Structural Health Monitoring and Its Role in Affordability

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Boeing Research & Technology

Boeing Products

Increased Performance Drives Design Complexity

Mission durations from hours to days

Payloads from thousands to millions of lbs

Data from notebooks to Giga Bytes

Life from years to decades

Complexity Increases Sustainment Needs and LCC

Comet
Fatigue

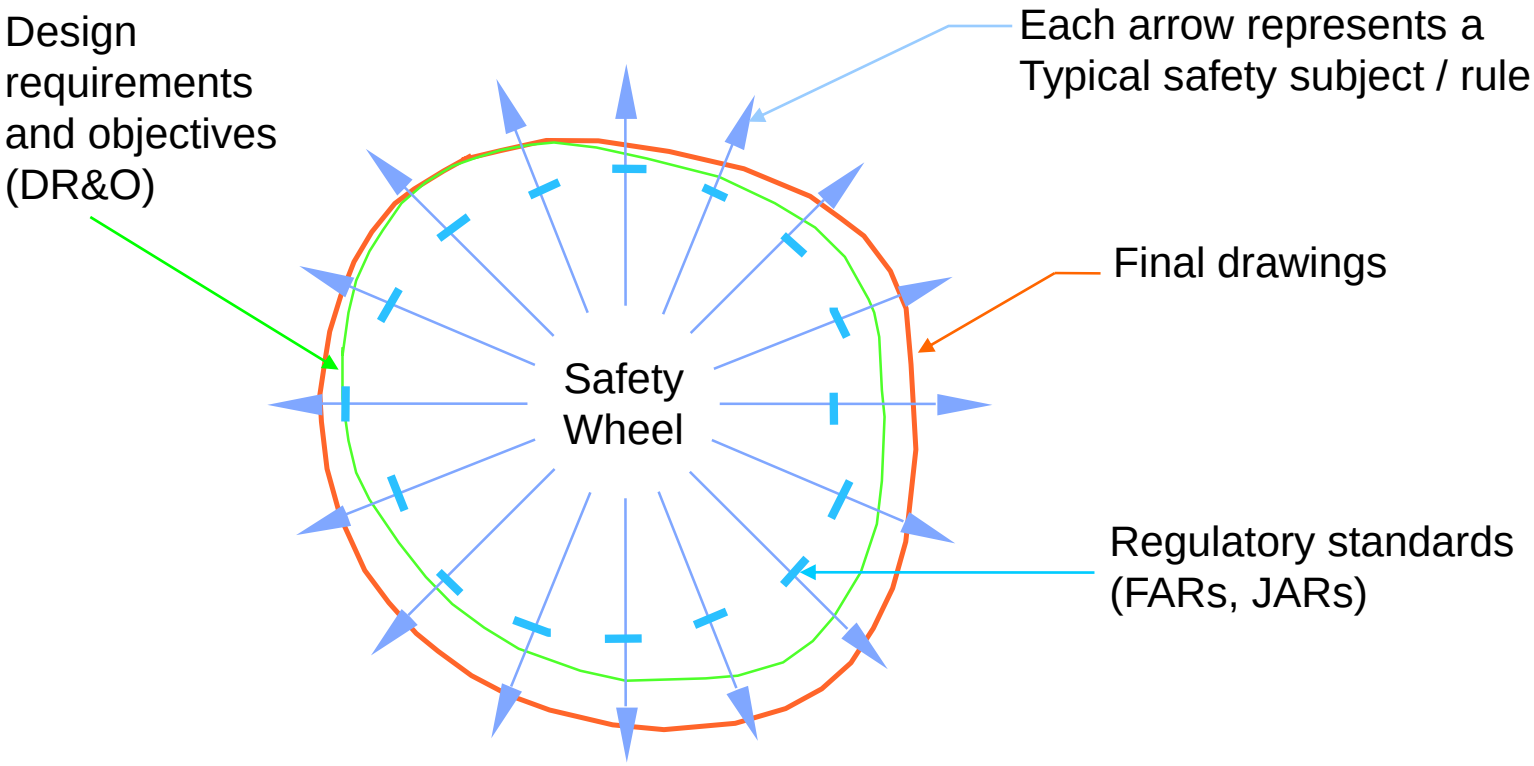
B-47
ASIP begins

F-111
Damage Tolerance

- The Comet failure in 1954 showed that static loading and a factor of safety was not sufficient to assure safe life of a pressurized aircraft
- The failure of 5 B47's with less than 2500 hours each resulted in a disciplined aircraft structural integrity program to ensure airframe design life requirements
- In 1969 an F111 failure due to a rogue manufacturing flaw illustrated a need for a damage tolerant design and certification philosophy

