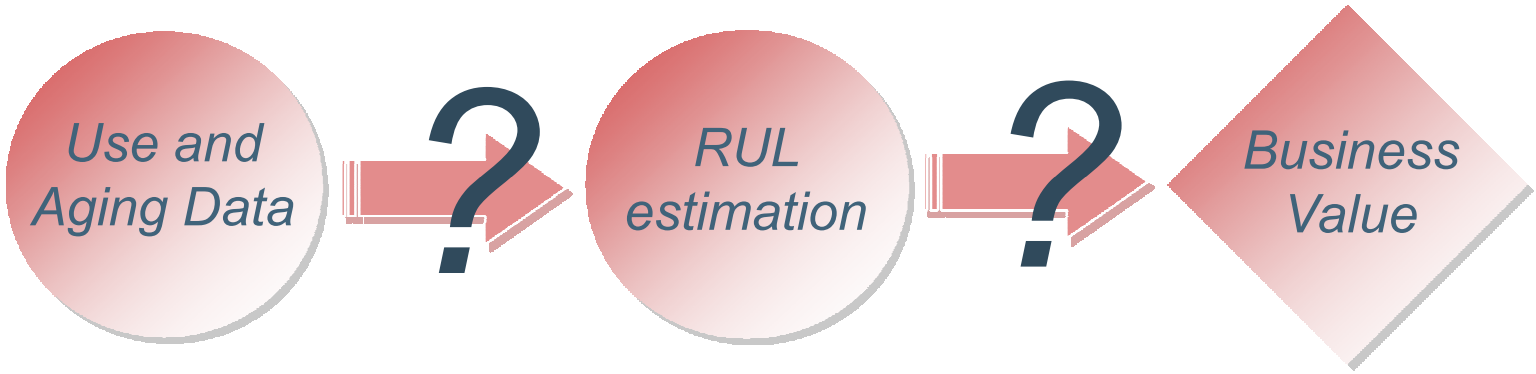
Is Prognostics a Mature Science?



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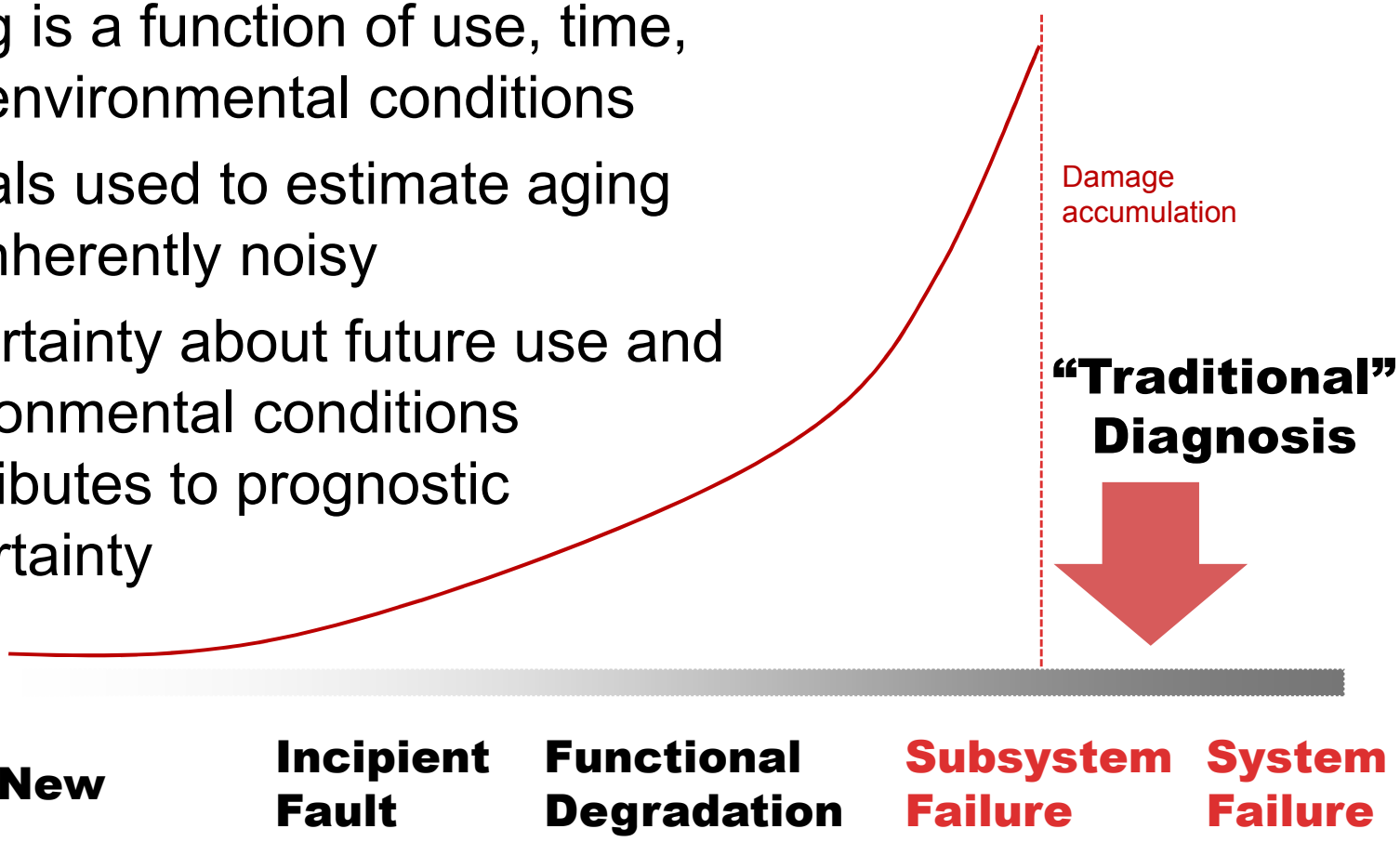
Challenges in Prognostics

