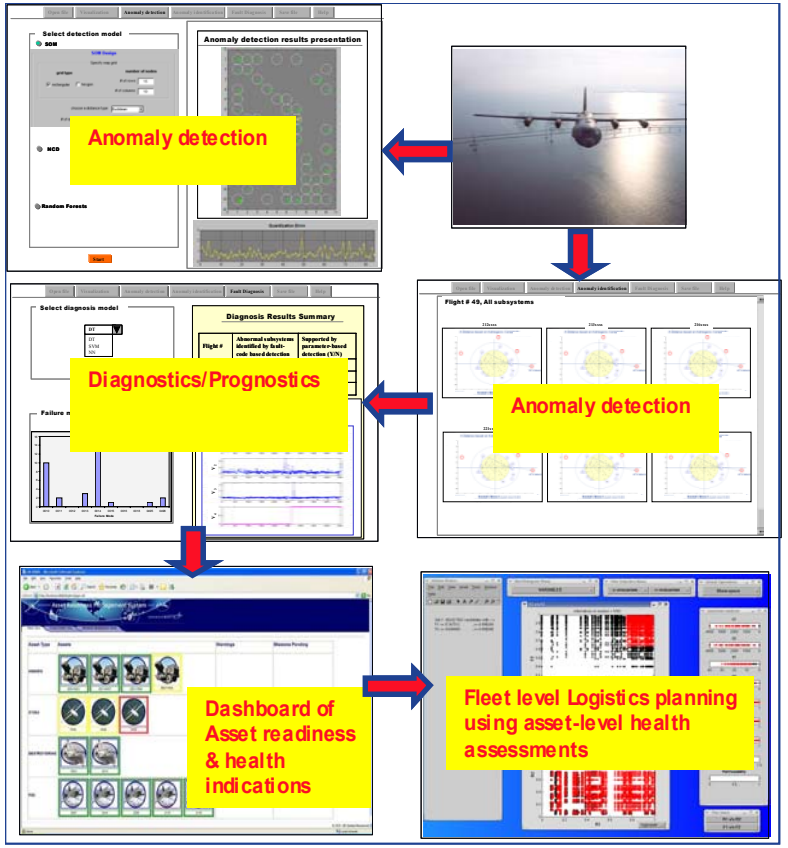
Prognostics & Health Management at GE

Dr. Piero P.Bonissone

Industrial AI Lab

GE Global Research



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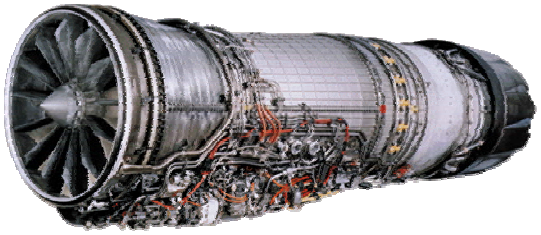
Prognostics & Health Management (PHM)

- **Expert-on-Alert (EOA™):** A Commercial Success Story

- **PHM Technology Development and Applications**



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Expert-on-Alert (EOA™): A Commercial Success Story for GE Rail

Complex, Mobile, Repairable System…

- ***24 Microprocessor Controllers***
- ***<u>No new sensors</u> (used existing controllers' sensors)***
- ***200,000 parts***
- ***100,000+ miles/year***
- ***Extreme operating environment***
- ***20 years of life***
- ***Continuous Field Modifications (multi/year)***
- ***3-4 Scheduled Shop-visits/year***
- ***4-5 Un-Scheduled Shop-visits /year***
- ***2-3 Overhauls over life***
- ***Distributed Maintenance Environment***

History of Expert-On-Alert™ (EOA™)

• Launched 1998 : **200** locomotives	– CBR + BBN
• 1999 : **600** locomotives	– CBR
• 2000 : **1000 – 1500** locomotives	– CBR + JDPAD(Rule Based):
• 2001 :	– CBR + JDPAD + Data Mining
• 2002 :	- Process Automation : Tools + 30% Auto RX
• 2003 : **4000** locomotives :	- Improved Rx Precision,
	- Vastly increased parameter availability
• 2004-05: **5000+** locomotives	- Improved Rx Precision and larger fleet coverage

Expert-on-Alert (EOA™): Proactive Maintenance Recommendations

EOA™ Overview

Expert on Alert™ RM&D Service

- Failure reduction… "Fix right the first time"
- Fewer shoppings… "Fix out of the shop"
- Shop efficiency… "Expert Diagnostics"
- Lower parts cost… "Correct part removal"

Enabled By…

- Wireless, real time data management
- Expert diagnostic tools & rules
- Closed loop diagnostic system & process
- Seamless B2B integration with maintenance systems

Benefits Proven On Over 4,000 Locomotives

MCES 2004 October 26 – 28, 2004 Page 3

Sensor Data
Maintenance Logs
Repair Data

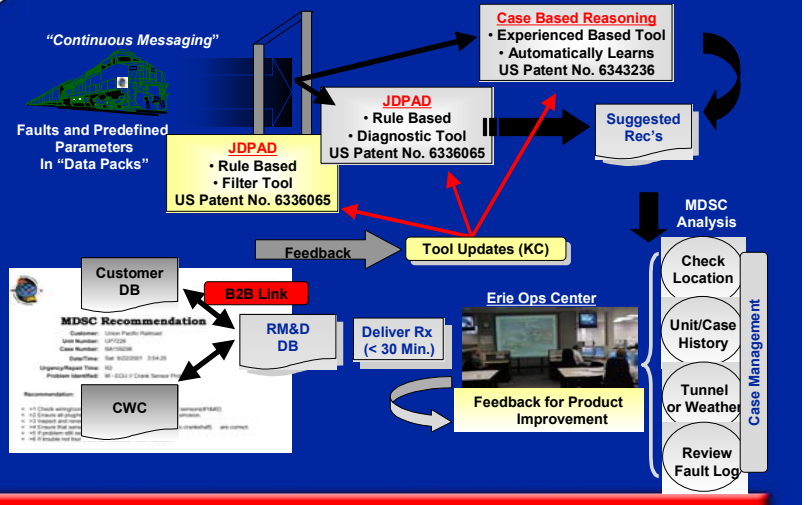
Fuzzy + CBR + RBR

- ***Key Goal:*** *Using existing locomotive sensors and wireless communication system, provide railroads with condition-based maintenance and repair service (advanced failure notifications to schedule corrective repair)*

- ***Solution:*** ***Hybrid rule-based & case based reasoners*** *predicting incipient locomotive failures. The reasoner uses a workflow system to specify best suggested repair procedure and notify the RR*
- ***Benefits:*** *Decrease number of road failures and increase % utilization. Change unscheduled maintenance events into scheduled ones.*
  24/7 Fleet Mgmt

Personnel reduced from 150 to 2 !!

EOA™ Continuous Learning



Technology … Fix it Right the 1st Time … Everywhere

MCES 2004 October 26 – 28, 2004 Page 4

Sample Case

Cust ID	Unit Numb.	Occur Date	Fault Code	Occur Hours	Reset Hours	Loco Sped	DIRECT	NOTCH	Eng Sped	Volt	Main Amps	Alt Fld	Wat Tmp	Oil Tmp	CALL	STATE	BLOWER	RADFAN	BF	INFO	Misc. Status	SE	Fault Description
AB	8894	03-mar-1996	453D	80377.61	80377.61	30.7	R	8	995	8	0	0	176	200	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	03-mar-1996	453D	80390.61	80390.61	6.2	F	2	580	5	16	0	169	177	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	03-mar-1996	49CC	80392.48	80392.50	0.0	C	S	0	3	0	0	176	178	R	E	O	O		F	_______V_		Intake Manifold Air Too
AB	8894	04-mar-1996	453D	80408.23	80408.23	13.7	F	8	1047	7	14	0	175	204	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	05-mar-1996	453D	80424.98	80424.98	14.9	F	7	992	7	14	0	176	194	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	05-mar-1996	450F	80428.70	80428.71	22.4	F	8	983	399	182	112	172	194	M	E	F	F		6	AB_M_S__		Load Limited: L
AB	8894	05-mar-1996	422E	80428.71	80476.26	22.0	F	8	962	548	105	242	174	194	M	E	F	4		6	AB_M_S__		Fault Reset While In Le
AB	8894	05-mar-1996	453D	80430.56	80430.56	35.1	F	8	992	9	4	0	187	197	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	05-mar-1996	428E	80442.03	80476.55	4.3	F	1	482	7	0	0	176	180	R	E	2	O		D	AB_______		TM Plug Attempted At To
AB	8894	06-mar-1996	452C	80451.88	80452.35	0.0	F	4	885	30	476	273	167	172	M	E	F	O		6	AB_M_S__		TM #3 Stalled (High Cur
AB	8894	06-mar-1996	452B	80451.88	80452.35	0.0	F	4	885	32	480	316	167	172	M	E	F	O		6	AB_M_S__		TM #2 Stalled (High Cur
AB	8894	06-mar-1996	452E	80451.88	80452.33	0.0	F	4	885	30	17	293	167	172	M	E	F	O		6	AB_M_S__		TM #5 Stalled (High Cur
AB	8894	06-mar-1996	454C	80451.90	80452.33	0.0	F	5	992	35	171	344	169	174	M	E	F	O		6	AB_M_S__		TM #5 Exceeded 240 C at
AB	8894	06-mar-1996	4548	80451.90	80452.33	0.0	F	5	992	35	161	343	168	173	M	E	F	O		6	AB_M_S__		TM #1 Exceeded 240 C at
AB	8894	06-mar-1996	454B	80451.90	80452.33	0.0	F	5	992	35	184	345	169	174	M	E	F	O		6	AB_M_S__		TM #4 Exceeded 240 C at
AB	8894	06-mar-1996	422E	80452.33	80486.86	0.0	C	1	323	6	0	0	176	180	R	E	F	O		F	AB_______		Fault Reset While In Le
AB	8894	06-mar-1996	453D	80454.98	80454.98	22.7	F	8	995	8	5	0	177	200	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	06-mar-1996	4016	80462.38	80462.38	0.0	F	2	0	3	1	0	170	174	M	E	O	O		D	_B_______		Unable To Load: Check S
AB	8894	07-mar-1996	453D	80476.21	80476.21	29.1	F	8	992	8	4	0	187	197	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	07-mar-1996	4006	80476.43	80476.43	0.0	F	1	436	10	955	78	170	172	M	E	F	O		5	AB_M_S__		T/L 8 And 9 Changed Whi
AB	8894	07-mar-1996	422E	80476.56	80539.41	0.0	C	1	332	5	3	0	177	181	R	E	F	O		F	AB_______		Fault Reset While In Le
AB	8894	07-mar-1996	453D	80480.83	80480.83	18.6	F	8	992	8	9	0	178	200	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	07-mar-1996	49CC	80493.33	80496.43	0.0	C	S	0	3	1	0	176	178	R	E	O	O			_________		Intake Manifold Air Too
AB	8894	08-mar-1996	49CC	80496.45	80496.45	0.0	C	S	0	2	0	0	138	129	R	E	O	O		F	_________		Intake Manifold Air Too
AB	8894	08-mar-1996	49CC	80496.46	80496.70	0.0	C	S	0	2	1	0	138	129	R	E	O	O		F	_________		Intake Manifold Air Too
AB	8894	08-mar-1996	453D	80500.16	80500.16	29.8	F	8	992	8	1	0	179	202	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad
AB	8894	08-mar-1996	452C	80500.60	80514.63	0.0	R	4	882	34	975	296	171	181	M	E	F	O		6	AB_M_S__		TM #3 Stalled (High Cur
AB	8894	08-mar-1996	452B	80500.60	80514.63	0.0	R	4	882	33	825	290	171	181	M	E	F	O		6	AB_M_S__		TM #2 Stalled (High Cur
AB	8894	08-mar-1996	452A	80500.60	80514.63	0.0	R	4	885	36	994	293	171	181	M	E	F	O		6	AB_M_S__		TM #1 Stalled (High Cur
AB	8894	08-mar-1996	49CC	80506.80	80514.61	0.0	C	S	0	3	0	0	173	181	R	E	O	O		F	_________		Intake Manifold Air Too
AB	8894	08-mar-1996	453D	80518.68	80518.68	38.3	F	8	989	10	3	0	174	197	M	E	O	O		6	_B_______		FDP Or FCFP RU Is Bad

