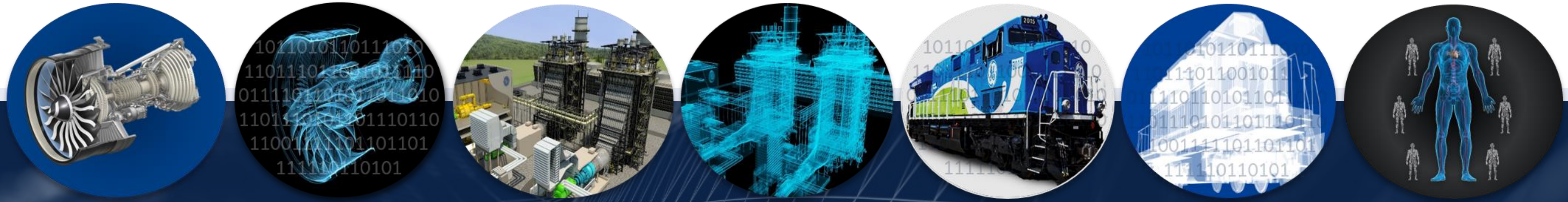
Industrial Digital Twins

LEVERAGING MACHINE HEALTHCARE



RUSTY IRVING

Digital Twin Platform Leader & Chief Engineer
GE Global Research

20 MARCH 2019

Healthcare – People vs. Automobiles

PEOPLE

- You manage your 'maintenance appointments'
- You hope your doctor has your medical history with its scarce, discrete data
- You schedule appointments weeks to months ahead for non-emergencies

AUTOMOBILE

- Your car can tell you when to get an oil change, inflate the tires, add fluid, etc.
- Your dealer (and Carfax) has your data and ODB-II can provide more
- Most issues can be handled within days to a week

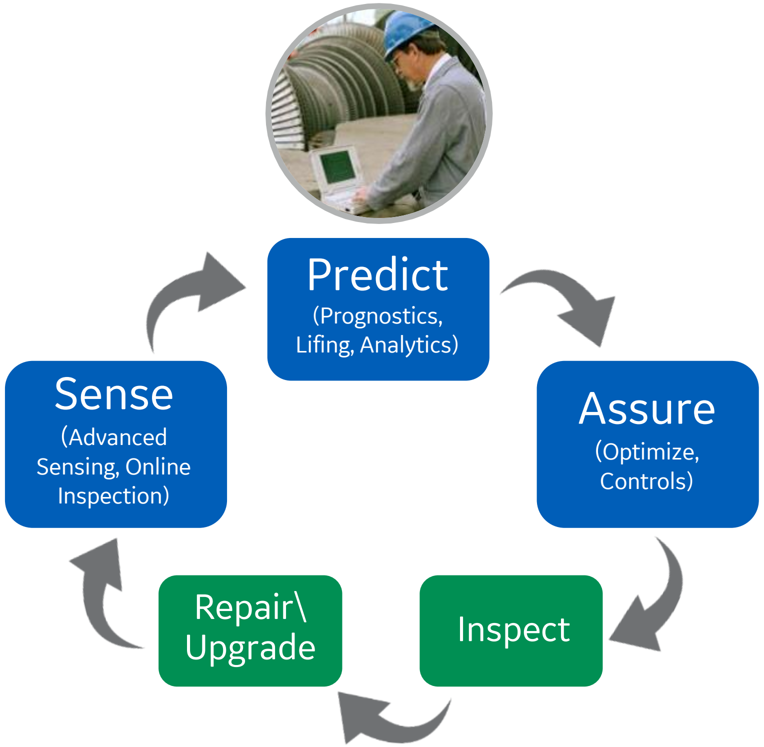
HEALTHCARE FOR AUTOMOBILES IS EASIER TO MANAGE.
AUTOMOBILE HEALTHCARE HAS BEEN DIGITIZED LONGER.

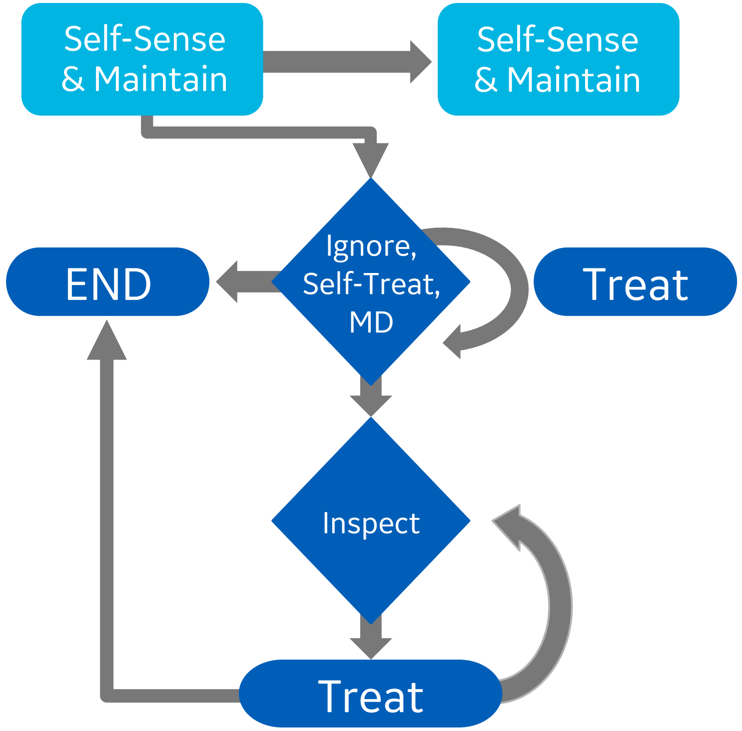
Healthcare – People vs. Automobiles

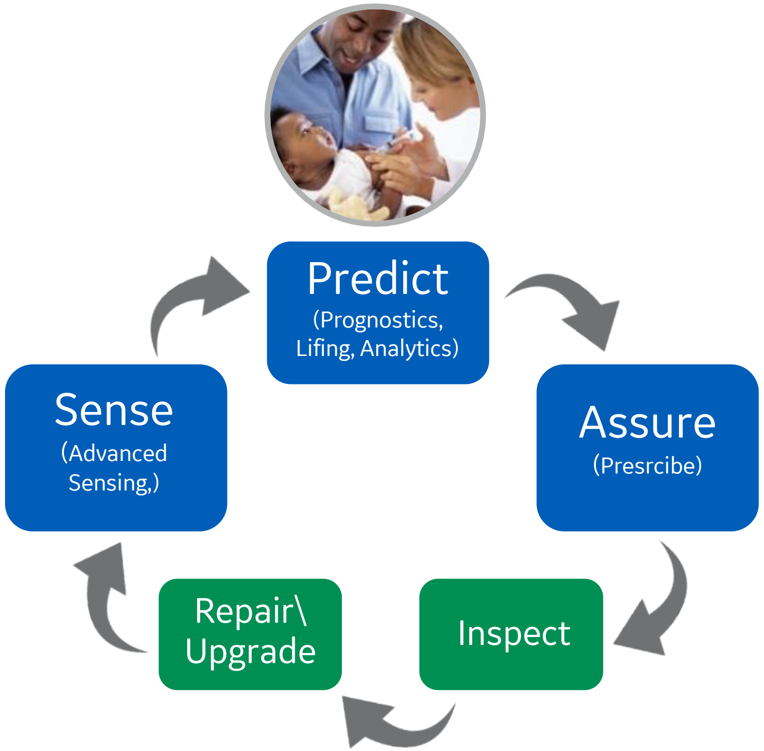
HEALTHCARE FOR AUTOMOBILES IS EASIER TO MANAGE.
AUTOMOBILE HEALTHCARE HAS BEEN DIGITIZED LONGER.

Healthcare … for Humans and Machines

TODAY'S MACHINE HEALTH	TODAY'S HUMAN HEALTH	FUTURE HUMAN HEALTH?
Monitoring, Diagnostics, Prognostics Personalized Machinecare	Healthcare System You are the QB	Healthcare System Personalized Healthcare