- Aging is a function of use, time, and environmental conditions
- Signals used to estimate aging are inherently noisy
- Uncertainty about future use and environmental conditions contributes to prognostic uncertainty



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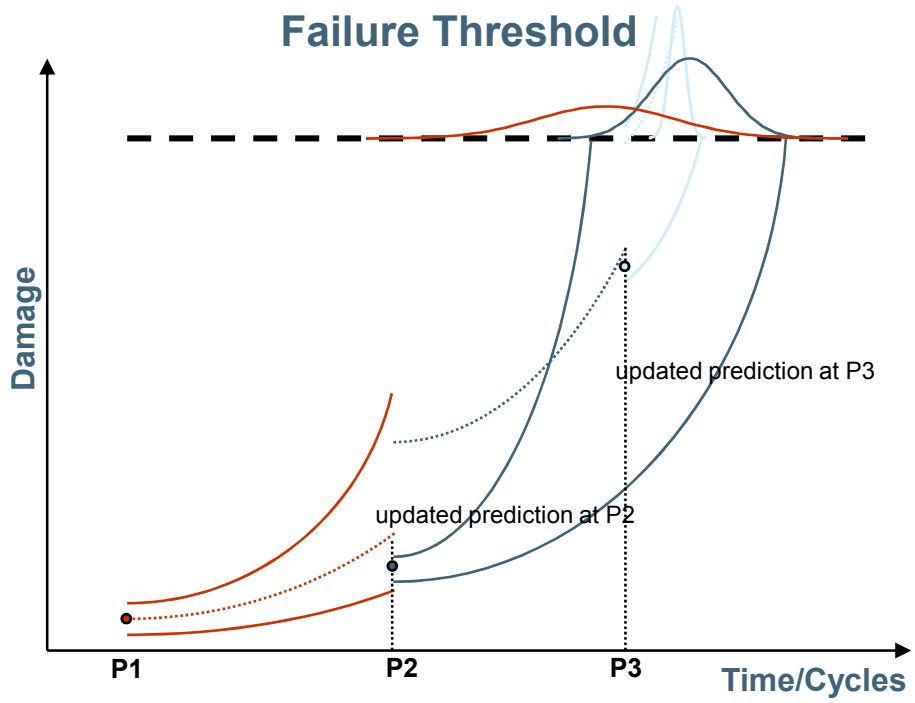
Remaining Useful Life Estimation