AB 8894 2501 1 8 08-MAR-1996 BRG_XY - Braking Resistor Grid X=StkY=R #1 STACK ALL GRIDS BURNT-REPL

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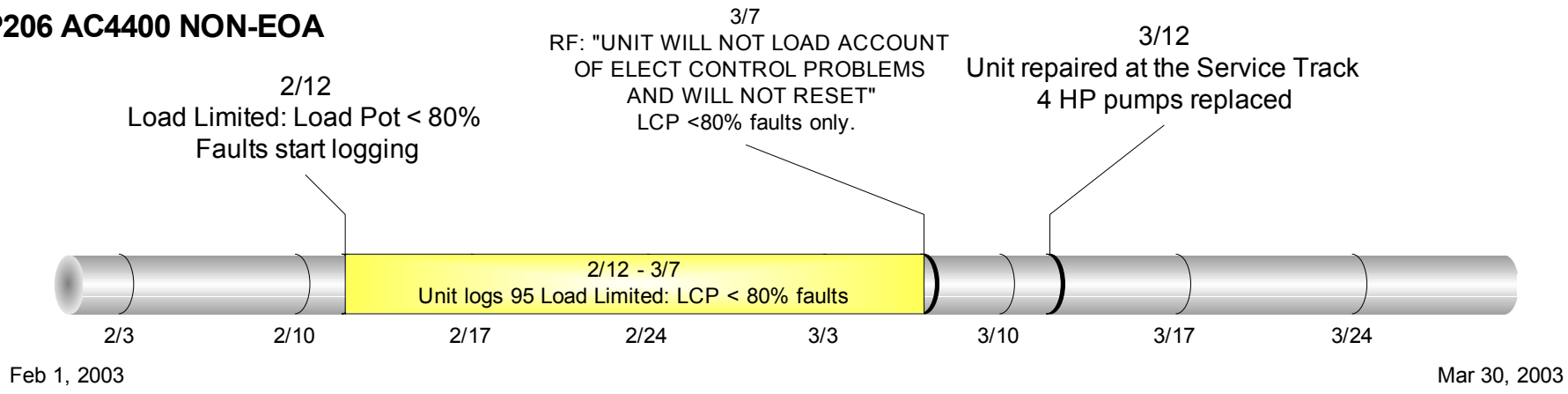
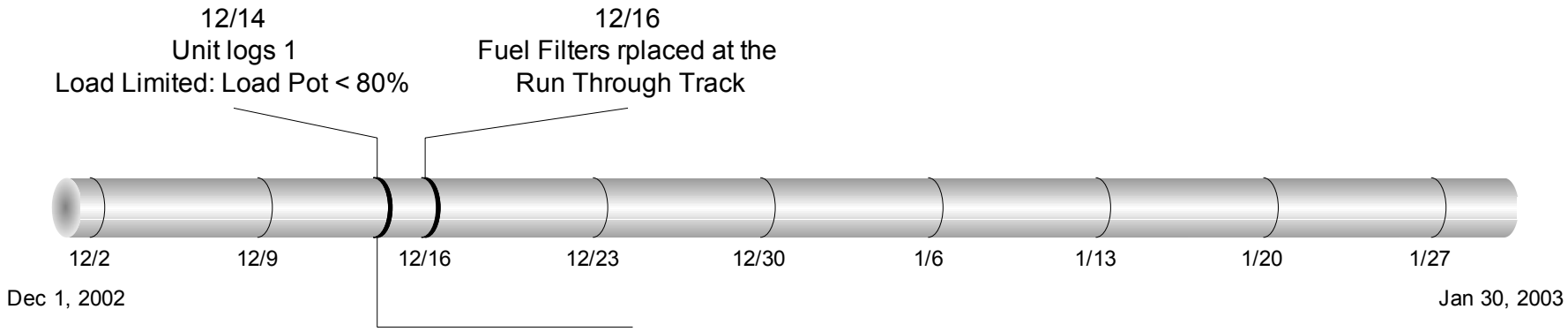
Fault codes collected over 5 days for loco #8894, leading to a repair recommendation on March 8 1996

Customer Impact - 1

SP206 AC4400 NON-EOA



SP250 AC4400 EOA



28 Days Saved

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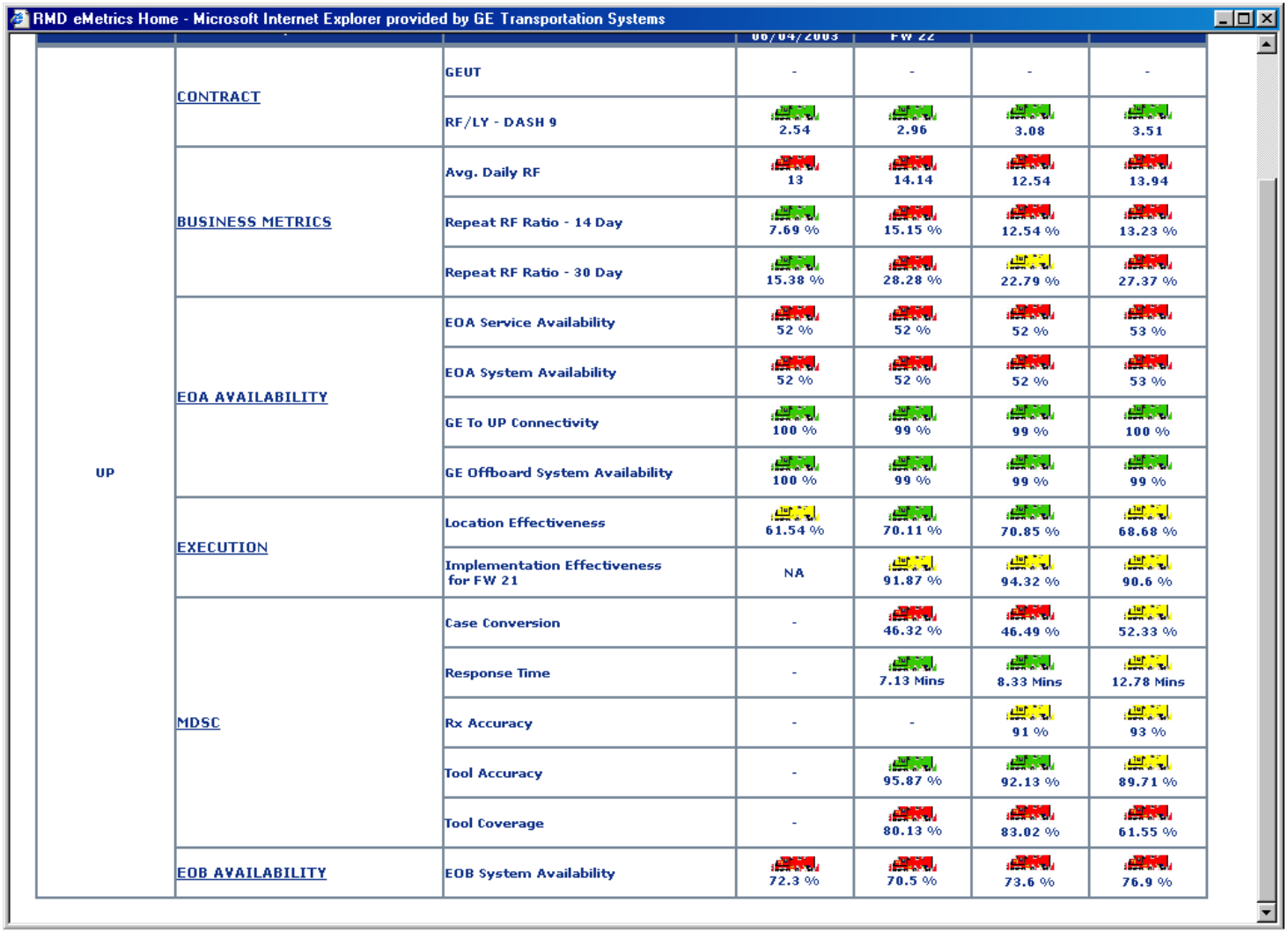
Application Walkthrough