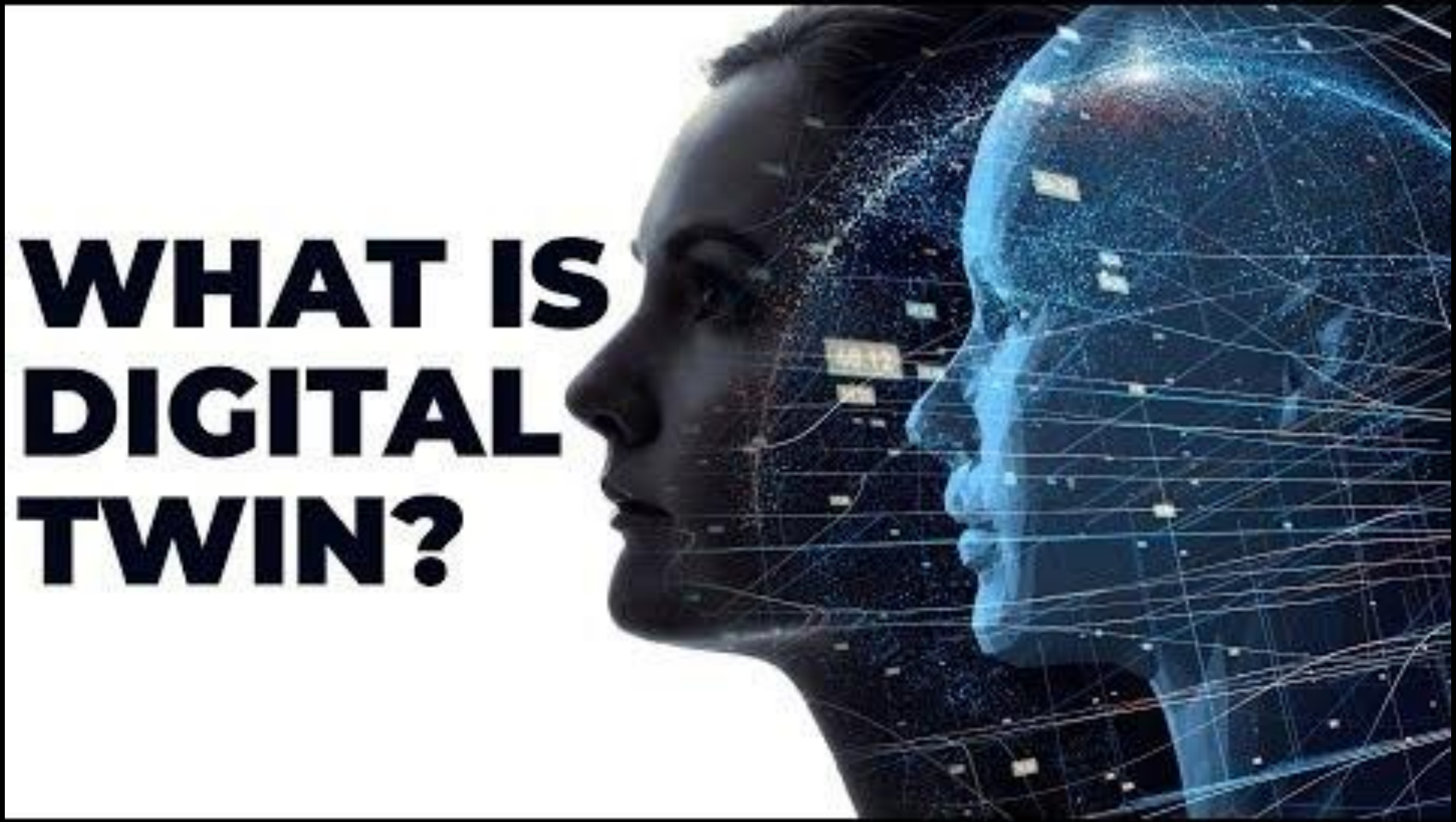


LET'S TAKE CARE OF OURSELVES AS WELL AS WE DO THE MACHINES

Outline

- **Industrial Machine** Digital Twin Defined and Explained
- **The Path** to Digital Twin
- **Digital Twin Examples** and Impact at GE
- **A Human Digital Twin** Example
- **Human Digital Twinning:** Possibilities, Benefits, Implications

DIGITAL TWIN
DEFINED AND EXPLAINED


WHAT IS
DIGITAL
TWIN?

GE is a pioneer in Digital Twin

Digital Twins, a name created by General Electric to identify the digital copy of an engine manufactured in their factories, are now a reality in a number of industries. They can be almost “identical” to the real thing, like in the case of General Electric engines and some modern keys where you have to take their digital twin to get a copy, or pretty accurate replicas like in case of Tesla cars or more coarse representation in case of other products.

What about us? Can we imagine a digital twin for us. Actually it is no longer science fiction

From: http://sites.ieee.org/futuredirections/2017/09/27/can-we-have-a-digital-twin/

GE's path to Digital Twin

SYSTEM OF ASSETS
INDIVIDUAL ASSETS

1980s
"BREAK & FIX"

- 1st M&D Systems **answered the question? "What Happened?**"
- Tech: Rule-Based
- Examples: GETS Diesel Locomotive Diagnostics

1990s
"M&D BUILD OUT"

- Systems still Reactive, **answered the question? "What is Happening?**"
- Online centers built out across GE
- CSA Cost Productivity becomes business model
- Tech: Mix of Neural Networks, Case-Based, and other

2000s
"PROGNOSTICS"

- **Answered the question? "What will break?"**
- Examples: Early Warning Systems
- Tech: Prior Methods, Machine Learning, Statistical

2010s
"REMAINING USEFUL LIFE"

- **Answered the question? "When will it break?"**
- Examples: GE Power OnLine CBM
- Tech: Prior Methods, Deep Learning, Usage Based Lifing

2015+
"DIGITAL TWINS"

- Now **answering many questions: "Can I run the asset hotter?," "When should I Inspect?," "When should I replace?"**
- Enables What-If Scenarios, System Optimization
- Examples: GE Power Efficiency Optimizer, GE Aviation Analytics Based Maintenance
- Tech: Prior Methods, Cloud Computing, Learning

RULES » PHYSICS AND DATA BASED MODELS » PHYSICS MODELS WITH LEARNING ECOSYSTEM

What is a Digital Twin?

Physical Asset

f(x)

TRANSFER FUNCTION

Digital Twin

A **Learning** Digital Model

PHYSICS MODELS + MACHINE LEARNING

1 PER ASSET MODEL

2 BUSINESS OUTCOMES

3 CONTINUOUSLY LEARNS

4 SCALABLE

5 ADAPTABLE

DIGITAL TWIN INCREASES PRODUCTIVITY AND ACHIEVES BETTER OUTCOMES FOR CUSTOMERS

5 Criteria for analytic to be digital twin

Drives business outcomes

GE's Digital Twin must drive demonstrable business value and outcomes

Per asset/Process/Person

GE's Digital twin is applied to individual assets, systems, process or person

Continuously learns

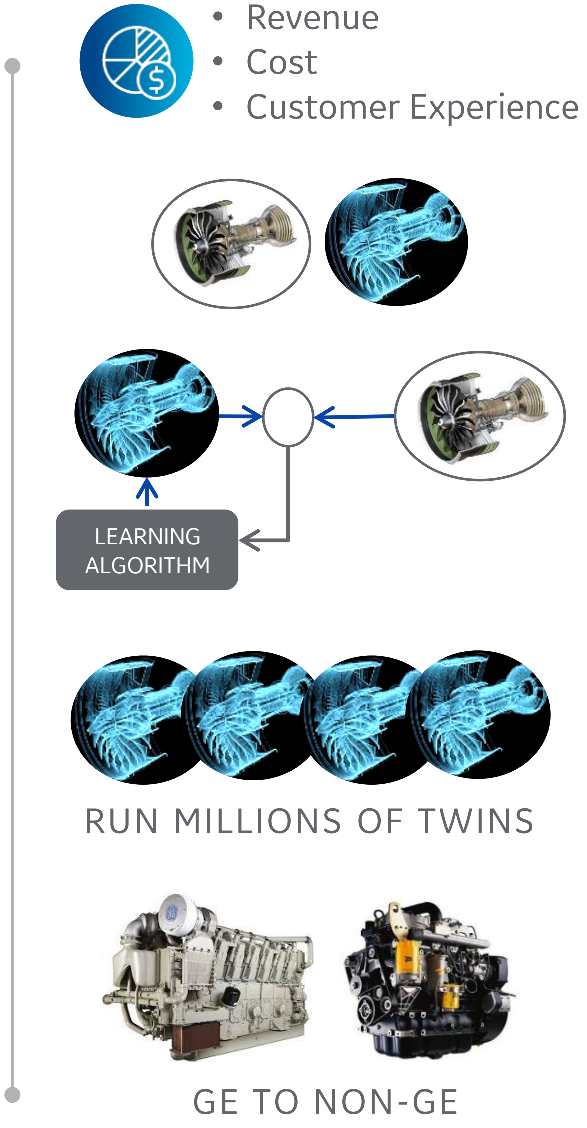
GE's Digital Twins continuously learn from new data to improve business outcomes

Scalable

GE's Digital Twins are scalable so as to be able to run millions of them

Adaptable

GE's Digital Twins are adaptable to other parts or asset classes, new scenarios or factors



DIGITAL TWIN IMPACT AT GE:

SUPPORTABILITY OF THE GE INSTALLED BASE OF INDUSTRIAL ASSETS

The GE installed base of industrial assets

> 34,000
UNITS

> 20,000
UNITS

> 20,000
UNITS

> 10,000
UNITS

> 200,000
UNITS

GE MANAGES OVER 300,000 INDUSTRIAL ASSETS DAILY

Transactional Service vs. Contractual Service Agreements:

Transactional Service:

Traditional Parts & Services. Based on a per incident basis.

Contractual Service Agreement:

Based on a multi-year time period. Customer pays for asset usage and transfers maintenance risk.

Services levers

SERVICES PROFIT = SERVICES REVENUE - SERVICES COST

1 | Reduce the Cost of Servicing

2 | Reduce the Frequency of Servicing

KNOW EVERYTHING YOU CAN
ABOUT THE ASSET

Reducing the frequency of service

EBI = Borescope Inspection
CI = Combustion Inspection (Light)
HGP = Hot Gas Path (Medium)
MI = Major Inspection (Heavy)

A GENERIC INDUSTRIAL ASSET EXAMPLE

Today's maintenance practice

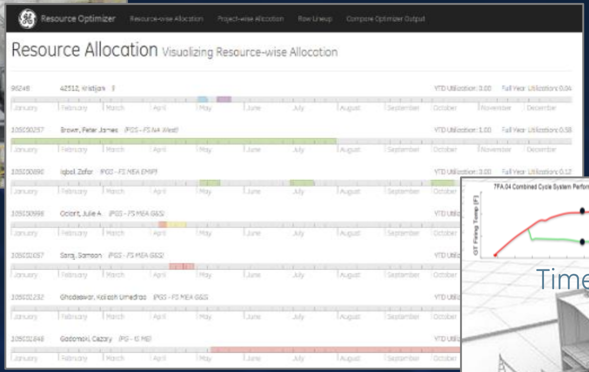
Tomorrow: Move 16K CI to 32K CI

REDUCE CYCLE TIME (20%)
AVOID FORCED OUTAGE ($2MM PER OUTAGE)