Manufacturer's Design Requirements & Objectives

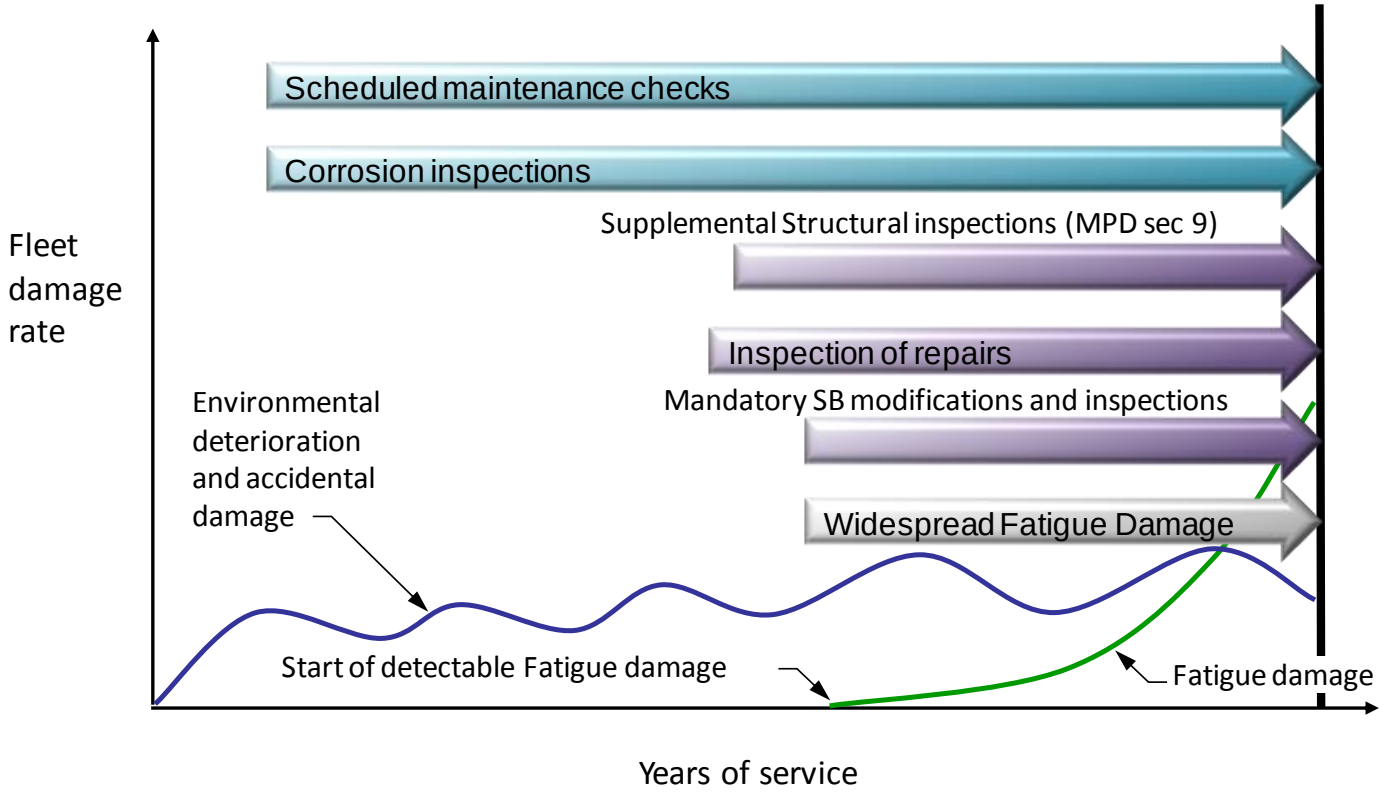
The DR&O Meets or Exceeds All Regulatory Requirements
The Final Design Meets or Exceeds the DR&O



What are the effects of change on **economics** and **reliability**?