- Physics-based modeling
  - Dynamic stochastic equations
  - Lumped-parameter models
  - Functional models
- Data-driven techniques
  - Bayesian Statistics
    - Kalman Filter
    - Benedict-Bordner
    - Relevance Vector Regression
    - Particle Filters
  - Computational intelligence
    - Neural nets
    - Case-based reasoning
- Statistical/lifing models
  - Weibull distribution

Remaining life estimates typically become more accurate and precise as the time to failure decreases.



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Prognostics in Medicine

- Despite significant advances over the last decade, PHM is still not widely accepted in business practice.
- On the other hand, prognostics is widely used in medicine to make treatment decisions.

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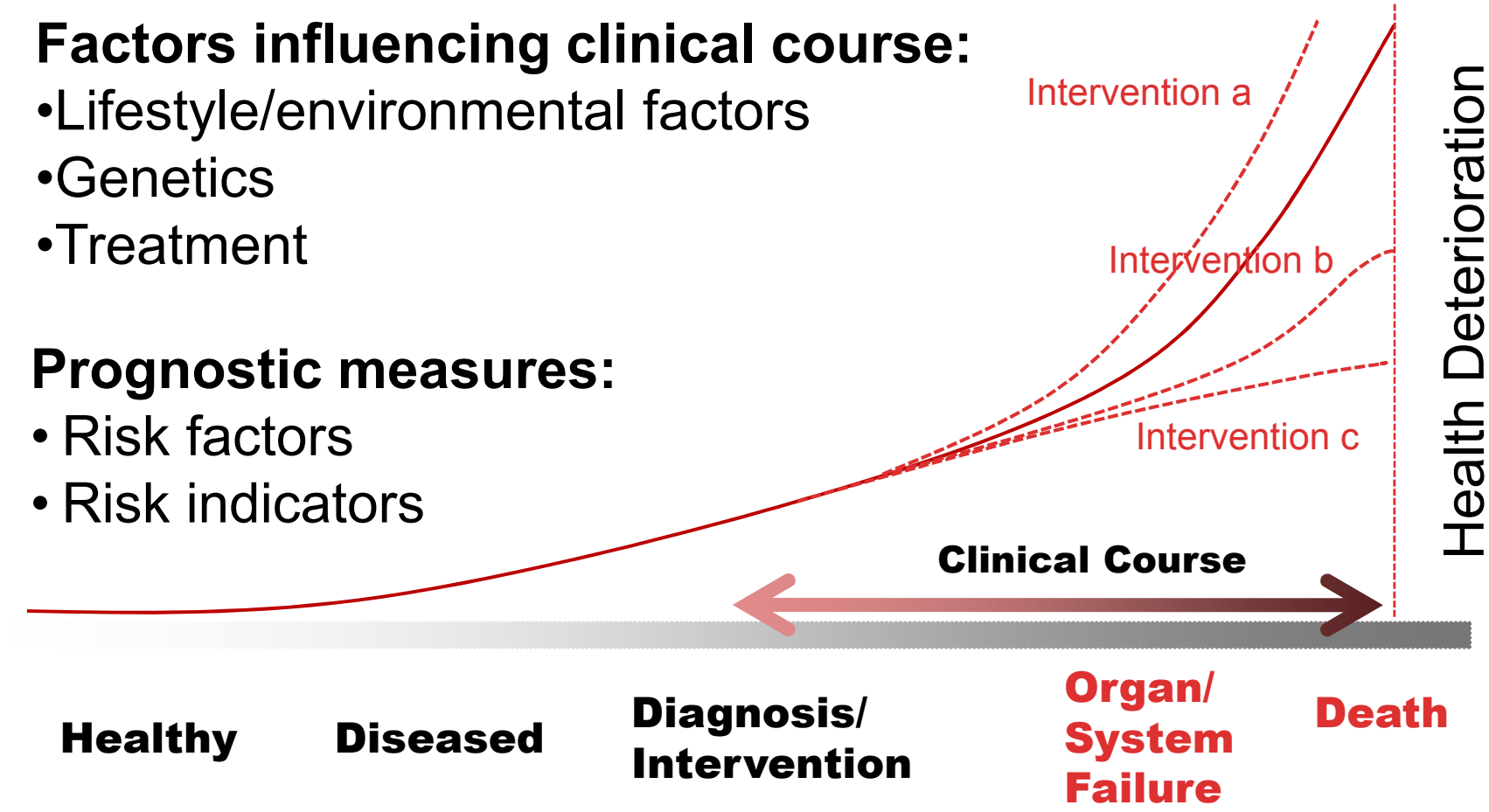
Prognostics in Medicine