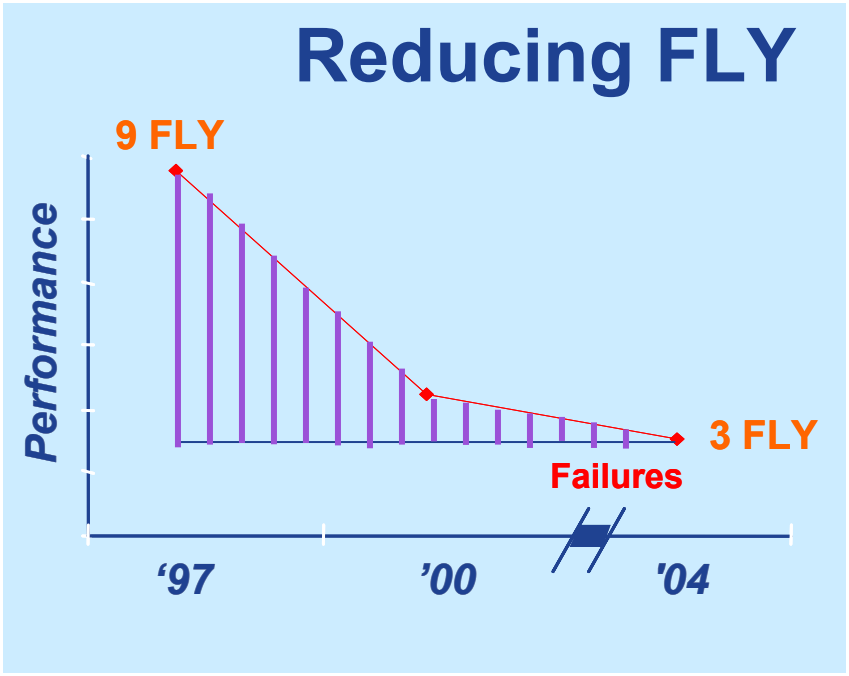


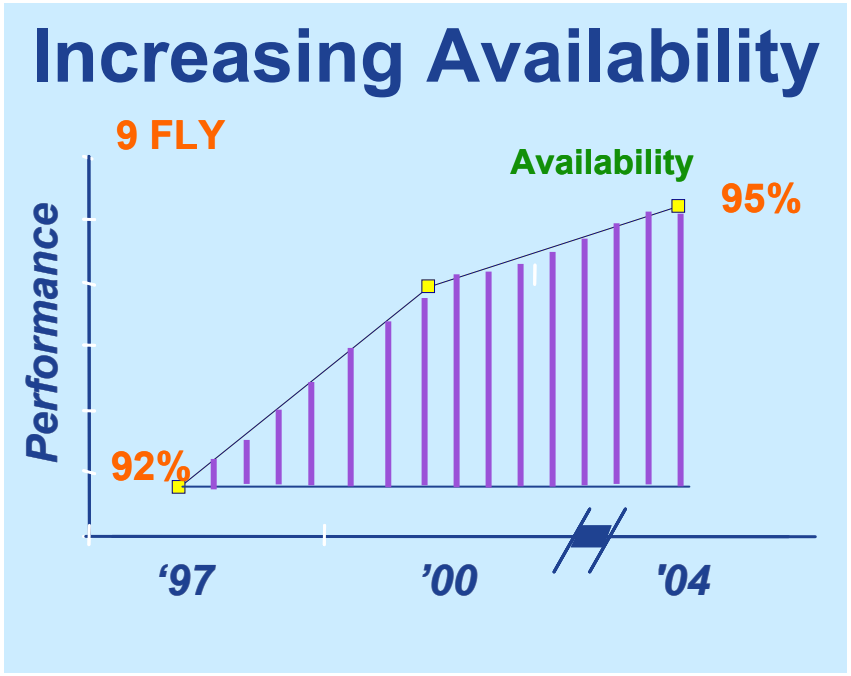
			06/04/2003	FW 22		
UP	CONTRACT	GEUT	-	-	-	-
		RF/LY - DASH 9	2.54	2.96	3.08	3.51
	BUSINESS METRICS	Avg. Daily RF	13	14.14	12.54	13.94
		Repeat RF Ratio - 14 Day	7.69 %	15.15 %	12.54 %	13.23 %
		Repeat RF Ratio - 30 Day	15.38 %	28.28 %	22.79 %	27.37 %
	EOA AVAILABILITY	EOA Service Availability	52 %	52 %	52 %	53 %
		EOA System Availability	52 %	52 %	52 %	53 %
		GE To UP Connectivity	100 %	99 %	99 %	100 %
		GE Offboard System Availability	100 %	99 %	99 %	99 %
	EXECUTION	Location Effectiveness	61.54 %	70.11 %	70.85 %	68.68 %
		Implementation Effectiveness for FW 21	NA	91.87 %	94.32 %	90.6 %
	MDSC	Case Conversion	-	46.32 %	46.49 %	52.33 %
		Response Time	-	7.13 Mins	8.33 Mins	12.78 Mins
		Rx Accuracy	-	-	91 %	93 %
		Tool Accuracy	-	95.87 %	92.13 %	89.71 %
		Tool Coverage	-	80.13 %	83.02 %	61.55 %
	EOB AVAILABILITY	EOB System Availability	72.3 %	70.5 %	73.6 %	76.9 %

Case Creation → Case Analysis → Equipment Detail → Maintenance History → Corrective Action → Feedback → Metrics

Benefits from PHM Technologies

Expert On Alert (EOA) system at GE Rail





Failures per Locomotive per Year [FLY]

- Cost for track-blockage & labor per FLY: **$17K per FLY**
-Cum.FLY reduction [1997-2004]: 6 FLY
-Cum.FLY cost reduction [1997-2004]: $102K/loco
-Cum.FLY cost reduction over fleet [1997-2004]:~ **$300MM**
(for average fleet size 3,000 locomotives)

Locomotive Availability

-Value of 1% increase in availability per locomotive: **$3.5K/loco**
-Cum.Availability Increase [1997-2004]: 3%
-Cum.Value increased Availability per loco.[1997-2004]: $10.5K/loco
-Cum.Value of Availability over fleet [1997-2004]: **~ $30MM**
(for average fleet size 3,000 locomotives)

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Bridging the Gap: UP problems with 'Hot Trains' for UPS

(NYT: March 31, 2004)

The New York Times **Business**

EVERY DAY

Freight-Car Congestion Is Worrying Union Pacific

Michael Stravato for The New York Times

Cars and trucks headed toward downtown Houston waiting for a Union Pacific train to go through.

By DON PHILLIPS

Freight congestion has spread across the Union Pacific railroad system, especially in Southern California and the Southwest, raising concerns about delays in agricultural shipments and international trade if a solution is not found before the rail freight rush begins in late summer and fall.

… U.P.S. has begun a new coast-to-coast premium service that requires high-speed train shipment to Dallas, Atlanta and New York. The New York train dispatched from Los Angeles on Tuesday is particularly time-sensitive because it is scheduled to arrive in time for package delivery on Friday rather than the following Monday.

To keep the train on time on the busy, largely single-track segment between Los Angeles and El Paso, called the Sunset Route, railroad dispatchers clear other trains onto sidings far ahead of the U.P.S. train, sometimes hours ahead. At times, trains are stalled because their crews have reached the maximum tour of duty under federal law of 12 hours, and no rested crews are available. It can take a week to sort out such situations. "***The hot trains are a challenge, particularly on the Sunset***," said Robert W. Turner, Union Pacific's senior vice president for corporate relations. …

… This operating data, reported by rail companies to the Association of American Railroads, gives evidence of Union Pacific's problems. Freight cars on line, which can be used as a measure of congestion, were at a high of 325,634 in the week ended March 19. The average time for a freight car in yards has also spiked upward. At West Colton, the major yard for Southern California, the average time was up to 49.0 hours in the latest week from 30.8 hours in the first quarter of 2003. Average train speed, which was 24.8 m.p.h. in the first quarter of 2003 and 22.1 m.p.h. in February, was down to 21.5 m.p.h. in the week ended March 19.

This is more important than the slight differences might indicate. Mr. Turner said Union Pacific estimated that each decrease of one mile an hour required 250 extra locomotives, 5,000 extra freight cars and 180 extra employees to make up for the decrease in efficiency. …

Dr. Piero P. Bonissone – General Electric Global Research

PHM Technology

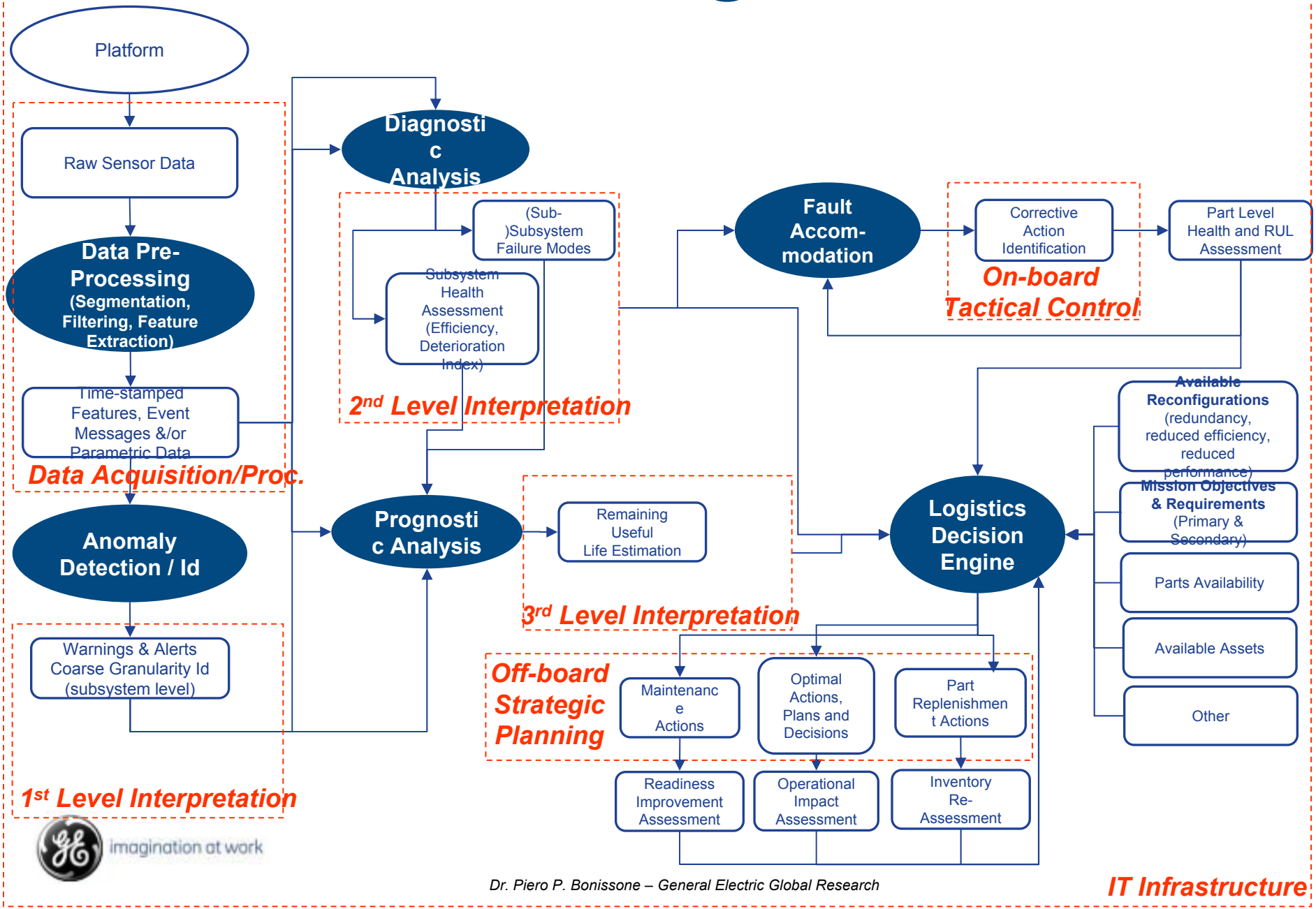
Objective
Develop algorithms for asset health assessment to support fleet-wide PHM

Goal
Address fleet-level metrics, such as safety, maintenance costs, asset readiness, reduced inventory, and operational success

Constraints
- No new sensors (using existing sensor-suite in legacy fleet)
- Platform-agnostic (data-driven approach not requiring platform-specific knowledge)

Approach
- **Anomaly Detection**
  - Provide early warning for incipient faults by characterizing regions of operational normality
  - Identify assets deviating from these regions
- **Diagnostics and Prognostics**
  - Provide assessment of sub-system health & remaining useful life for asset
- **Logistics Decision Support**
  - Select and deploy optimal decision across entire logistics infrastructure

PHM: The Big Picture



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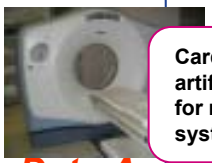
PHM: The Big Picture

Platform

Raw Sensor Data

Data Pre-Processing (Segmentation, Filtering, Feature Extraction)

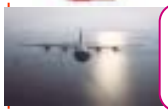


Cardiac CT image artifact reduction for multi-slice CT systems

Data Acquisition/Proc.