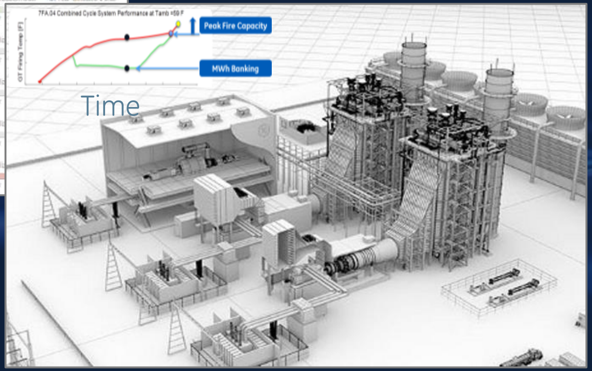
1,183,547 Twins and increasing

Parts Twins
Rotor failure prediction

Product Twins
Steam turbine life optimization

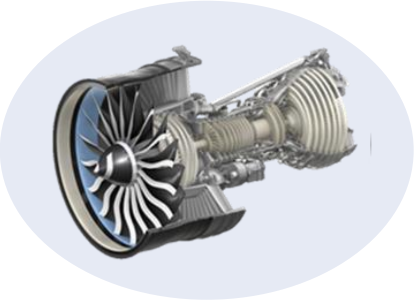


Process Twins
Field engineer scheduling



System Twins
Model based optimizer

Continuous prediction Digital Twin – Aviation engine

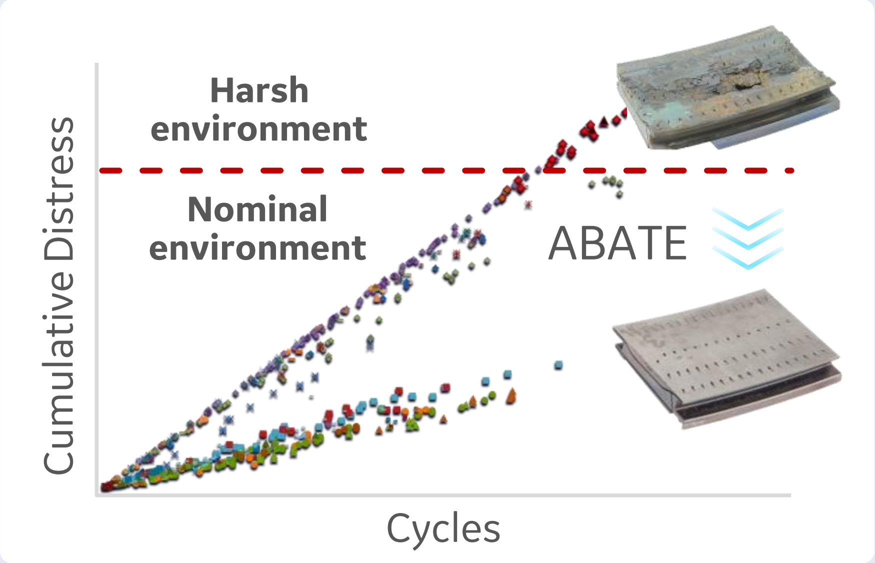


Environmental conditions

Per flight data

Prior condition

Digital Twin
Physics + AI Models

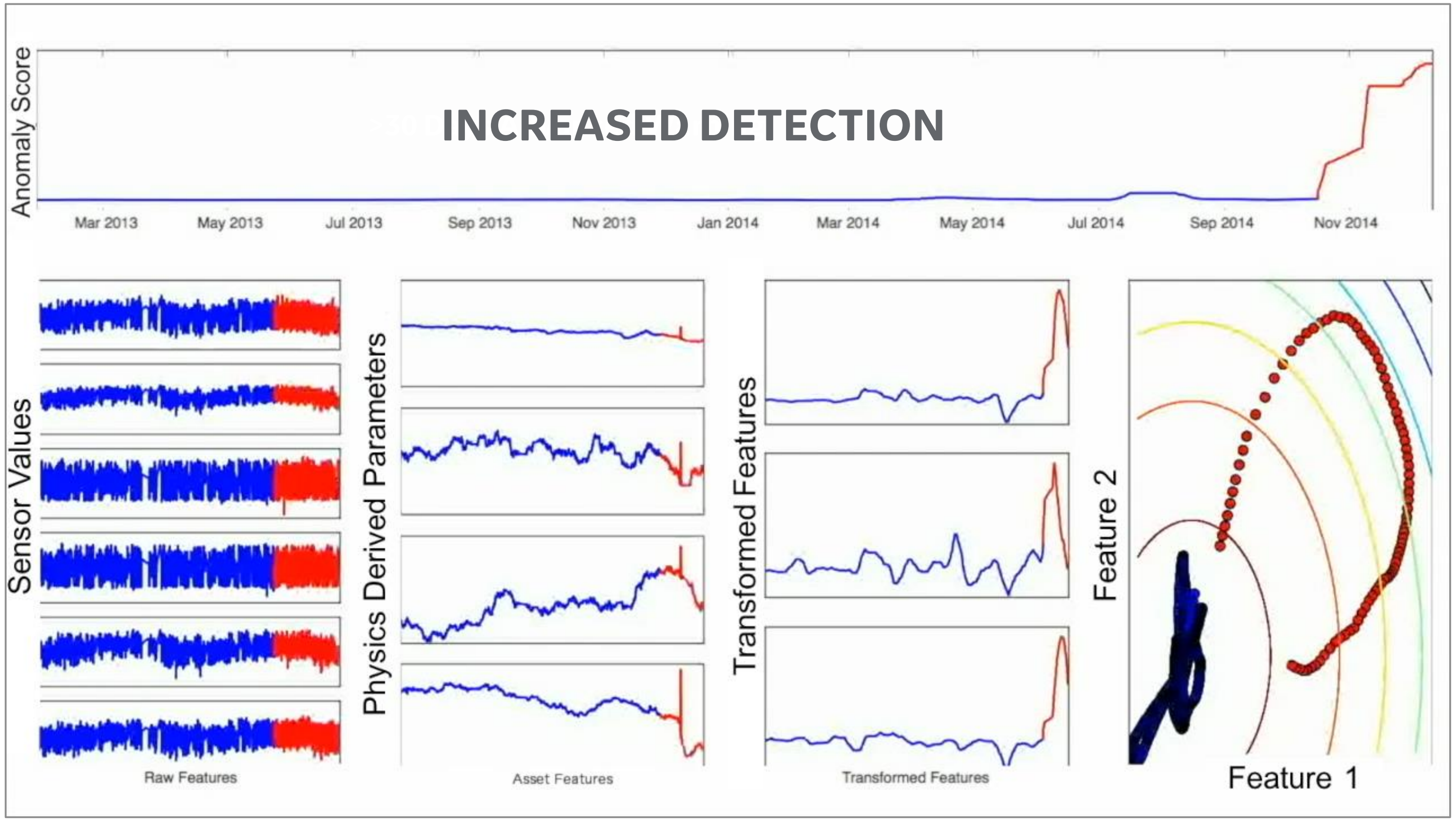


Optimized inspection time and Shop time

INCREASED AVAILABILITY TO CUSTOMER
SAVES TENS OF $MM IN UNNECESSARY SERVICE OVERHAULS

Increase customer value …
Improved reliability

Sufficient early warning to avoid customer disruption



PHYSICAL ASSET

Compressor Pressure & temperature, Exhaust Gas Temperature, etc.

DIGITAL TWIN

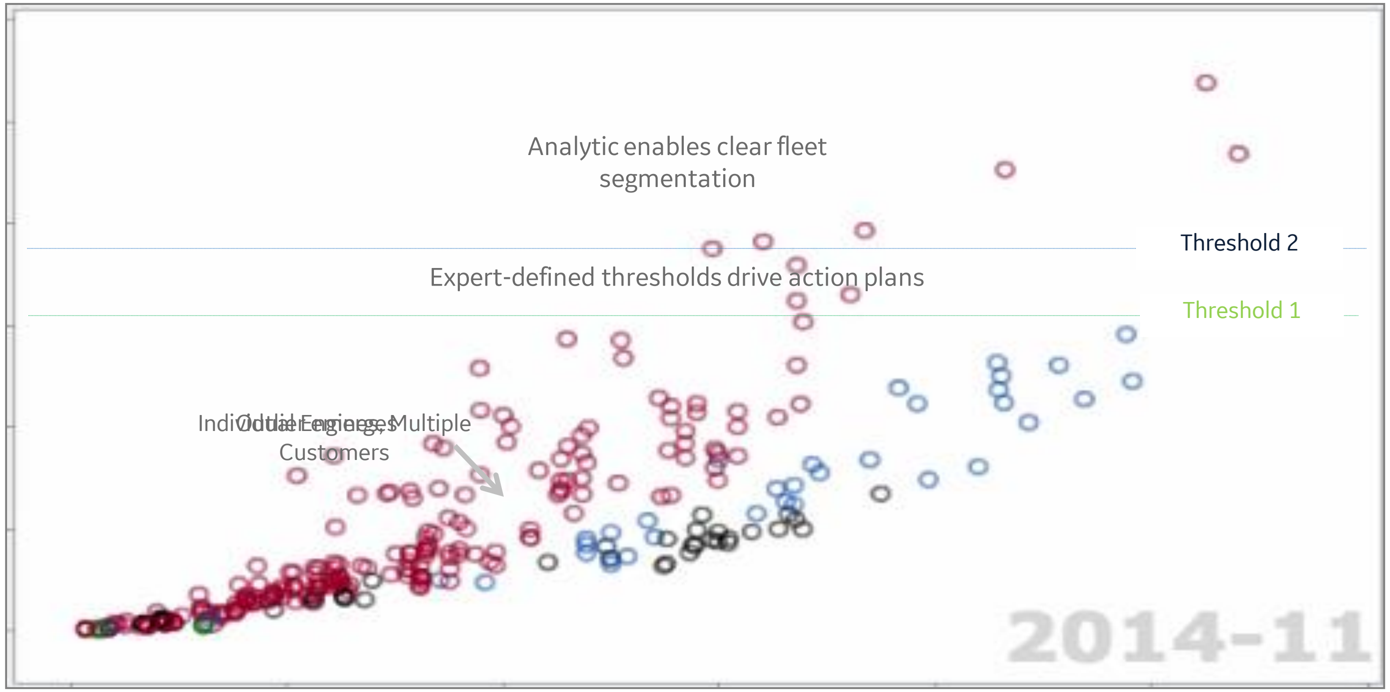
Engine efficiency parameters, environmental data – predict probability of failure

VALUE OUTCOMES

>30 days early warning of compressor issue

Increase customer value …
Improved availability

Continuous damage prediction to manage maintenance schedule



PHYSICAL ASSET

Engine sensor data, S1 Blade Thermal Barrier Coating , etc.