Factors influencing clinical course:

- Lifestyle/environmental factors
- Genetics
- Treatment

Prognostic measures:

- Risk factors
- Risk indicators



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The Scientific Method

Almost all progress in medicine is based on rigorous application of the **Scientific Method**

- Observe
- Form a conjecture
- Develop a hypothesis
- Design experiments to prove or refute the hypothesis
- Analyze results and draw conclusions based on statistical significance

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Randomized Clinical Trial

In medicine, the gold-standard approach to understanding clinical course of disease (and learning how to alter it) is the **Randomized Clinical Trial**

Used for measuring the efficacy of interventions as well as assessing risk factors and risk indicators

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Pros and Cons of RCTs

Pros

- ✓ One single global standard for medical research!
- ✓ Accounts for effects of variability in the population through rigorous application of statistics
- ✓ Instant credibility of findings

Cons

- ✓ Takes considerable skill and expertise to design
- ✓ Takes considerable money to conduct
- ✓ May take years to complete

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Medical Publications

- If a medical research project is based on a RCT, the abstract of the article tells you everything you need to know
  - Problem
  - Methods
  - Population
  - Findings (with statistical significance)
  - Conclusions
- Instant credibility regardless of where the research was performed or performed it*
  - No need to read the full paper!

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** Certain caveats apply*

Other Medical Research Methods

- Follow-up studies: measure the relative risk of a factor *F* on the outcome *O*
  - Observational or intervention-based

$$RR = P(O|F)/P(O|\overline{F})$$

- Case control studies: assess the factors that may have influenced a particular outcome
  - Often retrospective

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Prognostic Rules in Medicine

- Simple prognostic rules are popular in medicine
  - Based on observation of risk factors
  - Often expressed as simple integers
- Each risk factor is determined and incorporated in the rule based on rigorous studies
- Examples:
  - Glasgow Coma Scale
  - APGAR Score
  - International Prognostic Index for non-Hodgkin's lymphoma

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Cox's Regression

- Also known as Proportional Hazard Model
- Allows clinical course of disease to be modeled using a probabilistic survival function:

  $S(t) = P(T > t)$ (*probability of survival more than t years)*
- The hazard function measures the instantaneous risk of demise after time *t:*

  $h(t) = f(t)/S(t)$ *where* $f(t) = F'(t)$ *and* $F(t) = 1 - S(t)$

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Medicine vs Engineering
Similarities

- Concepts of natural history, clinical course, and disease progression are similar to component aging, damage accumulation and fault progression
- Risk factors in medicine are similar to prognostic indicators used in PHM
- In medicine, prognostics is used to select optimal treatment/intervention policies
- In PHM, RUL estimation is used to determine optimal maintenance policies