Anomaly Detection / Id

Event detection in reciprocating compressors

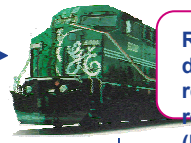


Anomaly detection in aircraft flights *[Lockheed Martin]*

1st Level Interpretation

Diagnostic Analysis

Automated interpretation of MRI calibration system test (SPT)



Remote Locomotive diagnostics and repair recommendation (EOA)

2nd Level Interpretation

Prognostic Analysis

RUL estimation for engine core comp. & Ball Bearings

Prediction of Time-to-break for paper web

Off-board Strategic Planning

Optimization of Coal-fired boilers (HR/NOx tradeoffs)

Fault Accom-modation

Rapid Fault Detection & Operability Restoration

On-board Tactical Control

Part Level Health and RUL Assessment

Logistics Decision Engine

Available Reconfigurations (redundancy, reduced efficiency, reduced performance)

Mission Objectives & Requirements (Primary & Secondary)

Parts Availability

Available Assets

Other

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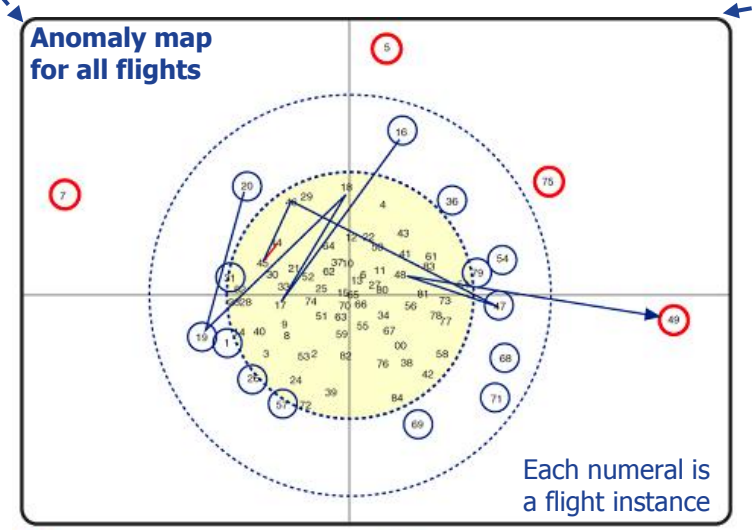
IT Infrastructure

Anomaly Detection Algorithms for PHM

Operational flight data recorded for multiple flight-instances → Algorithms for Anomaly/Novelty Detection → Anomaly Map with potentially anomalous flight-instances



1. Use operational data recorded from multiple flight instances to construct an anomaly map & detect potentially **anomalous** flights

2. Use properties of **anomaly map** to detect the onset of operational faults **early**

3. Use early detection of developing faults to drive **safety, maintenance preparedness, other metrics**

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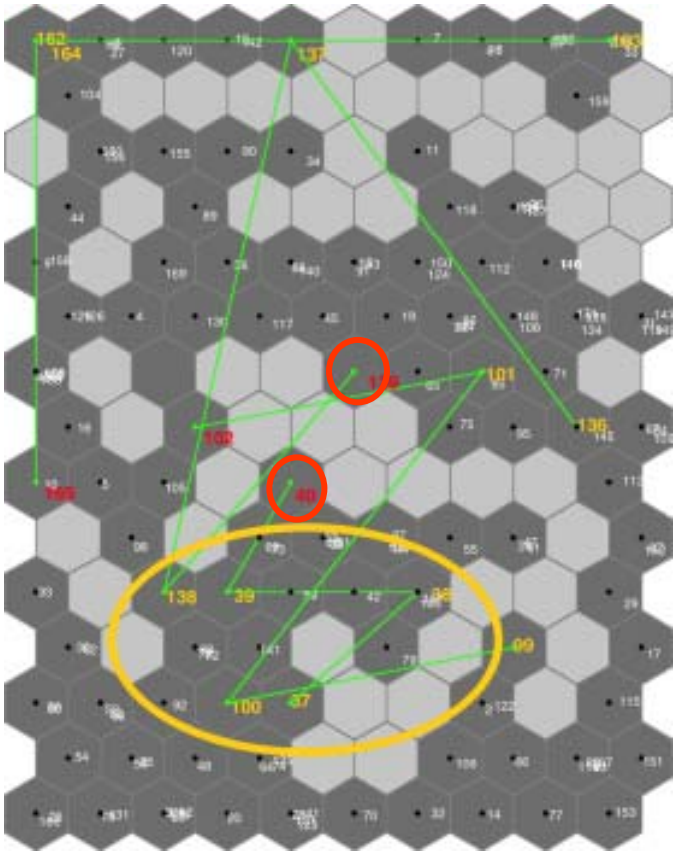
Self-Organizing Maps for Diagnostic and Prognostic Analyses

1. Train SOM on normal data to obtain normal operating envelope
2. Declare a case novel if its projection to the map falls outside the envelope



Flights known to have failures (Red numerals) generate trajectories that pass through common region

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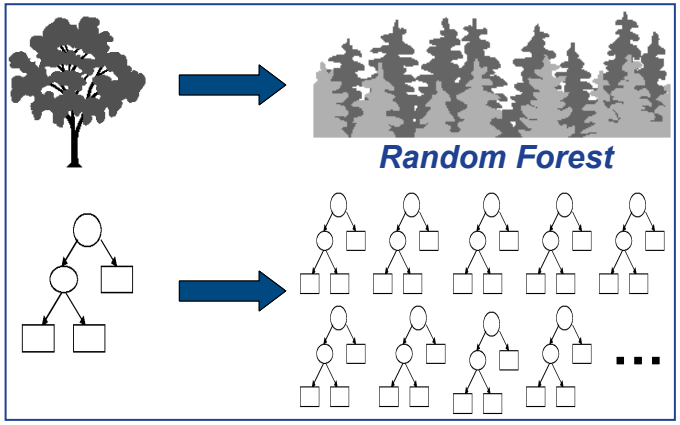
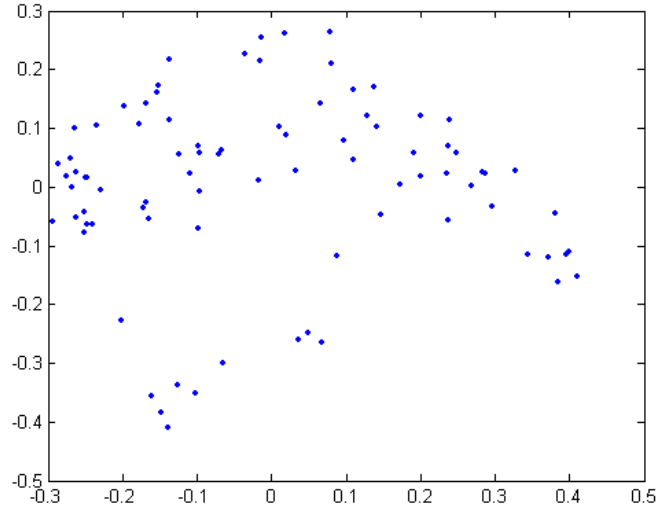
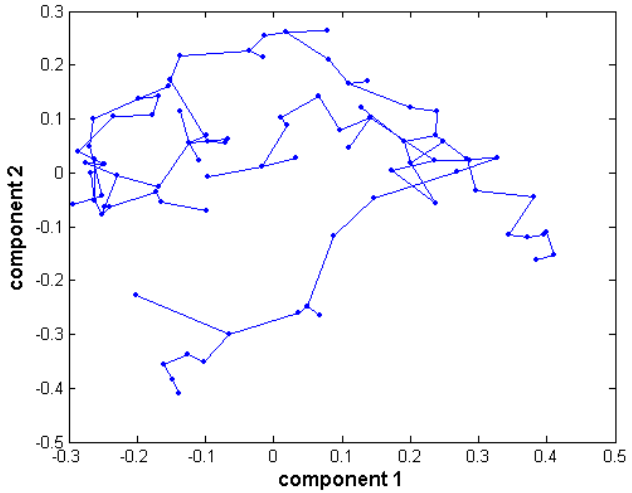
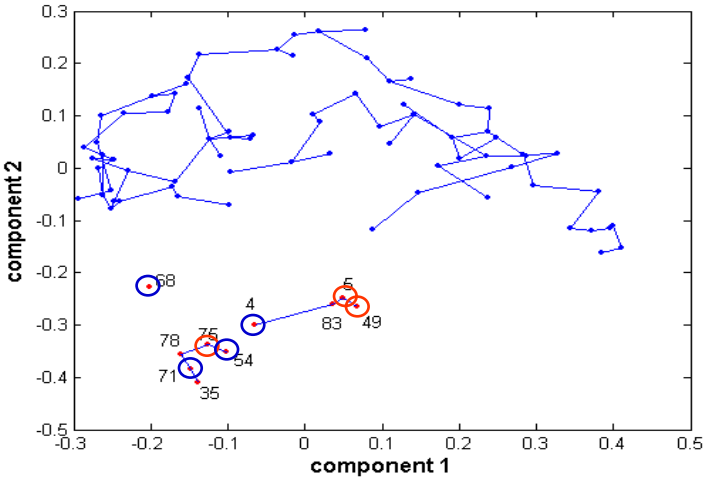
Random Forest Unsupervised Clustering for Novelty Detection









Flights known to have failures (Red dots) aren't connected to main body of Minimum spanning tree!