Current Structural Maintenance and Inspection System for Commercial Airplanes

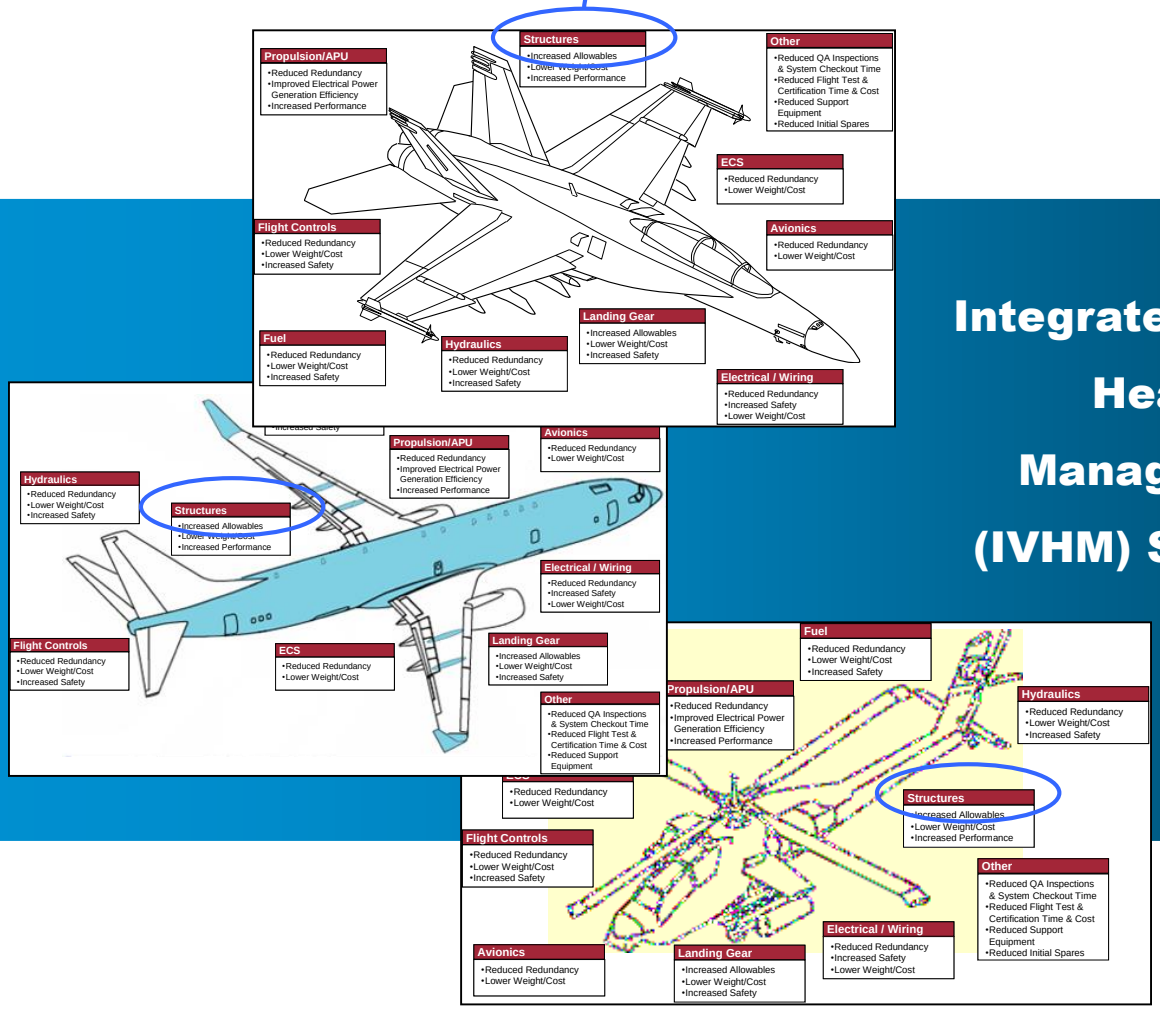
It is a regulatory requirement that operators have an approved baseline maintenance and inspection program for each airplane fleet



New technology must accommodate maintenance and inspection requirements with the **same or better reliability in a more cost effective manner**

IVHM Value Proposition

Structures is one of a number of subsystems and must be integrated at the system level



Integrated Vehicle Health Management (IVHM) Solutions

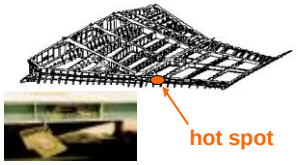
- Reduced Life Cycle Cost
- Improved Mission Reliability
- Improved Availability
- Improved Operational Plans
- Efficient Supply Chain
- Enhanced Design

Structural Health Management Approach

Structural Design

Analysis and Testing

Problem Areas Identified



Inspection Schedule Constructed

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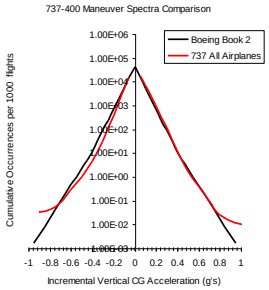
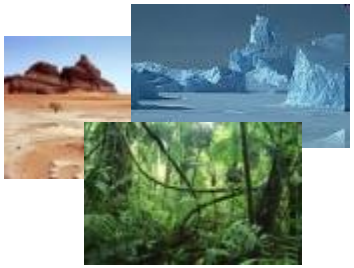
FIRST-HAND KNOWLEDGE