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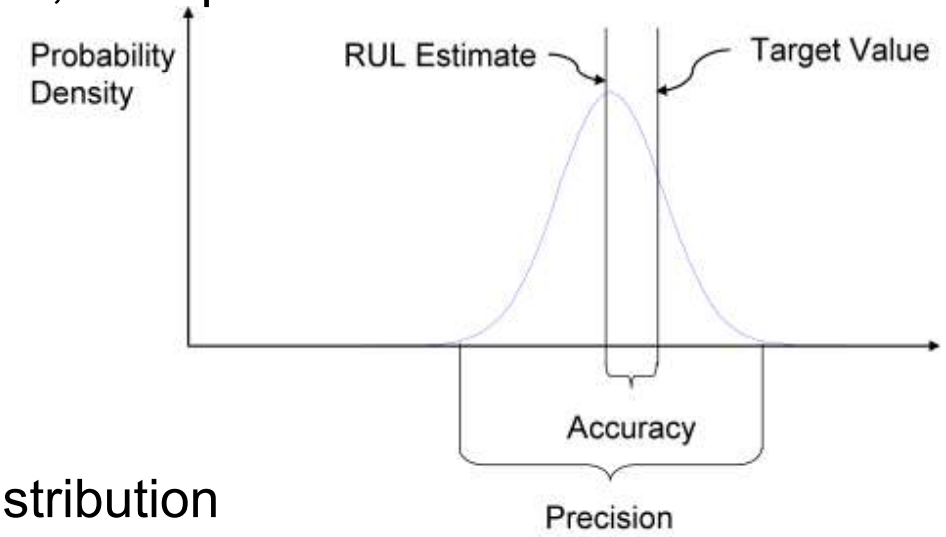
Medicine vs Engineering
Differences

- In medicine, prognostic models are used to predict morbidity and mortality and to select intervention
- No standards to measure benefits of prognostics in engineering (yet)
  - Need systematic, objective, and quantitative measures
- Two dominant metrics
  - Accuracy
  - Precision
- Other metrics
  - Prediction horizon length
  - Sensitivity
  - Modality of confidence distribution
  - Skewed preference distribution around actual time of failure
  - Stability/Robustness of prediction



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PHM Research Methods

- PHM is a maturing science that has not yet converged on a robust, repeatable, standard methodology
- Common features of most PHM research projects:
  - Arbitrary component aging process
  - Relatively unique methodology
  - Small sample size
  - Tentative nature of conclusions
  - No statistical significance!

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A Universal Research Methodology for PHM

- Derive the business case from high-level system requirements
- Select metrics to quantify benefits that satisfy the business case
- Select faults of interest and determine root cause
- Determine whether existing sensors / data rates are sufficient (or negotiate for more)
- Develop test methods to operate and age components under realistic use conditions
- Determine sample size required for statistical significance
- Conduct component aging tests and collect data
- Develop RUL algorithms using data
- Measure and report metrics
- Verify and validate models and algorithms

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Maturing PHM Research

- Medicine has figured out how to derive statistically (and clinically) meaningful prognostic estimators on very diverse patient populations.
- It is time to expect the same in PHM!
- The PHM community needs to reach an agreement on systematic, objective, and quantitative measures that can be used as prognostic metrics.
- The community needs to develop a standard research methodology that performs the same function that RCT performs for medicine.

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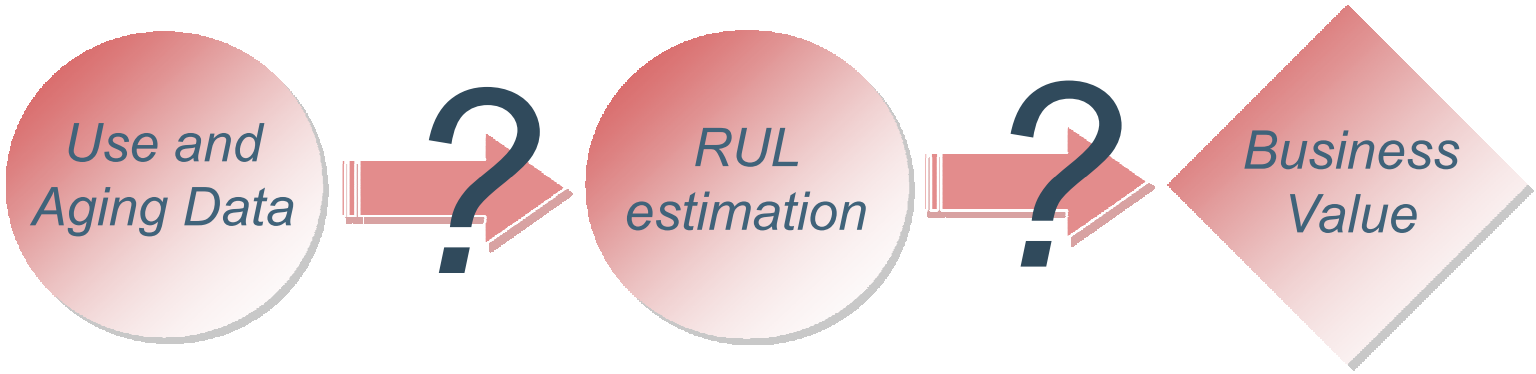