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Diagnostics based on Automated Fault Signature extraction & Pattern Recognition

Key Goal

Automated extraction and application of fault signatures from time-series data for asset diagnostics

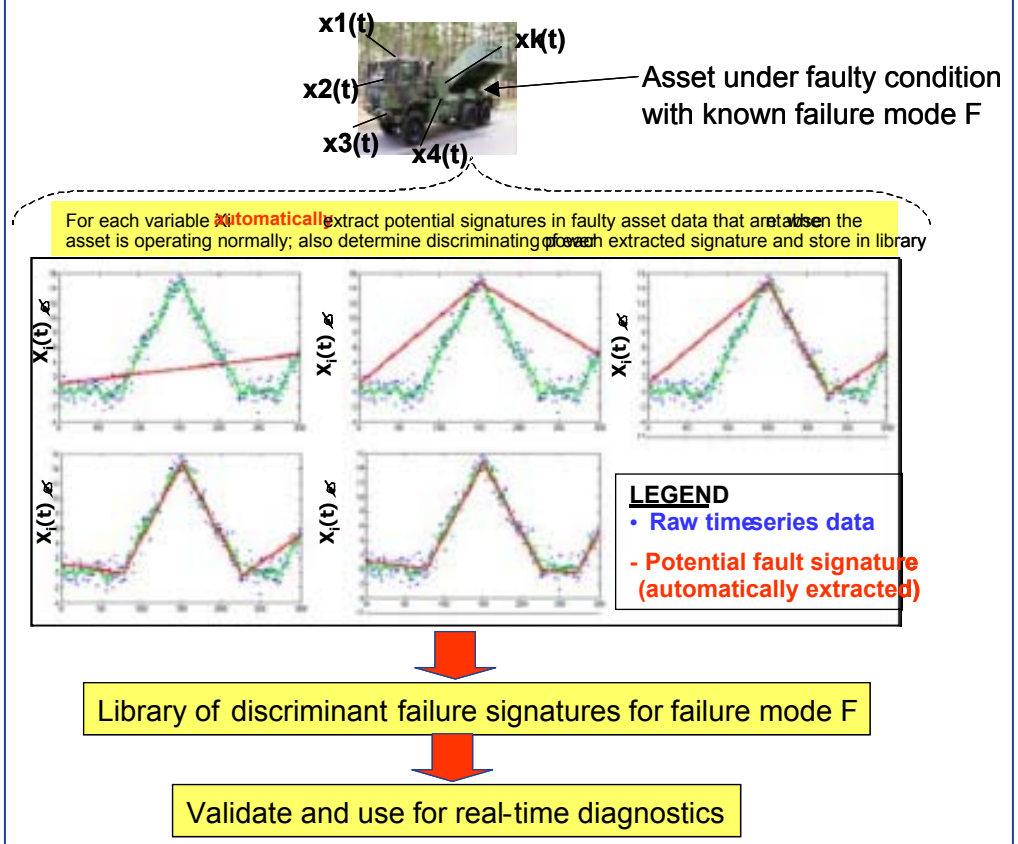
Solution

Automated signature extraction and pattern recognition based detection

- Use knowledge of existing fault condition and failure mode of asset to extract and learn potential fault signatures from multiple time-series variables
- Perform analyses to retain most discriminating set of signatures
- Apply pattern recognition techniques to locate presence or absence of failure-mode in real-time using library of signatures learned.

Benefits

- Advanced diagnostic ability
- Potential prognostic ability



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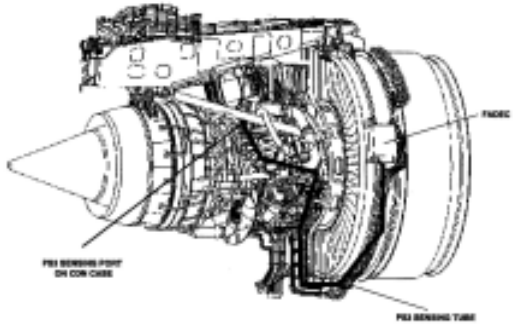
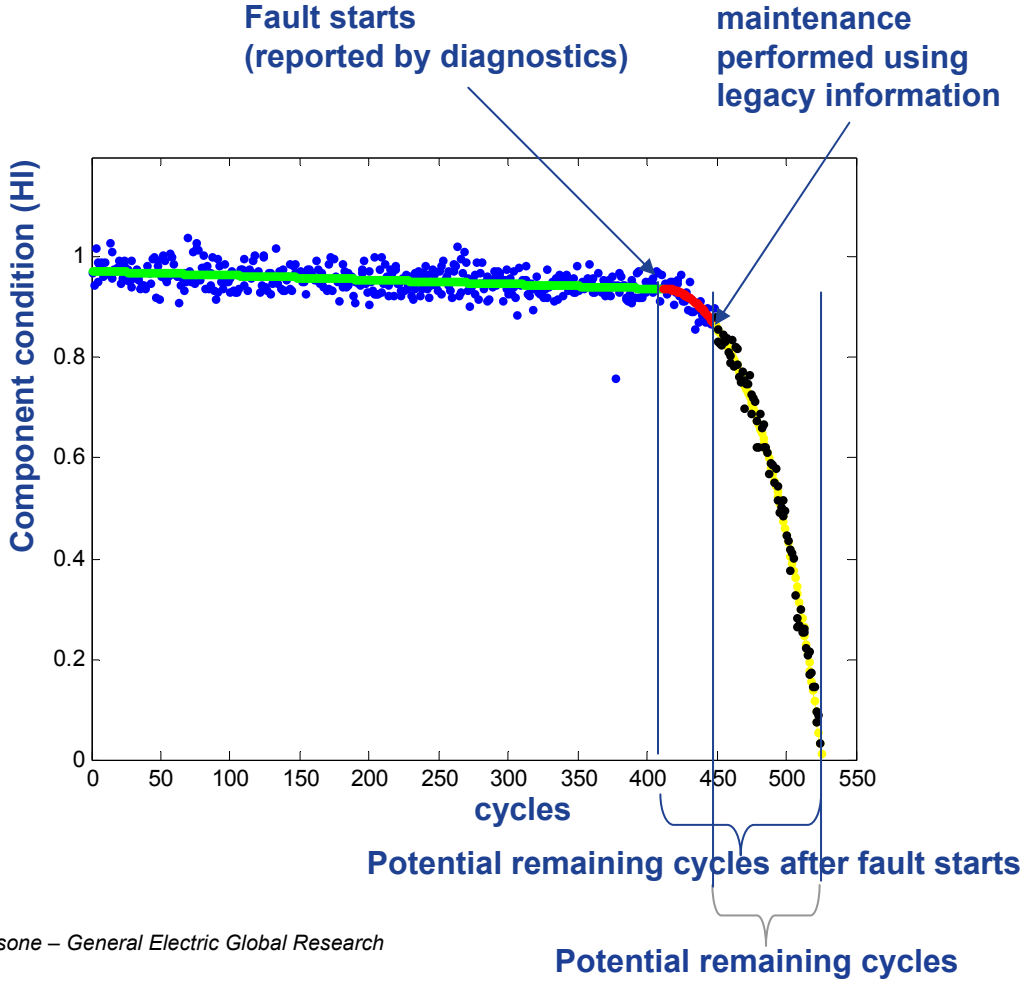
GE Aviation/DARPA: Equipment Prognostics

- ***Key Goal:***
  - Estimate remaining equipment life in presence of fault
- ***Solution***
  - ***1. Physics and Experience-Based Reasoner***
    - Apply detailed materials-based damage propagation model
    - Apply data-driven damage propagation model
    - Fuse estimates for reduced uncertainty and improved accuracy
  - ***2. Derive Operations-based Equipment Health***
    - Convert proximity to operational margins into equivalent equipment health
    - Track and extrapolate health when fault is present
- **Benefits**
  - Reduced maintenance cost
  - Fewer unscheduled maintenance
  - Increased TOW



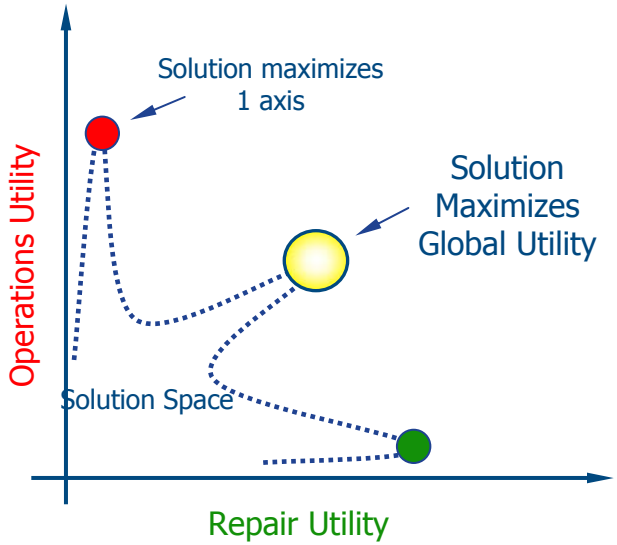


Decision Making and Health Management

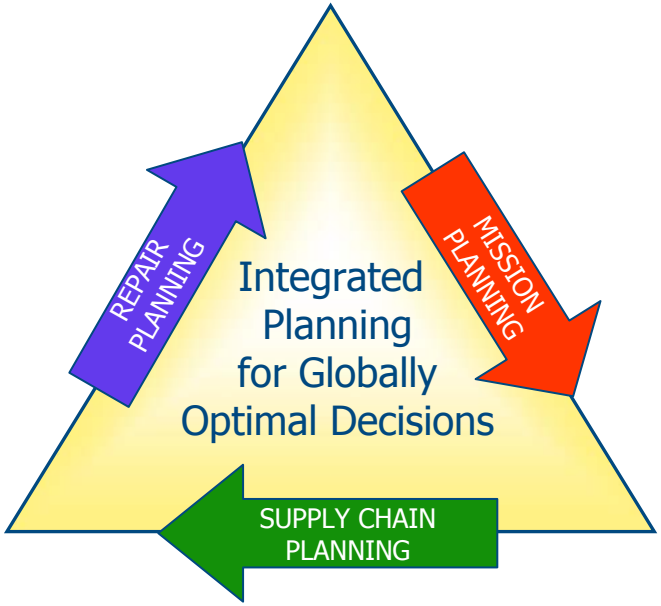
"Health Management is the capability to make appropriate decisions about maintenance actions based on diagnostics/prognostics information, available resources and operational demand."