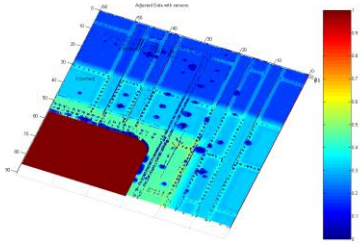
usage



environments



damage



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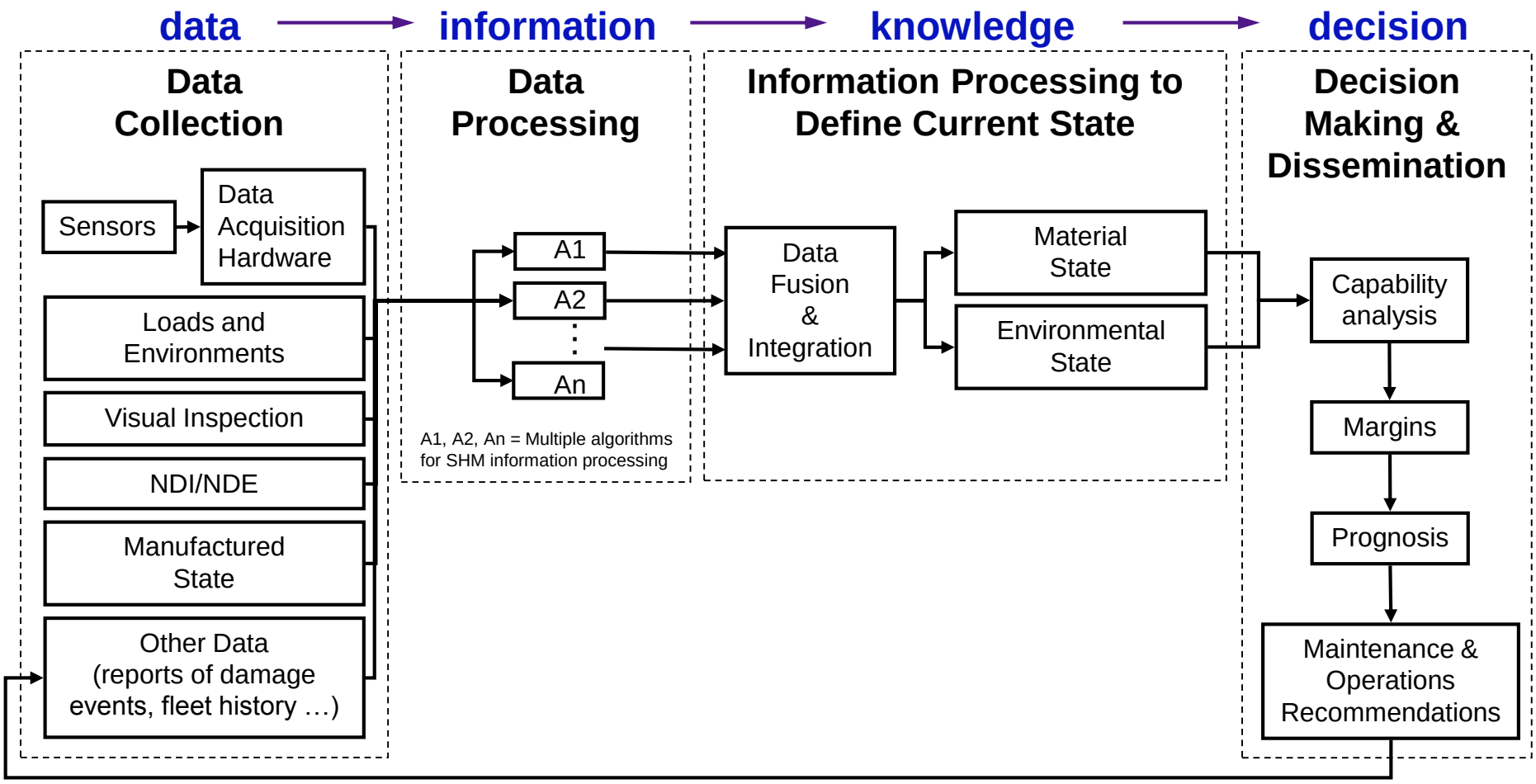
IMPROVED RELIABILITY