DIGITAL TWIN

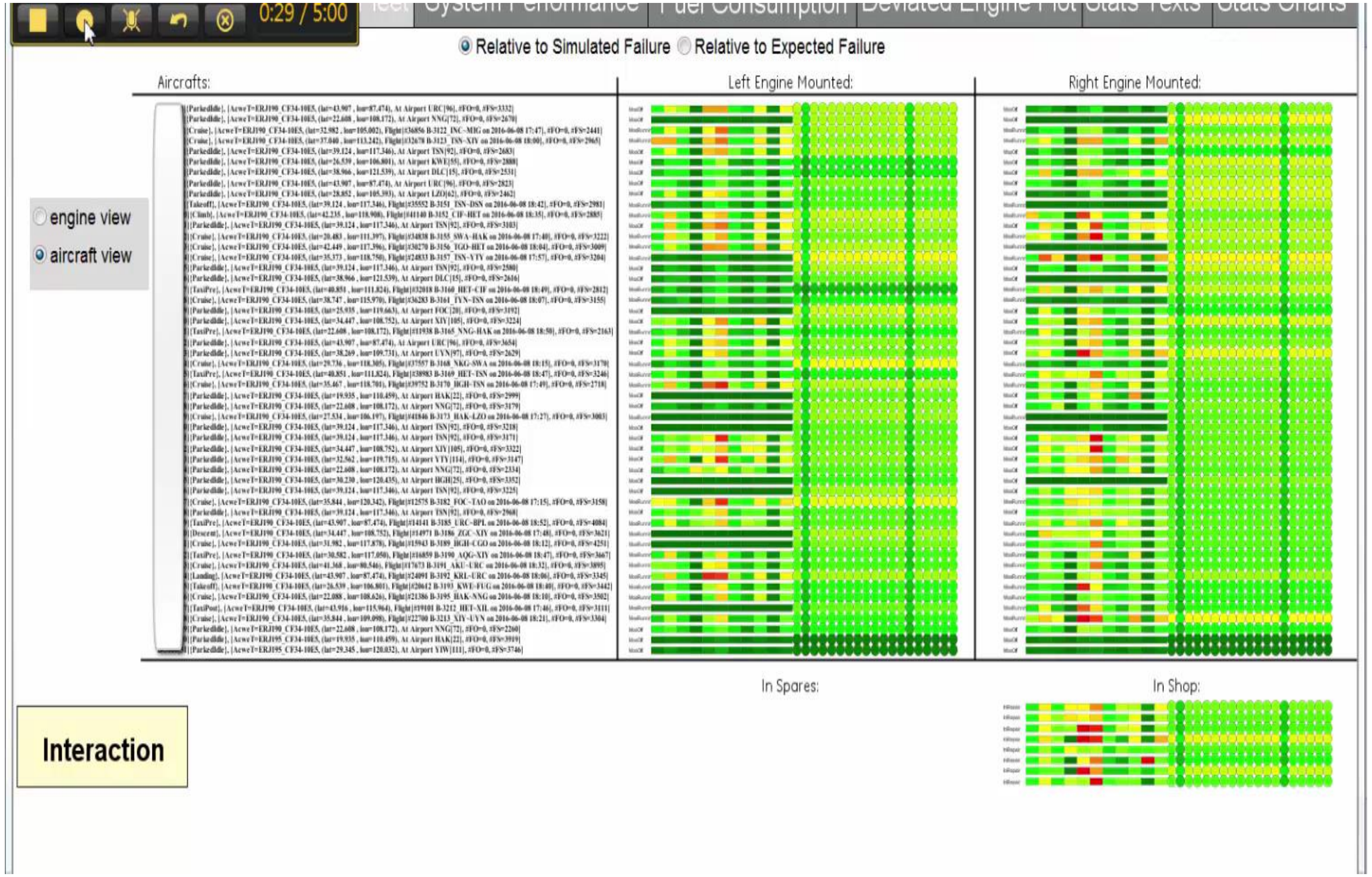
Operating data, and environmental data (cities pairs, hot and harsh values) - predict level of deterioration.

VALUE OUTCOMES

Optimal inspection schedule. **56% planned inspection reduction**

Increase customer value …
Asset utilization and cost

Understand and create fleet conditions for business flexibility



PHYSICAL ASSET AND STATE

Engine life and performance, flight schedules, operator details - thrust, etc.

DIGITAL TWIN

MRO Service data - Simulated 'What-if' Futures: Operations, Spares/MRO TAT, Financials

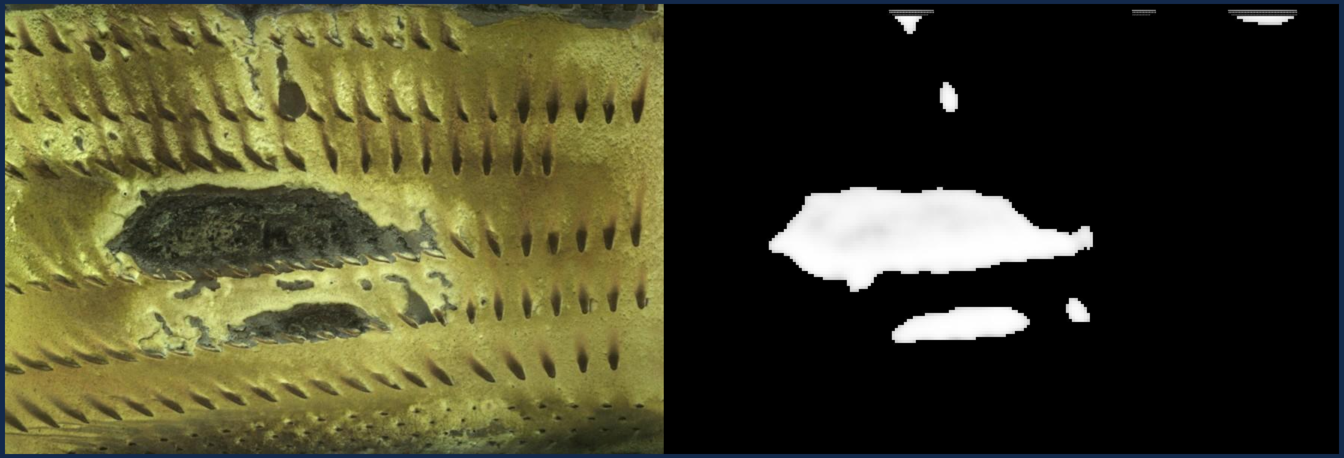
VALUE OUTCOMES

Optimal engine assignment to routes, on-wing operations and MX

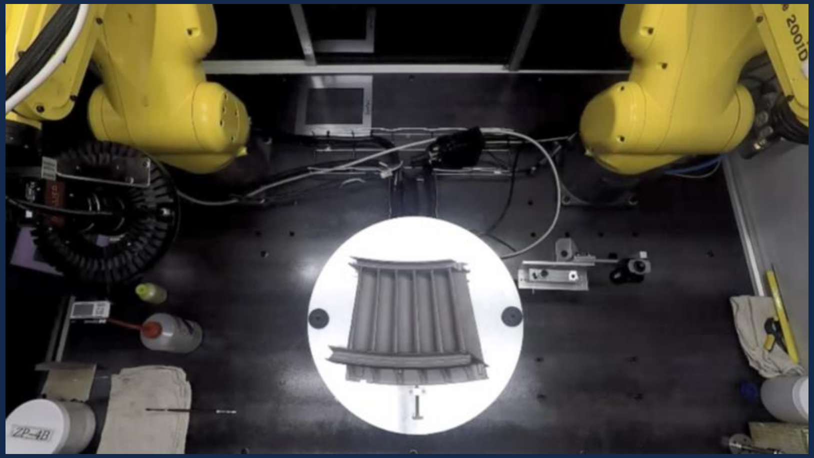
Improving data quality - Intelligent data acquisition

AUTOMATED DATA ACQUISITION TO CREATE AN AI INSPECTION ASSISTANT

Component distress ranking



FPI Robotic inspection in shops



ASSISTANT FOR SCANNING, SORTING, DETECTION, CLASSIFICATION AND REPORTING IN MAINTENANCE

Improving the product – Continuous learning

Continuous learning for service and design

Engine

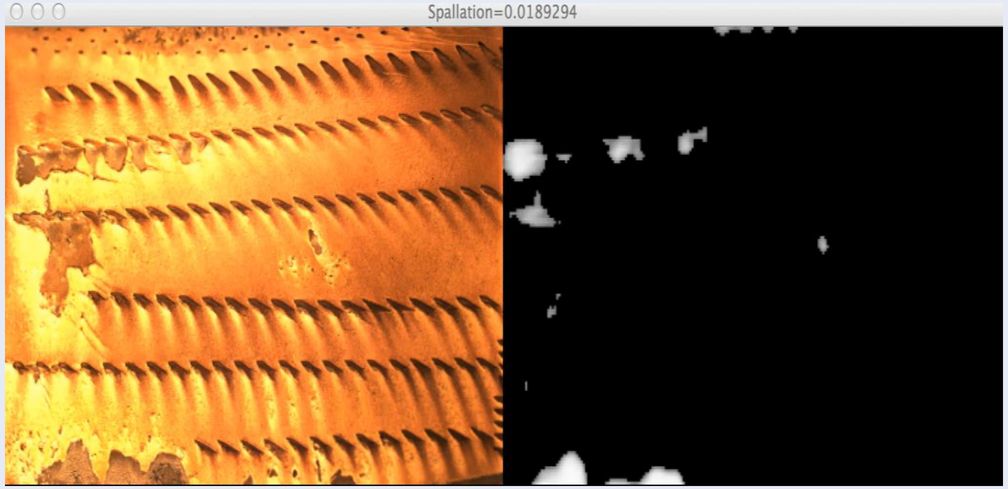
S1 BLADE; TB COATING

Digital Twin

(LIFE PREDICTION)