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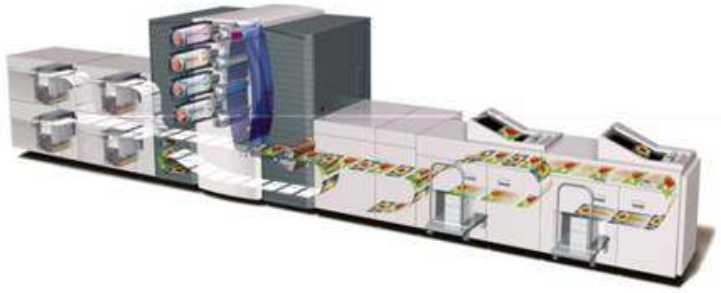
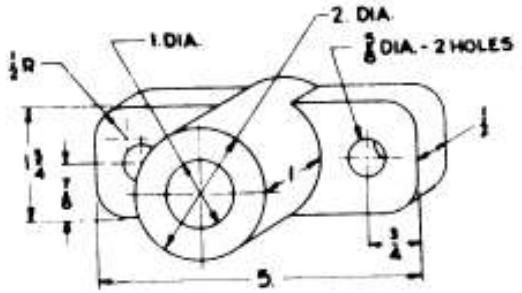
Business Implications of PHM



Real-Time Health Management
Fault Detection
Diagnostics
Prognostics

Product Lifecycle Management
Maintenance planning
Auto-dispatch
End-of-life decisions



System Design
Sensor Selection
Diagnosability
Maintainability
RUL estimation methods

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Measuring Business Impact

- In medicine, business impact is relatively straightforward to measure:
  - For patients, it's Quality of Life
  - For insurance companies, it's Total Cost
- In engineering, business drivers are rather diverse:
  - Safety (e.g., aerospace)
  - Availability (e.g., manufacturing, consumer)
  - Lifecycle cost (e.g., military)
- Business value needs to be measured against implementation cost

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Safety-Critical Applications

- Most obvious need for RUL estimates
  - … as long as RUL uncertainty can be minimized!
- Example: Ares I crew abort determination
- Loss of crew probability requirement is an order of magnitude lower than the Space Shuttle
- Very low false positive and false negative rate requirements for abort trigger

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Mission-Critical Applications

- Cost of PHM investment is judged against cost of inconvenience or opportunity cost
- Availability ≠ Reliability
- Redundancy is often a viable alternative to health management