INCREASED PERFORMANCE

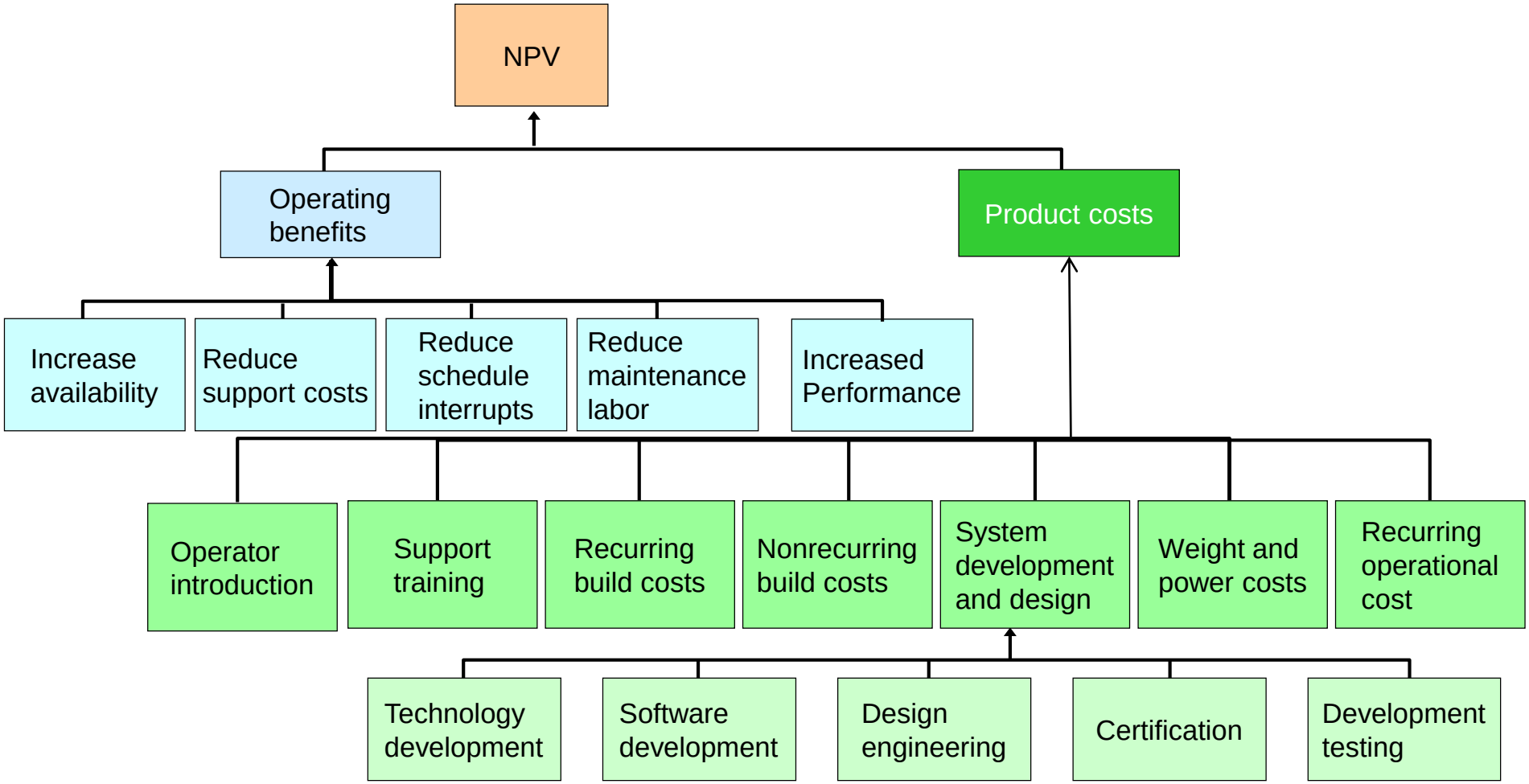
DECREASED Life Cycle Costs

SHM is an evolution to the design process by introducing new technology and criteria that increase the structural knowledge throughout a product's lifecycle and therefore better predict life cycle cost drivers in time to minimize them

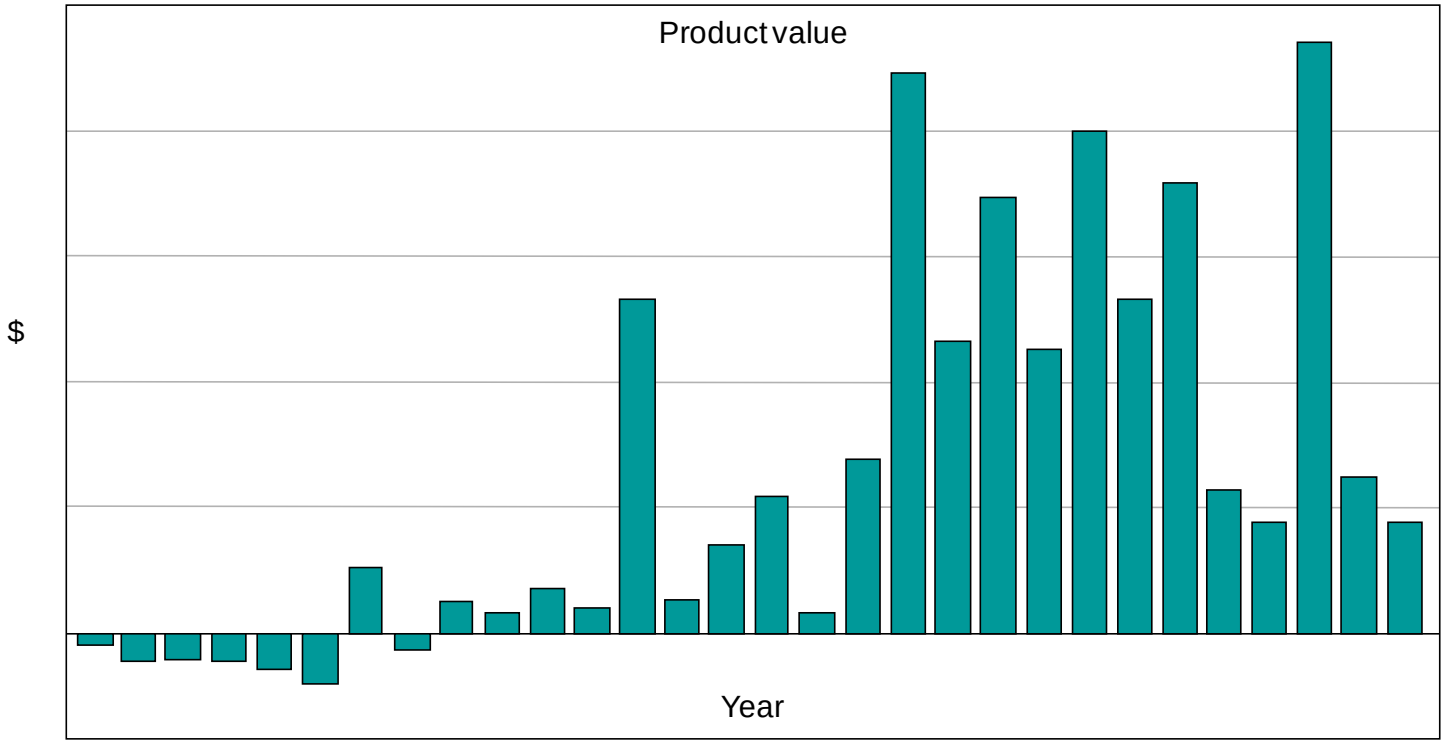
SHM System Design Approach to Drive Requirements that Address Decisions that Reduce LCC



Quantifying Affordability
Simplified Cost Benefit Model



SHM Cash Flow is a Key Driver for Affordability Operational Damage Monitoring Example