COATING LIFING

Automated distress ranking



IMPROVE DESIGN

IMPROVE TWIN

CONTINUOUS LEARNING

PHYSICAL+ AI + DATA + COMPUTING SYSTEMS FOR CONTINUOUS IMPROVEMENT

Optimization Digital Twin – 6FA Turbine CC Plant

Plant operational data;
Weather data

Operational set points for
plant optimization

KEY TECHNOLOGIES

Twins (gas turbines, bottoming cycle)
Learning
Optimizer

AUTOMATED OPTIMIZER + TWIN TARGETING 0.5% HEAT RATE IMPROVEMENT

Optimization Digital Twin – Locomotive

Track topology
Locomotive data

DIGITAL TWIN

Optimal speed
and horse power

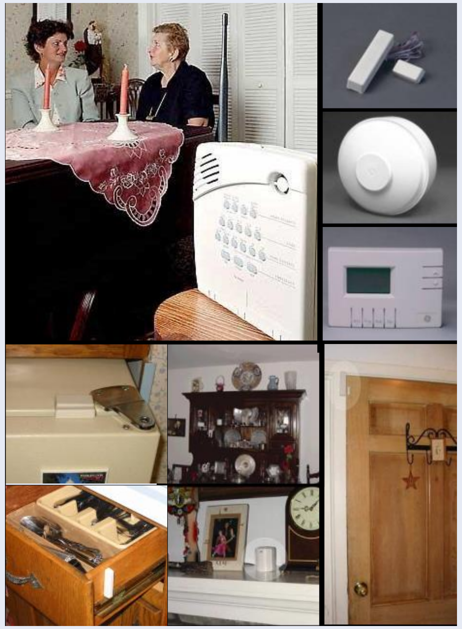
32,000 GALLONS/LOCOMOTIVE-YEAR SAVED
174,000 TONS EMISSIONS REDUCED/YEAR

A HUMAN DIGITAL TWIN EXAMPLE

Home assurance – Providing an elder care solution for caregivers

MISSION

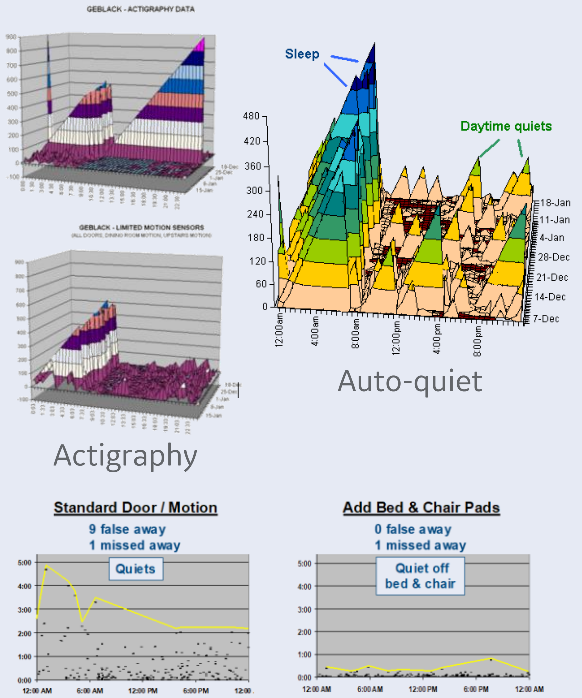
Reducing caregiver stress



1500 days of 24x7 data
10 homes

TECHNOLOGY

Sensor informatics adaptive models



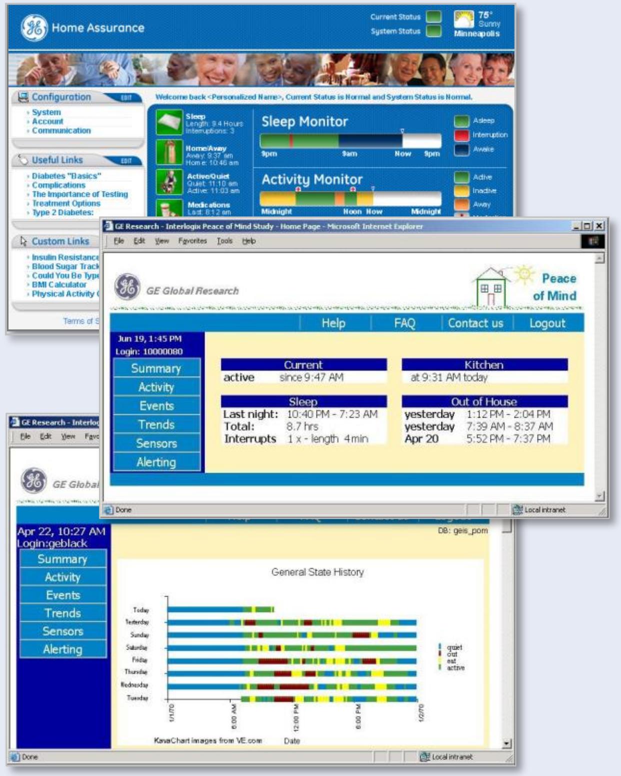
Actigraphy

Auto-quiet

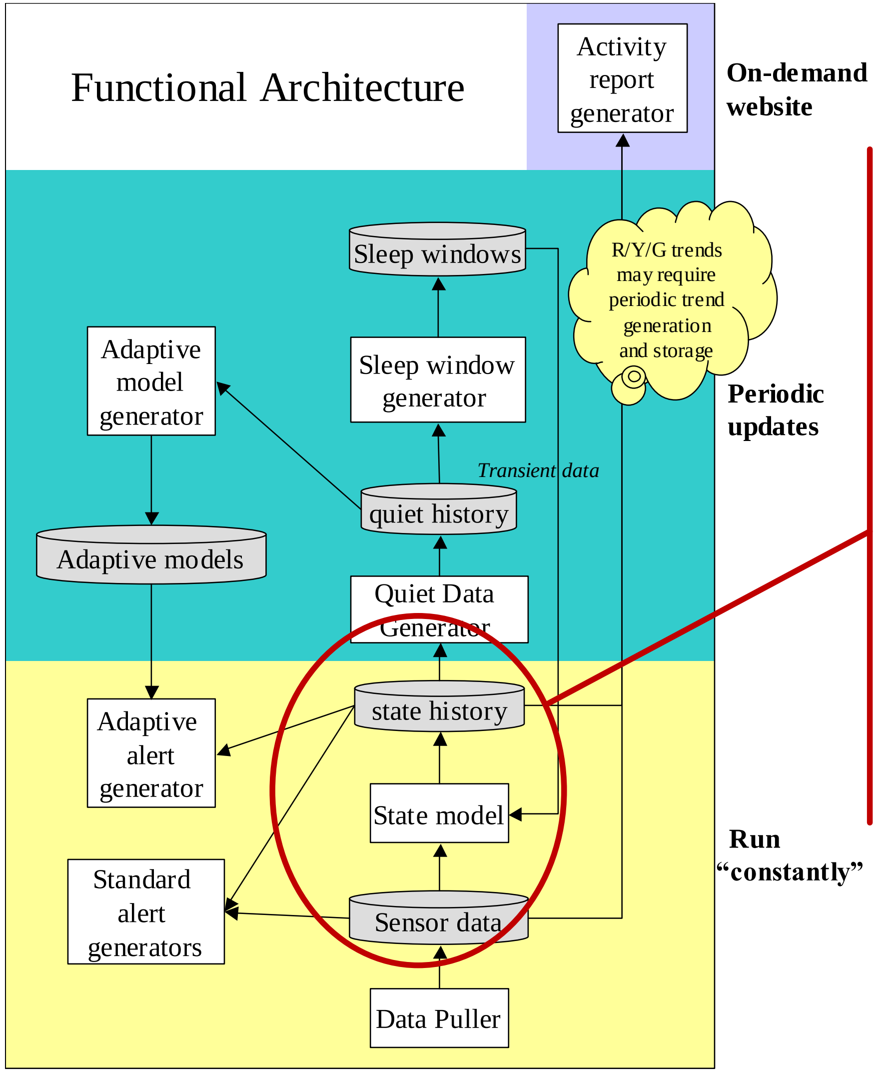
Pressure pads and PIRs

FUTURE

Unobtrusive health monitoring

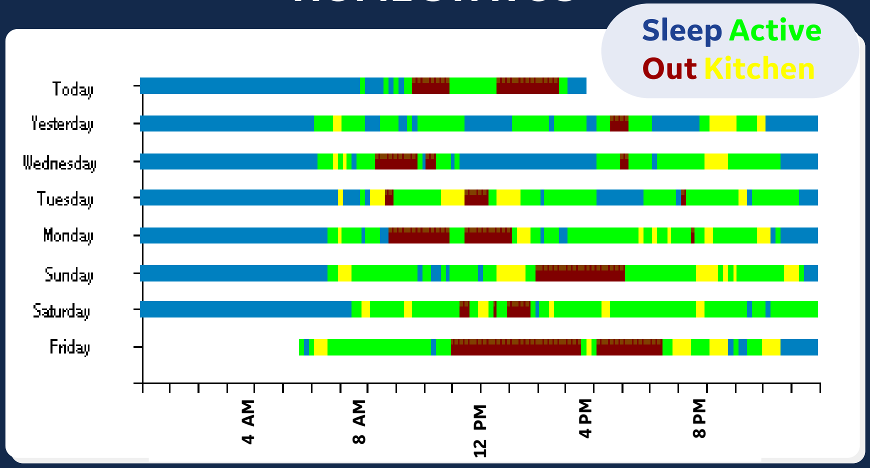


Home assurance algorithms



HOME STATUS DETERMINATION

HOME STATUS



State model

SENSOR DATA

SENSOR	EVENT	DATETIME	ACTIVITY
upstairs motion	opened	2003-05-27 07:31:41	Activity
dining room motion	opened	2003-05-27 07:59:47	
kitchen motion	opened	2003-05-27 08:00:07	
silverware drawer	opened	2003-05-27 08:01:15	Kitchen
silverware drawer	closed	2003-05-27 08:01:32	
upstairs motion	closed	2003-05-27 08:13:37	
dining room motion	closed	2003-05-27 08:16:26	
refrigerator	opened	2003-05-27 08:17:37	
refrigerator	closed	2003-05-27 08:17:52	