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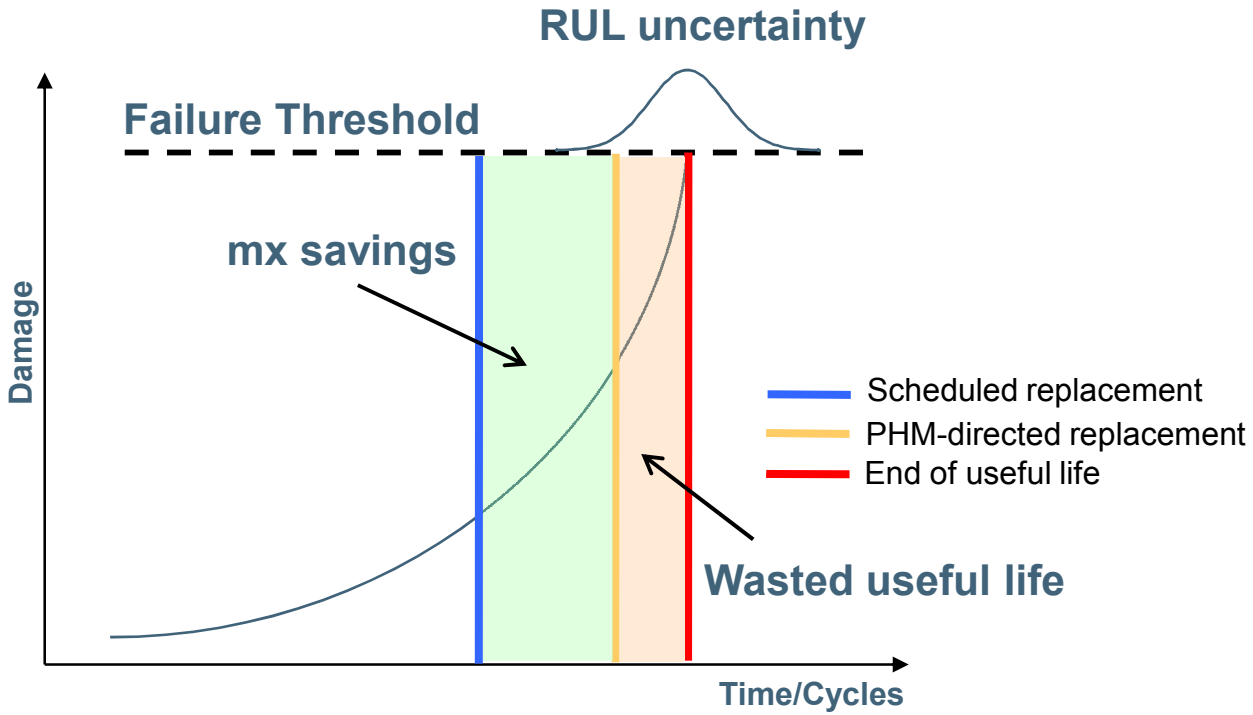
Logistics Applications

- The Joint Strike Fighter argument for PHM



- Actual financial impact is very difficult to quantify
  - (randomized trials are not feasible!)

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Next Steps for PHM

- Medicine is a good role model for PHM
- We need to mature research methods and business propositions for PHM
- Distinct roles and responsibilities for:
  - Government agencies
  - Industry
  - Academia
  - Professional organizations

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Role of Government Agencies

- The primary funding source behind medical research in the U.S. is the National Institutes of Health (NIH)
- NIH promotes long-term research goals and pervasive research programs that are (largely) immune to non-scientific influences
- In contrast, the primary funding source for basic PHM research in the U.S. is SBIR / STTR programs
  - No long-term direction, no pervasive programs
  - Funding not sufficient for research that can deliver statistically-significant results
  - There is little/no coordination between the government organizations that fund PHM research through SBIR/STTRs

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Role of Industry

- Another major source of R&D funding in medicine is the pharmaceutical industry
- In contrast, manufacturers or integrators of engineered systems provide very little internal funding for PHM research
  - They depend on government funding (just like academia)
- Unlike medical research, results are often kept proprietary
  - Secrecy undermines credibility!
- Challenges in incorporating SBIR-funded small company work (or university work) in products

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Role of Academia

- PHM is not widely recognized in academia as a wide open research area
- Academic participation is still limited in PHM
  - The same few universities often get involved as subcontractors to SBIRs and PHM contracts
- PHM is very interdisciplinary
  - It does not fit well into academic organizations based on individual disciplines
  - Organizations like CALCE, MRC, and IMS are necessary to leverage interdisciplinary strengths

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Recommendations

1. Establish a basic academic curriculum for graduate-level specialization in PHM
2. Develop a joint PHM R&D program between multiple U.S. government organizations (DARPA, NASA, Air Force, Army, Navy, NSF)
3. Form an alliance between industrial organizations to share fundamental PHM information (component RUL models, failure physics, etc.) on a precompetitive basis

We are establishing a non-profit called the PHM Society to initially address (1) and (3)

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QUESTIONS or COMMENTS?

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