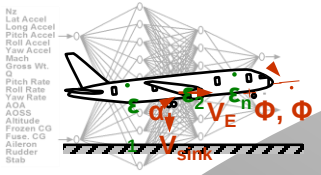


- Increased life cycle capabilities can bring cash flow earlier into a products life cycle
  - Incorporation as part of life cycle design
    - Improved performance and reduced sustainment costs
  - Manufacturing monitoring
    - Better insight into anomalies and reduced redesign costs

SHM Vision

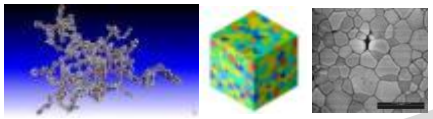
In-Situ Fatigue Crack Monitoring

Flight parameter load monitoring



Accidental Damage

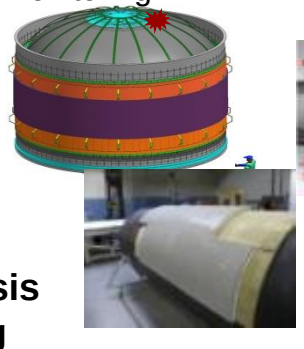
Multi-Scale Material modeling and prognostics



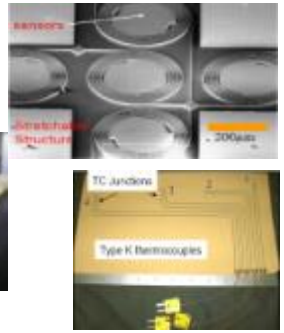
2015-2020

- **SHM Confidence Building**
- **SHM Expanded Area Damage Detection**
- **SHM for Corrosion**
- **Multi-Scale Physics Based Prognosis**
- **Virtual Life Extension**

Real-Time Impact monitoring



Broad area sensing

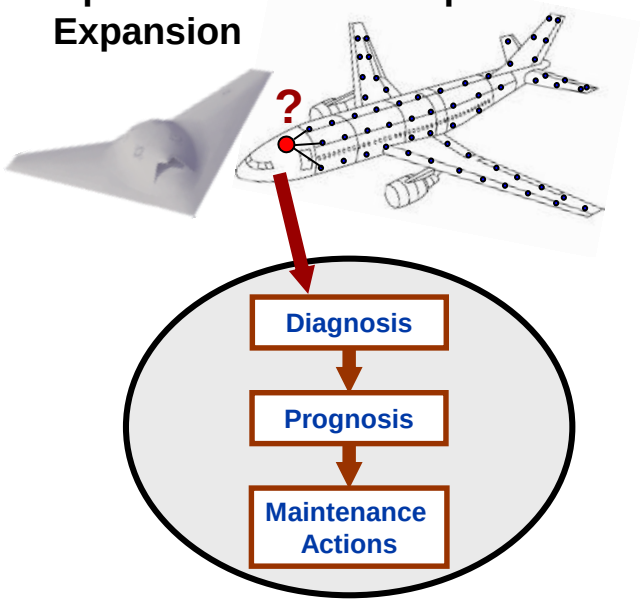


Present

- **NN Based Load Monitoring**
- **Hot Spot Damage Detection**
- **Bayesian Data Fusion/Prognosis**
- **Accidental Damage Monitoring**
- **Risk Enabled CBM+SI**