Waking up and going to kitchen

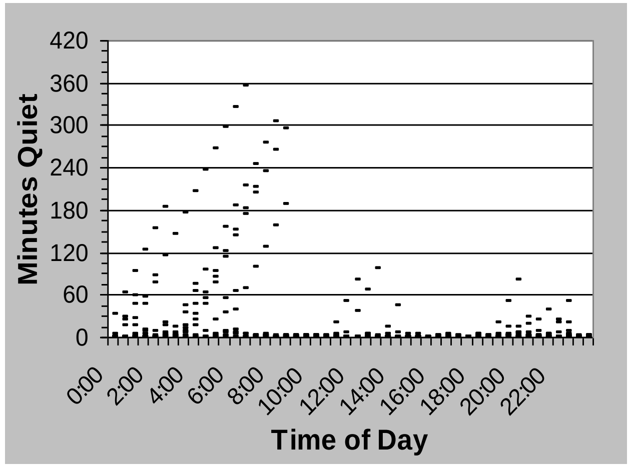
~150 messages/day

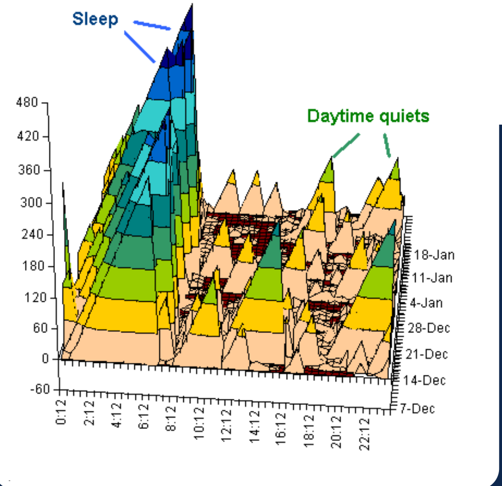
Home assurance algorithms – Automatic inactivity detection

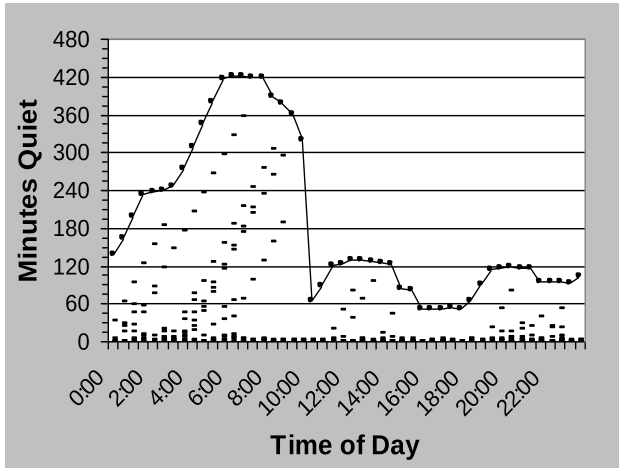
INACTIVITY IS RECORDED AND BINNED INTO INTERVALS.

Date	0:00	...	6:00	6:30	6:00	7:00	7:30	8:00	8:30	9:00	9:30	10:00	10:30	…	23:30
12/1	96	...	251	281	311	25	0	14	44	0	15	3	33	…	42
12/2	52	...	412	442	472	502	12	0	0	2	16	8	0	…	-1
12/3	-1	...	-1	-1	-1	-1	-1	-1	-1	-1	0	2	32	…	45

RECORDING FOR SEVERAL DAYS ENABLES ALERT LINE CREATION.







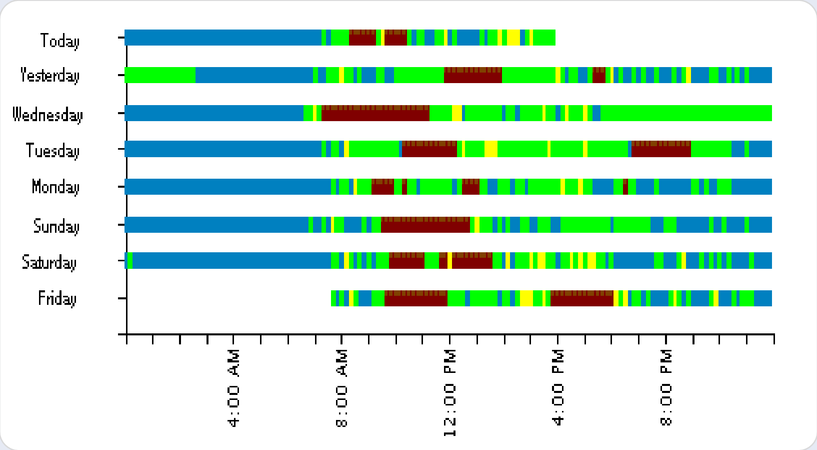
ALERT LINE OPTIMIZED USING 1000+ DAYS OF REAL DATA.

US Patent 7091865. System and method for determining periods of interest in home of persons living independently.