- Andy Hess, PHM Lead for Air Systems on JSF

Decisions in Isolation
Do Not Maximize Global Utility



Integrated Planning
Maximizes Global Utility



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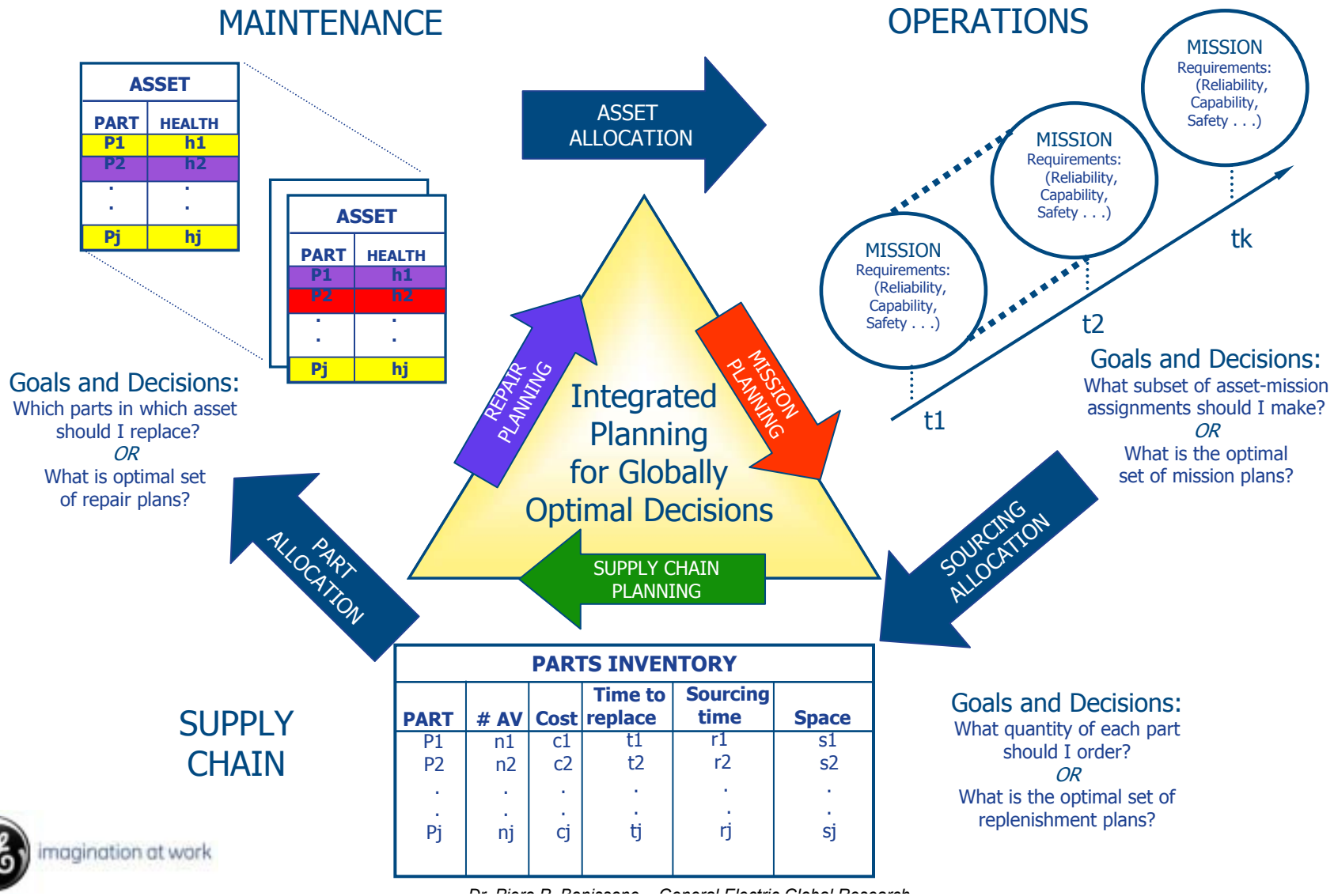
Decision Making and Health Management



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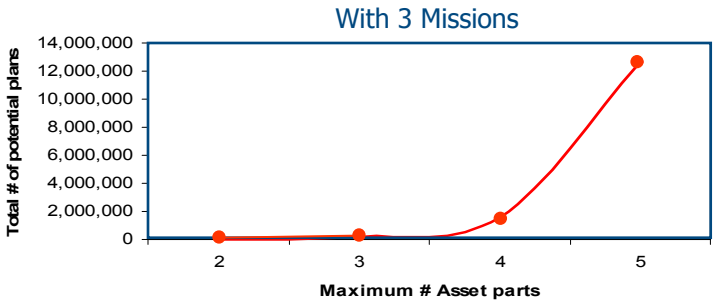
Integrated Decision Making in PHM: A Closer Look

Advantages of Integrated Planning

- Maximal global utility across all 3 platforms
- Increased number of satisfiable missions, mission reliability, safety, mission success rate and part availability
- Reduced sustainment costs, turnaround times, and spare requirements

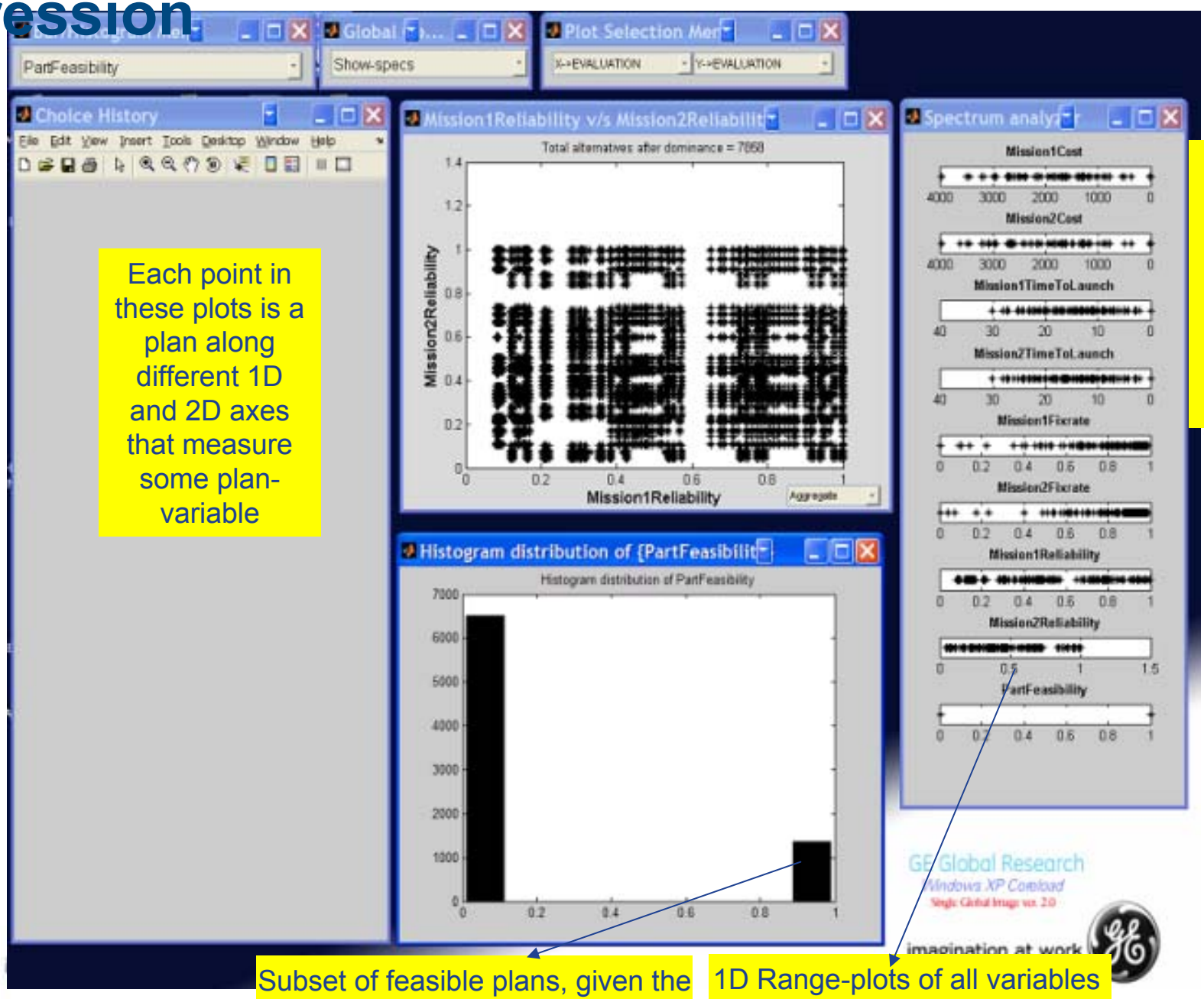
Disadvantages of Integrated Planning



With 3 Missions to be Satisfied	
Max # of Asset Parts	Total # of Potential Plans
4	24,576
5	196,608
6	1,572,864
7	12,582,912

Emphasizes the need for decision support

Interactive visualization and preference expression



Each point in these plots is a plan along different 1D and 2D axes that measure some plan-variable

- 7858 plans to begin
- All are optimal
- Only some are feasible

Subset of feasible plans, given the part availability (inventory)

1D Range-plots of all variables of interest to user

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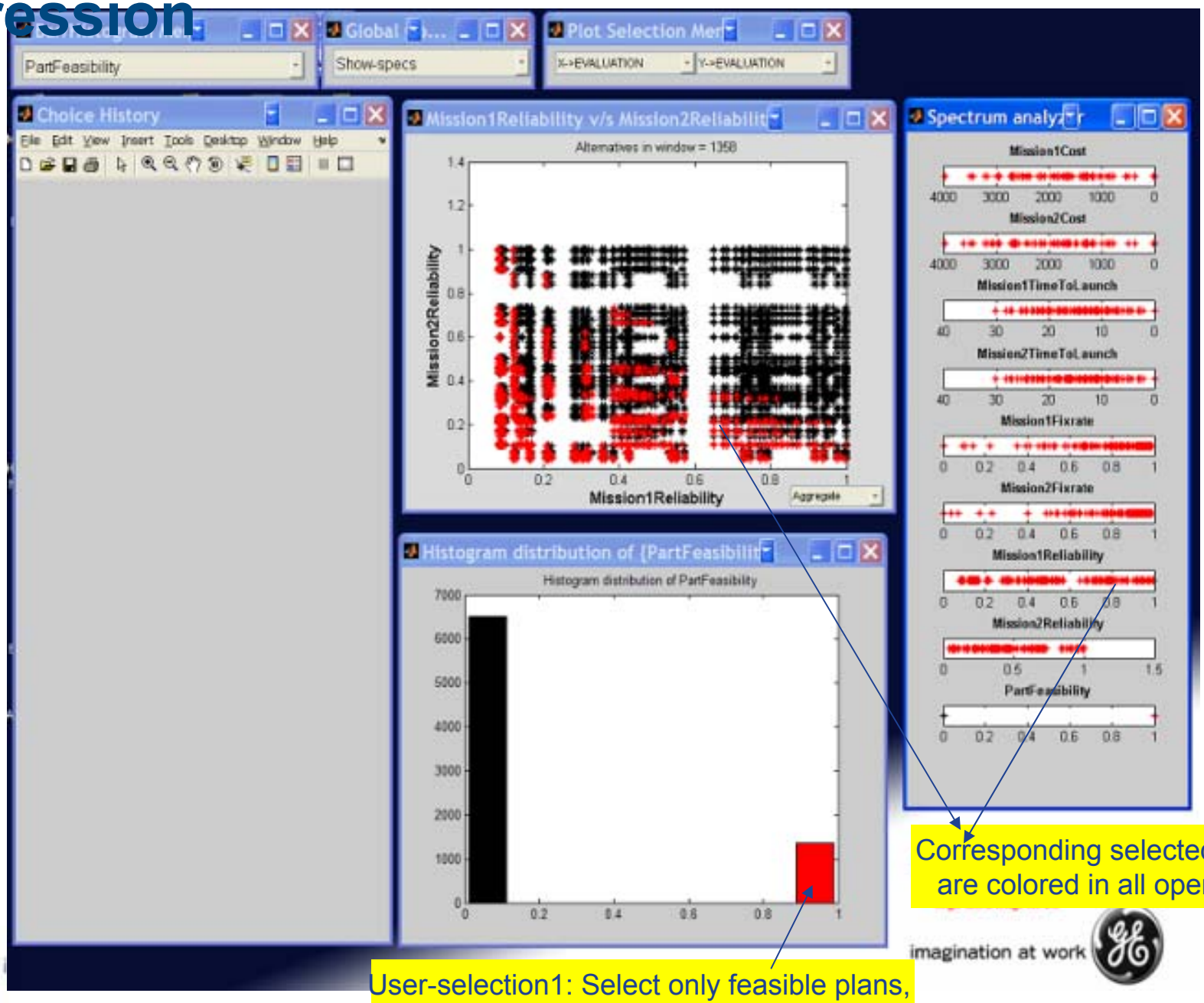
Interactive visualization and preference expression