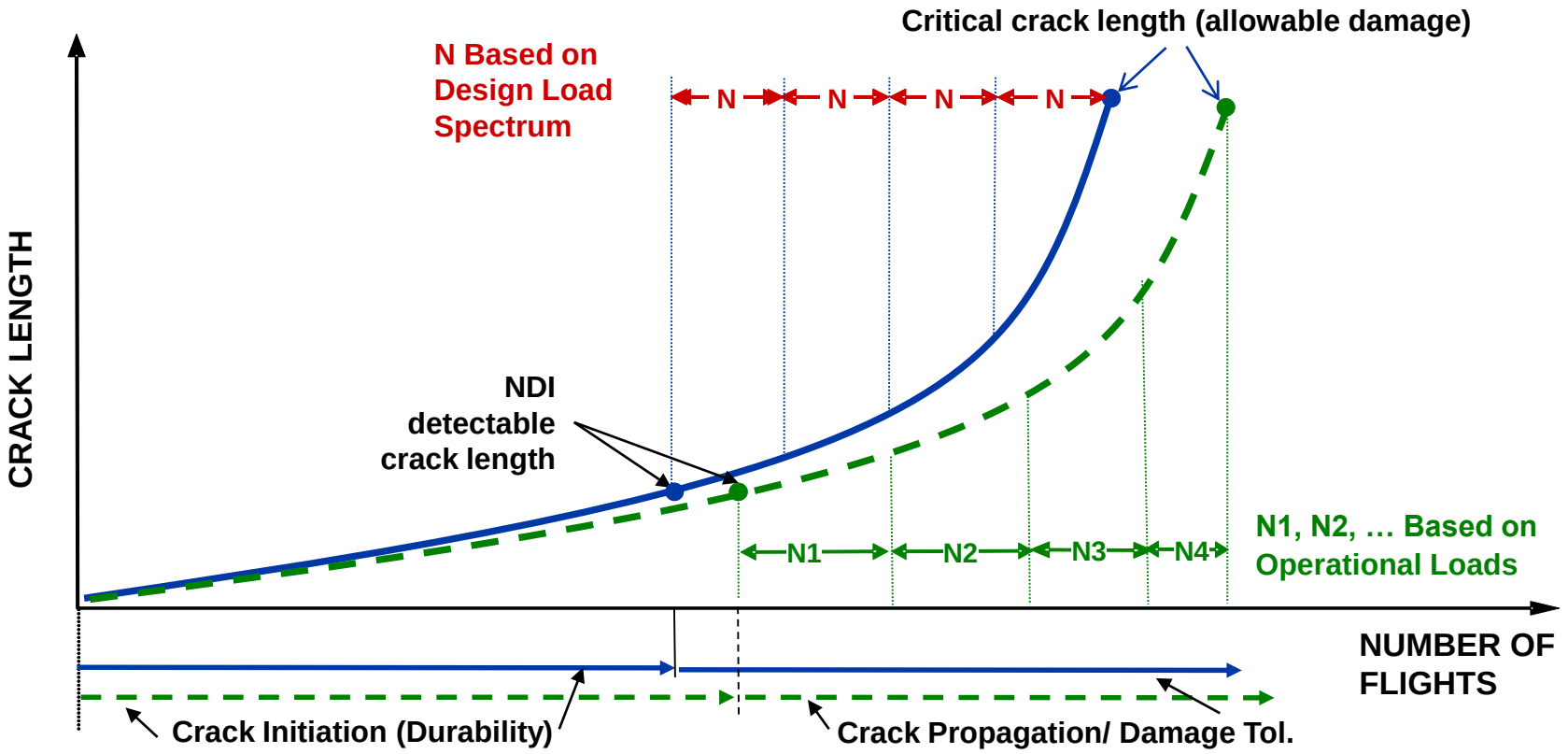
2020+

- **Broad Area Diagnostics and Diagnostics**
- **Identification of "Unknown Unknowns"**
- **Reliability Based Design**
- **Bio-Inspired Sensing and Self-Healing Materials**
- **Fly-by-Feel Vehicles**
- **Operational Mission Space Expansion**



Broad area autonomous diagnostic and repair system as part of integrated design

Enhancing an Inspection Based Paradigm



Can operational usage knowledge be used to change inspection criteria and improve design, manufacturing, and maintenance efficiency (reduced life cycle costs) ?

Hard Landing Detection Capability Demonstrates Basic Load Monitoring System

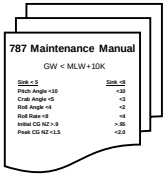
GOALS - Reduce aircraft schedule interrupts by:
1. Reducing number of falsely reported hard landings
2. Aiding the maintenance process

MAINTENANCE INFORMATION

CURRENT APPROACH
- Pilot "by feel" initiated inspection
- Limited flight data usage with AMM
- Large number of false positives

GOOD

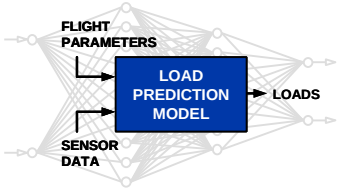
ENHANCED MAINTENANCE INFORMATION



PHASE 1 APPROACH
- Pilot "by feel" initiated inspection
- Flight data provided
- Lookup table used to determine maintenance action

BETTER

AUTOMATED LOAD PREDICTION

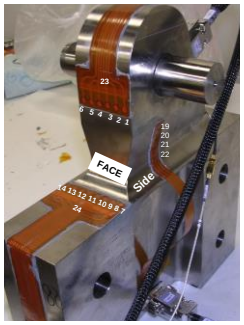


PHASE 2 APPROACH
- Pilot "by feel" initiated inspection
- Flight data and limited sensor information used to predict loads
- Recommend maintenance action
- Aid maintenance procedure