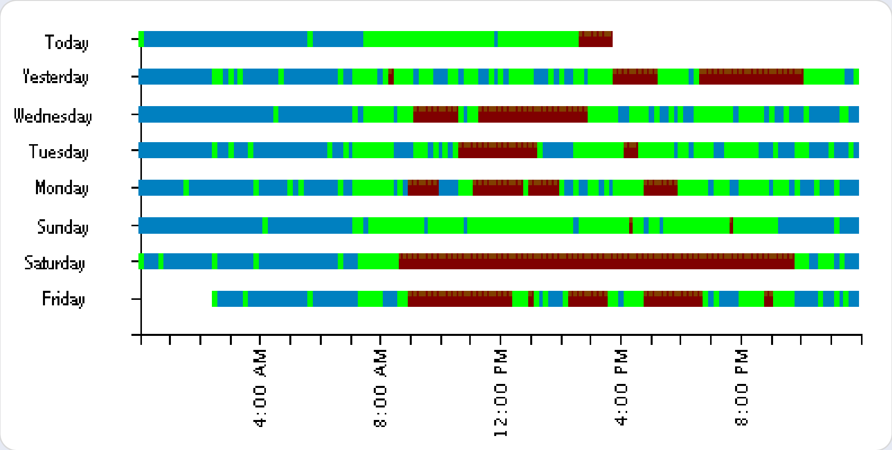
Sleep patterns

ANECDOTES FROM HOME ASSURANCE: PIR MOTION SENSOR PATTERNS SHOW BASIC HEALTH

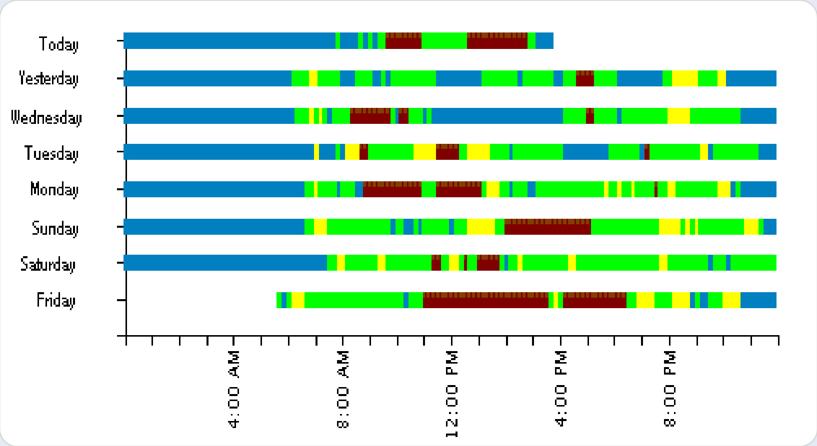
HEALTHY



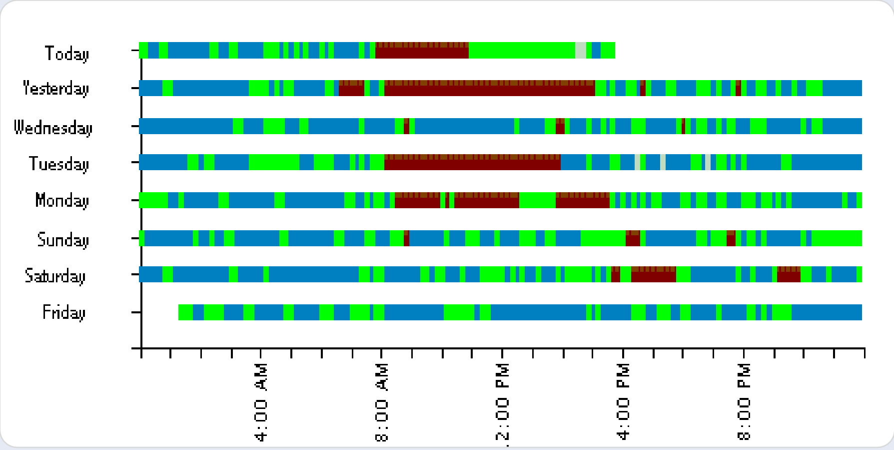
SLEEP DISORDER



HEALTHY



DEMENTIA



The commercial product

Introducing an innovation in proactive care technology

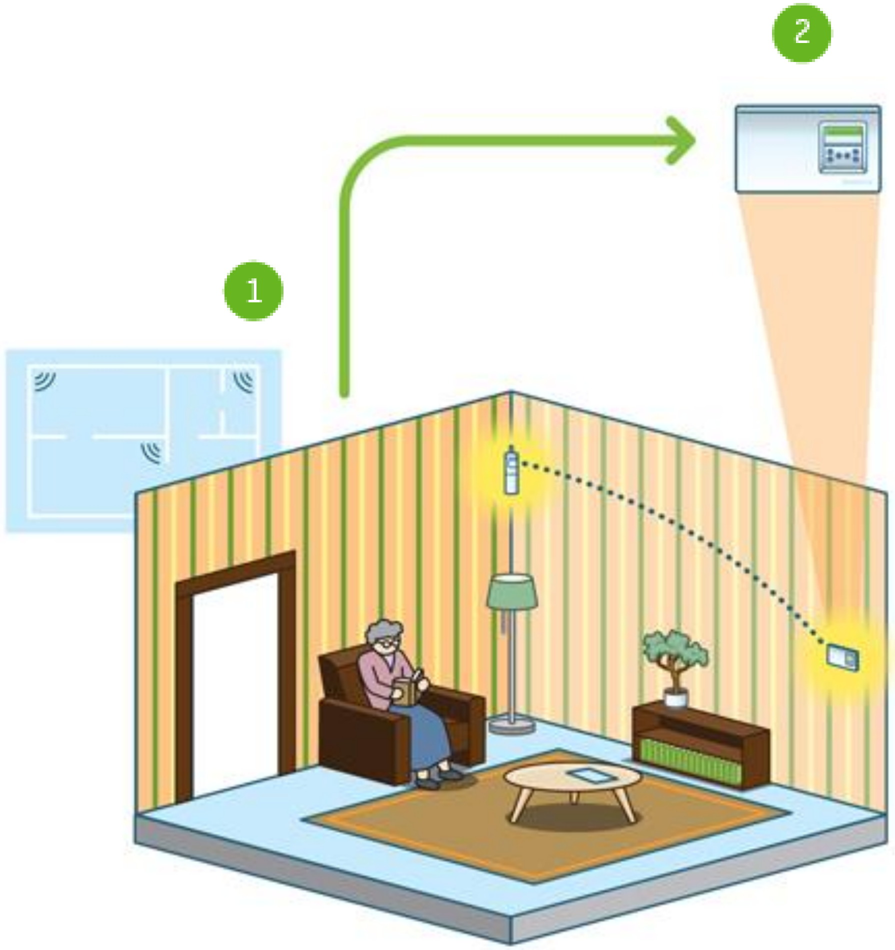
QuietCare®

- Motion sensors vs. cameras
- Learns residents' daily in-home routines
- Sends alerts when out-of-the-ordinary situations occur

How proactive care works

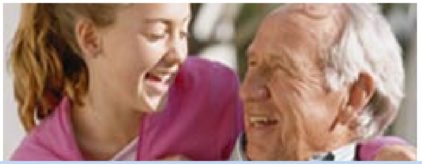
SENSORS ARE PLACED THROUGHOUT THE RESIDENCE TO TRACK DAILY ACTIVITIES.

Sensors transfer resident's data
to a communicator, which then relays he information to the QuietCare server. Powerful software analyzes data and automatically establishes individualized norms.



Data reporting tools to track patients

QuietCare™



HELP LOG OUT Welcome:

02:27 PM on Fri Sep 12, 2008

Current Status Show all active clients

Resident	#	Bedroom Exit	Bath Falls	Meds	Meals	Activity	Night Bath	Bathroom Visits	Door Motion	Room Temp	Client Settings
Anna Marie S	F116										
Ruth D	Vac F117	10:20 AM									
Vita B	F122						0				
Margaret K	F139		06:24 AM								
Daniel R	Vac F140	01:29 PM									
Inez M	Vac F141	09:27 AM									
Helen M	D106				1						
Marguerite H	D107		11:01 AM								
Evelyn Lo	D125	Base station disconnected from phone jack or power outlet, power/phone outage, or phone off the hook.									
Marilyn S	D128		02:16 PM								
Donald W	Vac D133	unknown									

Review Alerts/Actions or Motion Through Door or Client Norms or Client Outcomes for Group AL

Green light means that everything is normal.

Yellow light means that this situation requires monitoring.

Red lights mean that situation requires immediate attention!

Digital Twinning – People and machine differences

PEOPLE	MACHINE
• We don't have all the blueprints	• We have the CAD models
• We make artificial materials	• We make the materials
• Many confounding factors	• Fewer confounding factors
• Very limited sensor data	• Massive sensor data
• Understand little about environmental exposure	• Environmental exposure can be tracked
• People are unpredictable	• Machines are more deterministic

EACH PERSON IS MUCH MORE UNIQUE THAN INDIVIDUAL MACHINES. UNDERSTANDING THE TRANSFER FUNCTIONS IS MUCH HARDER FOR PEOPLE. THE BOUNDARY CONDITIONS HAVE MORE VARIANCE.

Digital Twinning of humans – Possibilities, Benefits, and Implications

POSSIBILITY

- Basic biometrics
- DNA Analysis
- Real-time Control
- Addiction Control
- Redesign Parts

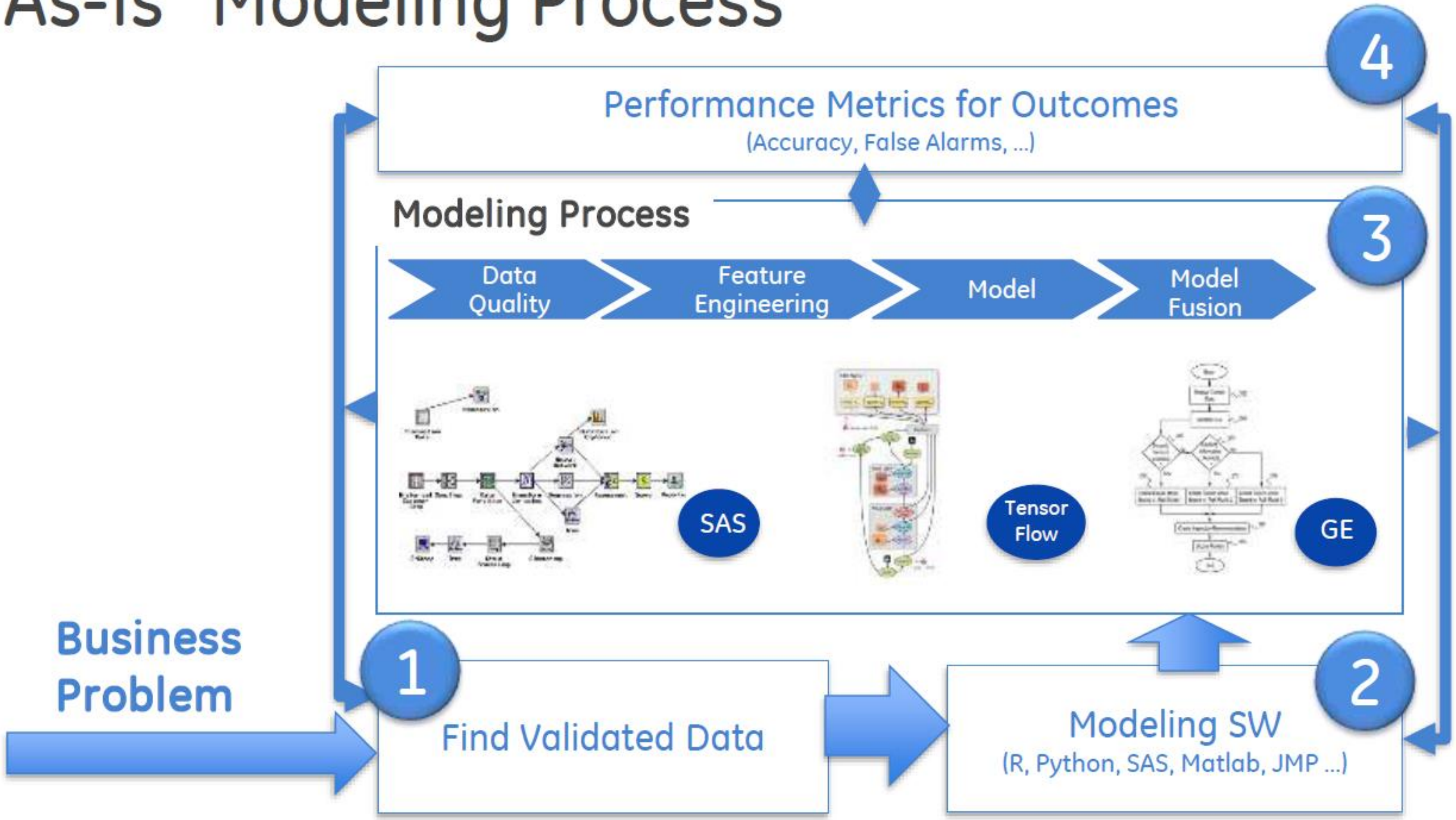
BENEFIT

- Heart attack and stroke remediation
- Disease prediction
- Human performance enhancement
- Prevent overdoses
- Increased Quality of Life

The Technical Possibilities Can Outpace Our Regulatory Development.
There Are Also Economic Consequences that Are Not Understood.
Do We Mess With Evolution?