Corresponding selected points are colored in all open plots

User-selection1: Select only feasible plans, using mouse-click

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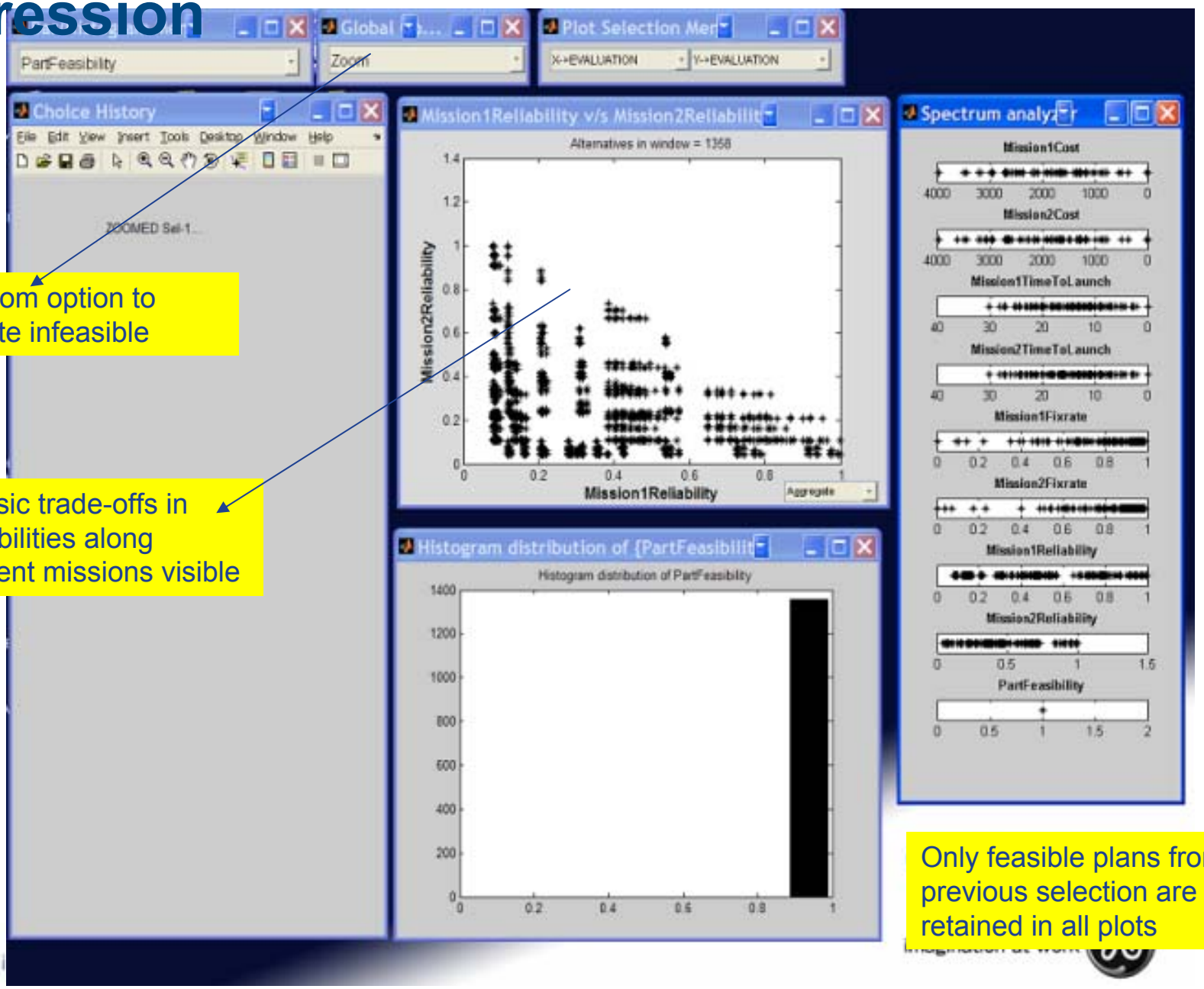
Interactive visualization and preference expression

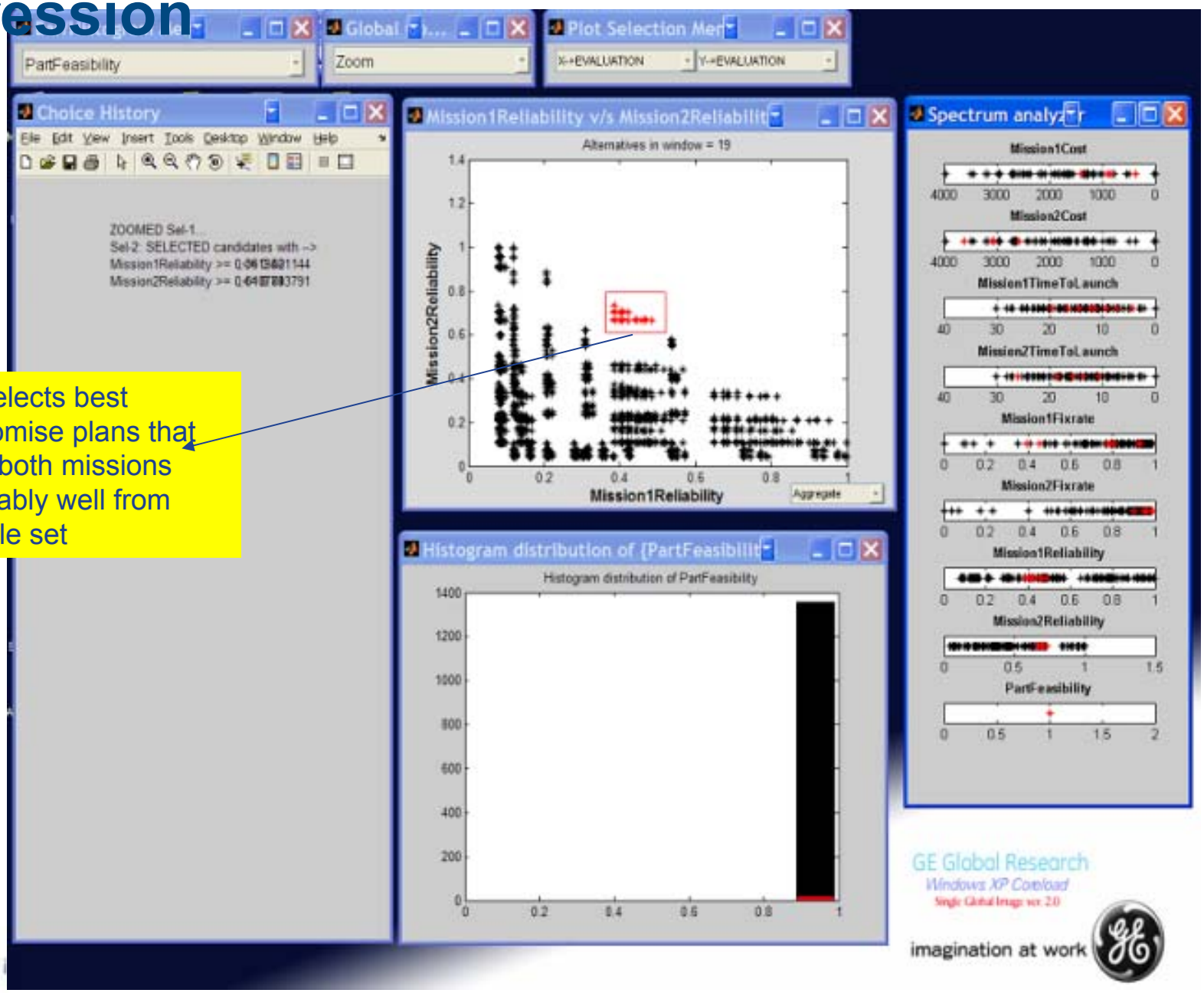


Use Zoom option to eliminate infeasible plans

Intrinsic trade-offs in Reliabilities along different missions visible

Only feasible plans from previous selection are retained in all plots

Interactive visualization and preference expression



User selects best compromise plans that satisfy both missions reasonably well from available set