BEST

INSPECTION

Multistage Approach for System V&V



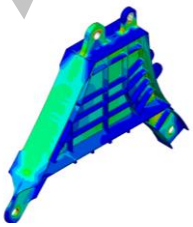
Flight and user demo

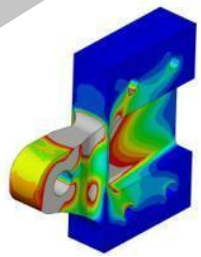
Full Scale

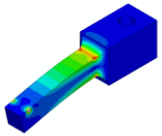
Component

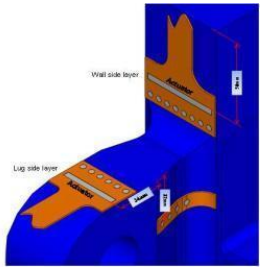
Cantilever

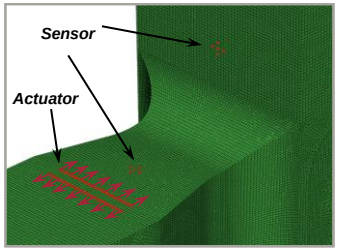
Coupon

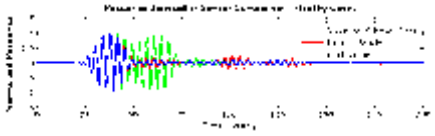






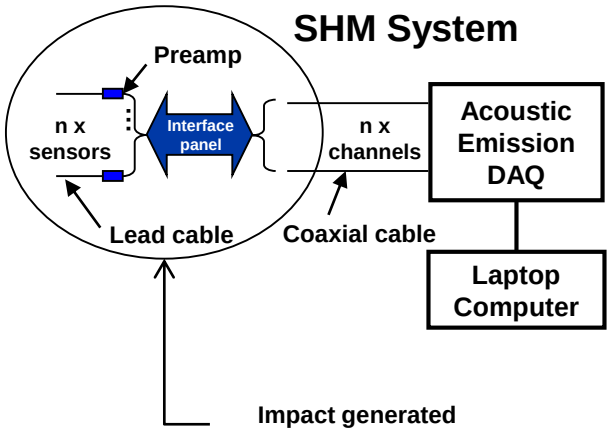


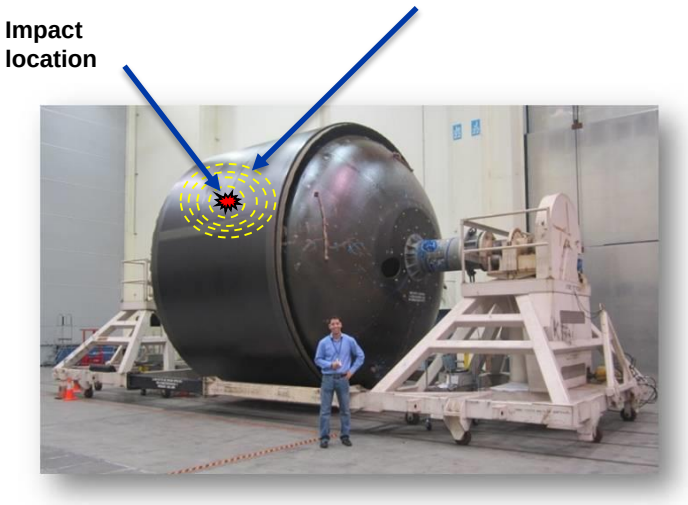


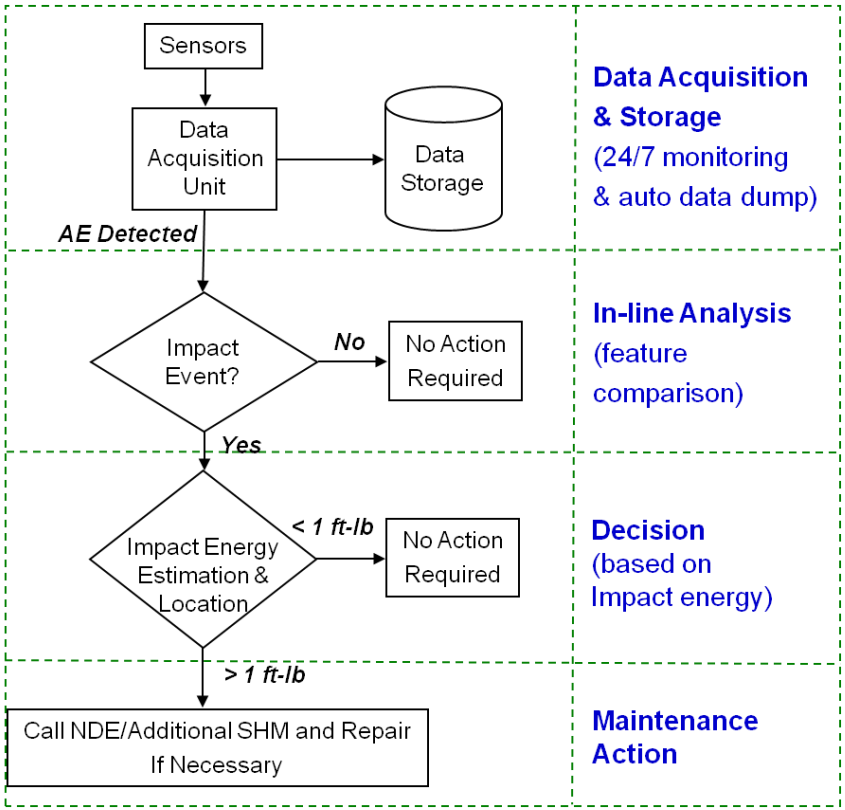


Increased multi-physics and multi-scale simulation with limited testing improves design optimization for significantly less cost and development time

Weight Reduction via SHM-Enabled Design Criteria







SHM-based damage tolerance approach to enable significant weight savings by reducing conservatism associated from damage uncertainty

Summary of Key Challenges

DATA	INFORMATION	KNOWLEDGE	DECISION
• Light weight broad area monitoring • Relational data base technology for maintenance and management • Data mining methods to optimize PDF development	• Disparate source data mining and fusion in the context of structural criteria • Process based cost modeling to assess application benefit • Culture: multidisciplinary, collaborative optimization methodology	• Multi-scale modeling integrated with monitoring information • Open system architecture for better integration of capabilities and knowledge • Cradle to grave knowledge integral with design optimization	• Expert system development coupled with DR&O and certification criteria development • Open system architecture for platform awareness • Decision process integral with design optimization in terms of life cycle cost optimization

Technology challenges exist at all stages of an SHM design process