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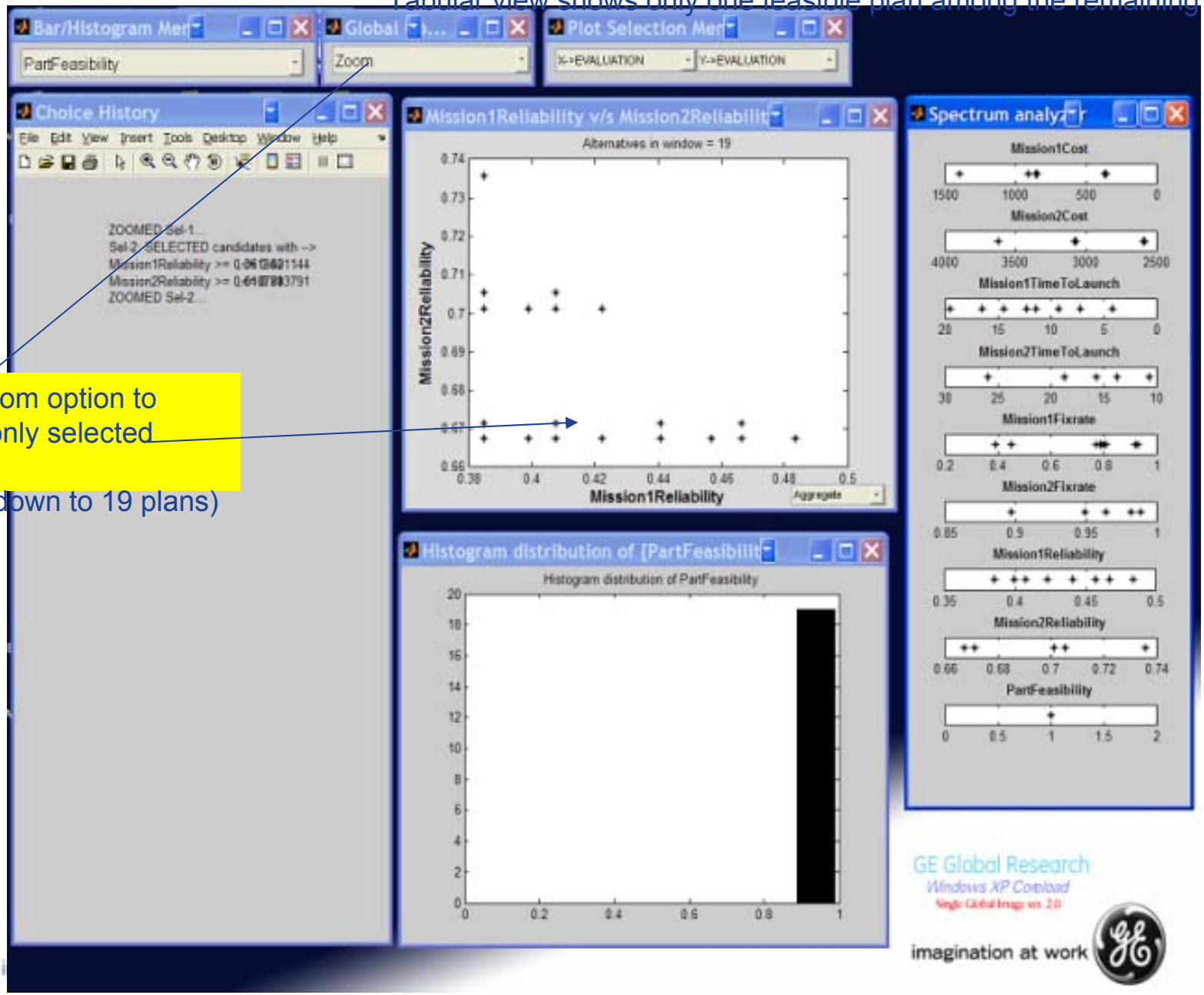
Tabular view shows only one feasible plan among the remaining ones



Use Zoom option to retain only selected plans
(we're down to 19 plans)

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Single Global Image ver. 2.0

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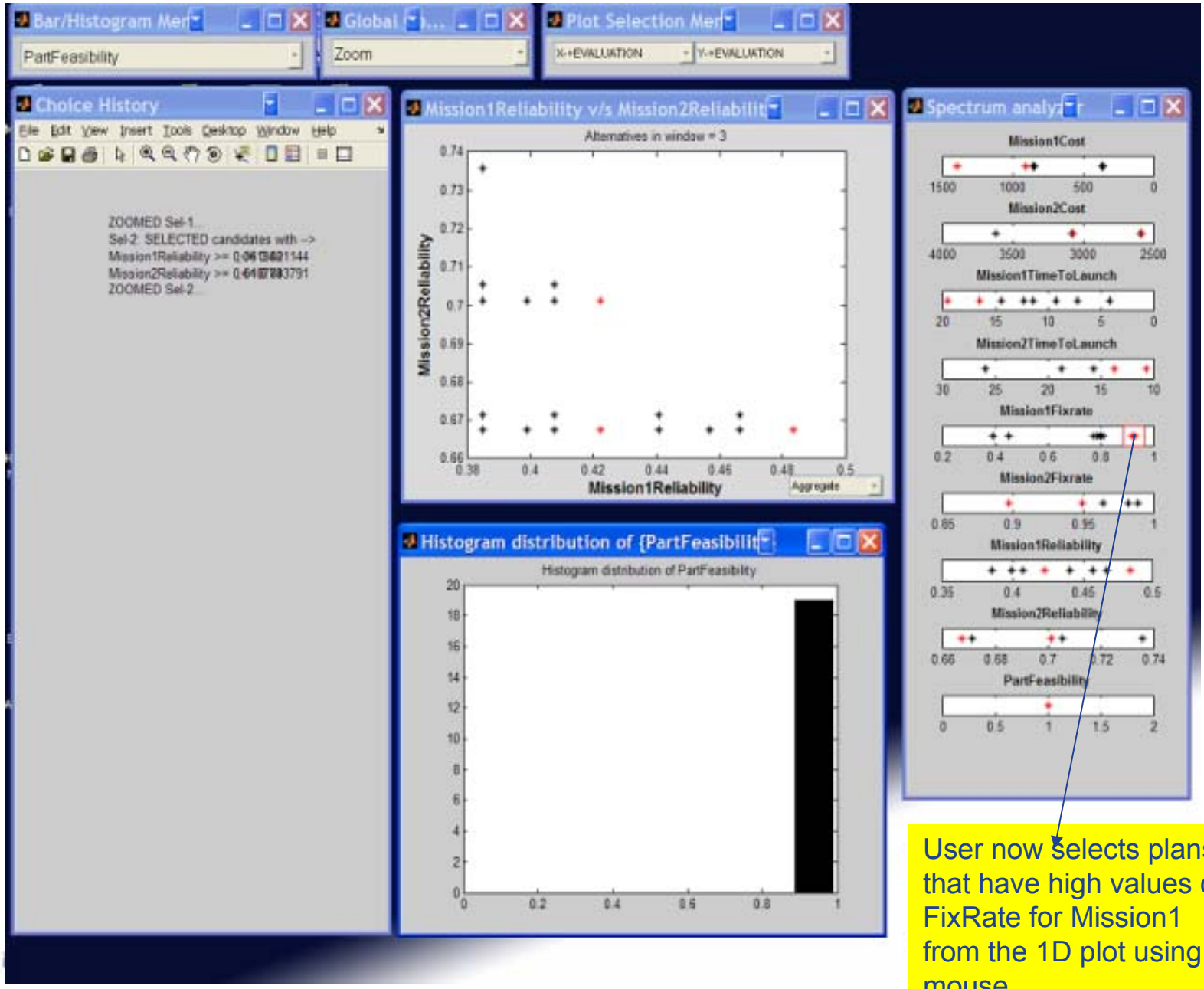
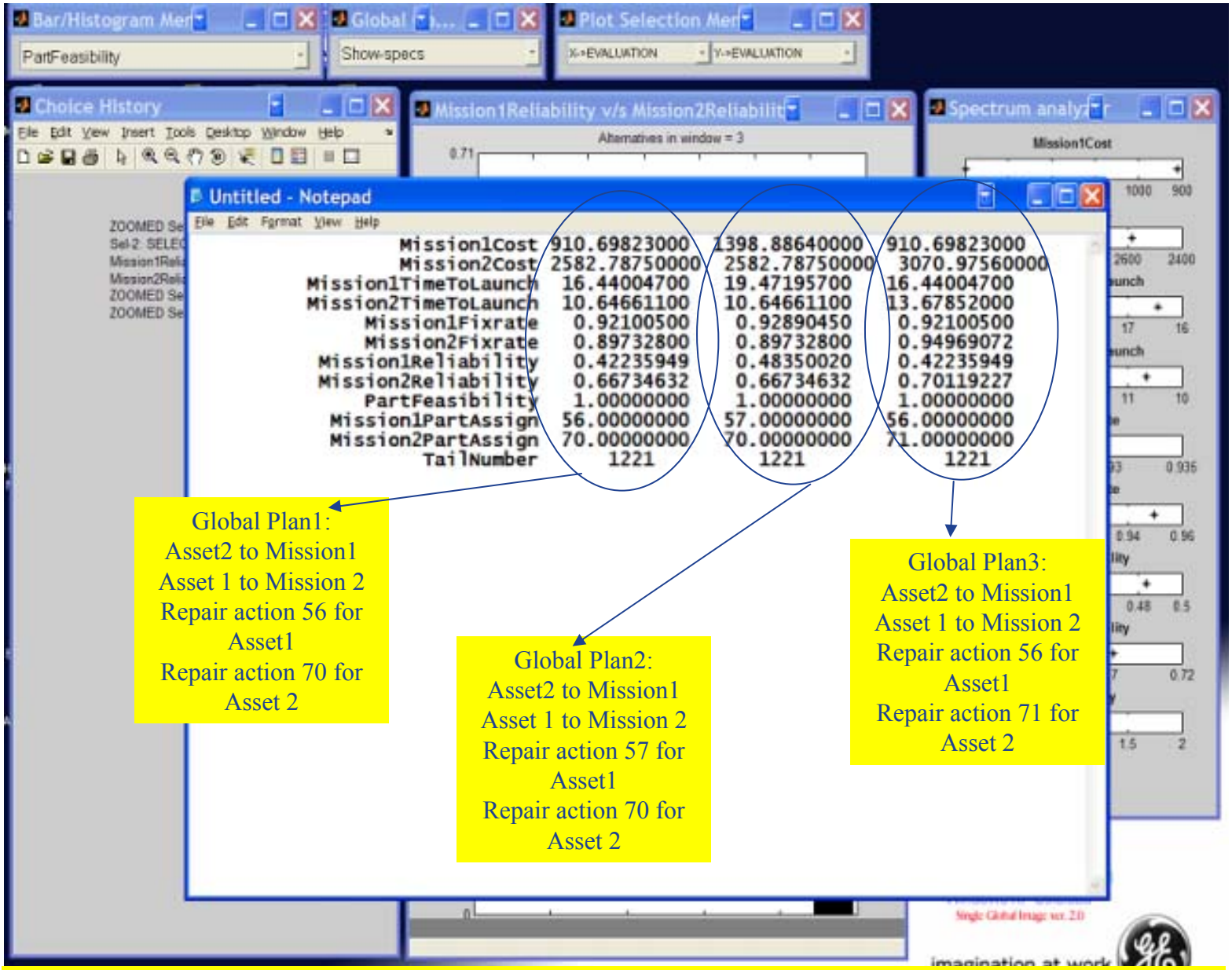


User now selects plans that have high values of FixRate for Mission1 from the 1D plot using mouse
(we're down to 3 plans)



With only 3 plans left to examine, user looks at tabular representation of the remaining plans and selects one for deployment to maintenance and operations platform

Conclusions

- Developed broad set of algorithms for asset health assessment to support fleet-wide PHM
- Addressed various fleet-level metrics, such as safety, maintenance costs, asset readiness, reduced inventory, and operational success
- No new sensors (using existing sensor-suite in legacy fleet)
- Platform-agnostic (data-driven approach not requiring platform-specific knowledge)
- Proven Commercial Success for GE Rail: EOA™
- Extending PHM technology for military platforms under GE/LM Shared Vision