TUTORIAL:
HOW TO BUILD A DIGITAL TWIN

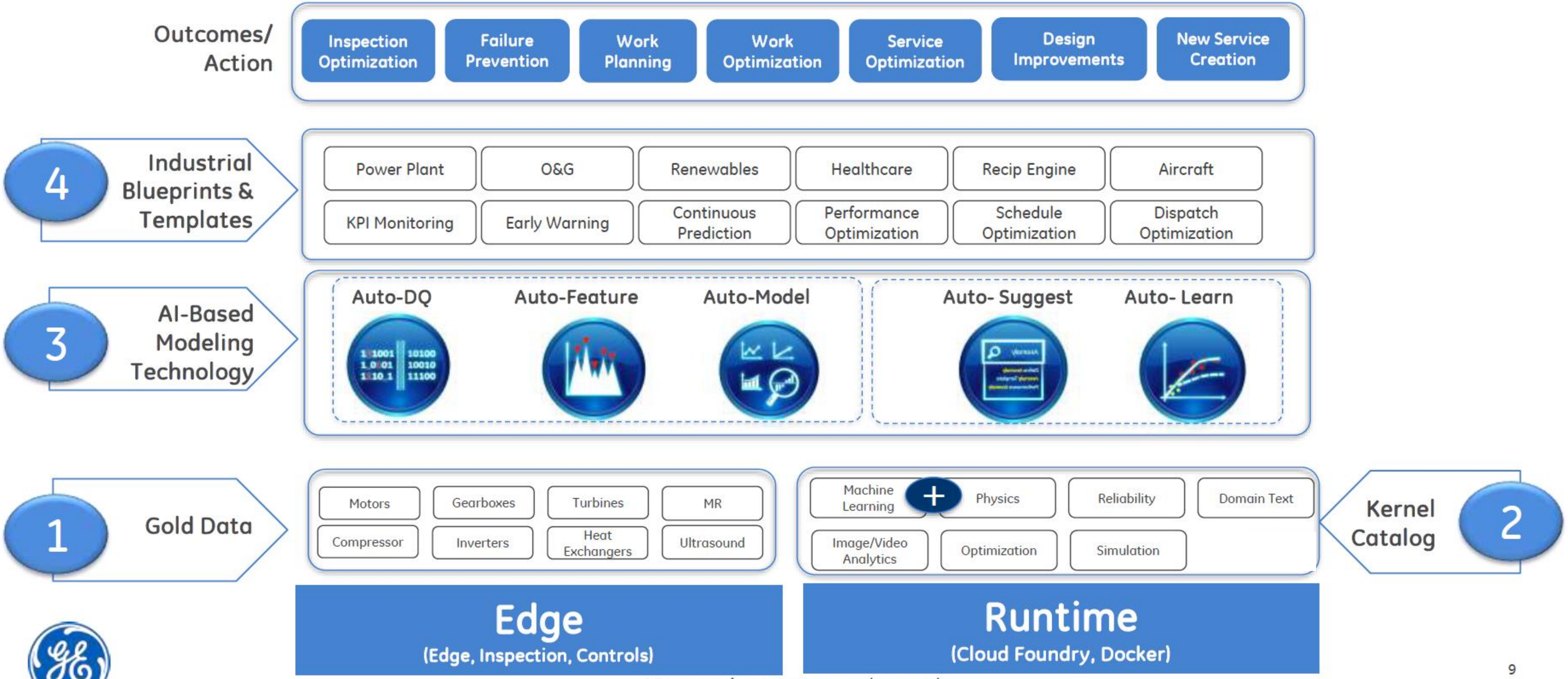
Digital Twin Technologies – Why?
"As-Is" Modeling Process



Too Much Iteration, Validation Data Difficult to Get, Little Sharing, Scaling Difficult

Digital Twin Framework - Technologies

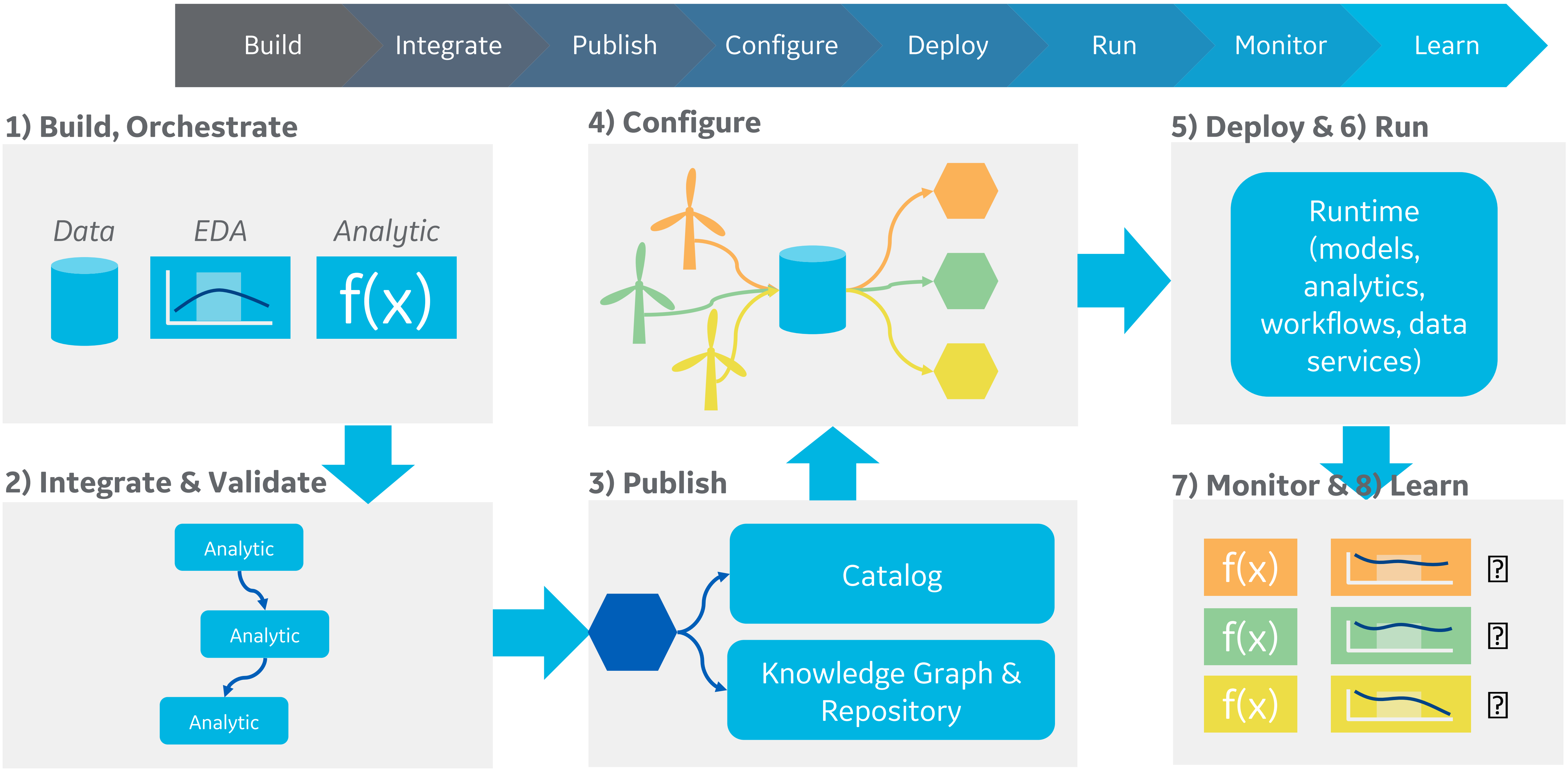
Driving Speed, Scale, Accuracy & Differentiation



Steps to Build a Digital Twin

1. Decide the business outcome you are trying to change. Start with your Pareto of Pain.
2. Determine the model(s) that need to be built.
3. Build the team that builds, feeds, and validates the model.
4. Identify the data need to build, train, and validate the model.
5. If the model does not meet the need, determine why not. Is proper data unavailable?
6. Determine computing requirements.
7. Build process for model operationalization.

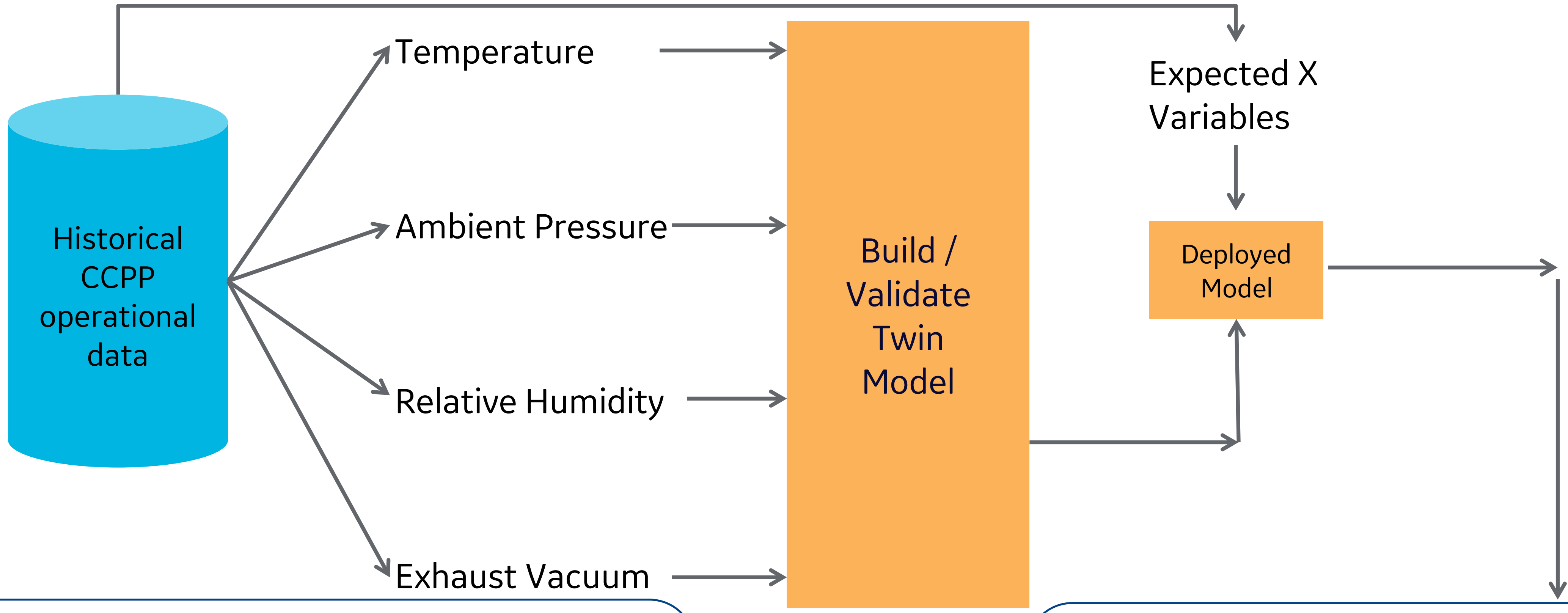
Digital Twin Build, Run, & Manage Process



Digital Twin Example: Combined Cycle Power Plant (CCPP) Output Prediction

Build a Digital Twin for a particular CCPP that predicts the Power Output using using public data from: http://archive.ics.uci.edu/ml/datasets/Combined+Cycle+Power+Plant

Digital Twin Build for Output Prediction



Training Data

Temp	ExhaustVacuum	AmbientPressure	RelativeHumidity	EnergyOutput
9.44	40	1015.62	81.16	471.32
23.49	49.3	1003.35	77.96	442.76
4.99	39.04	1020.45	78.89	472.52
18.24	58.46	1017.38	86.92	449.63
27.49	63.78	1015.43	47.45	445.66
13.61	41.16	1020.49	75.09	462.67

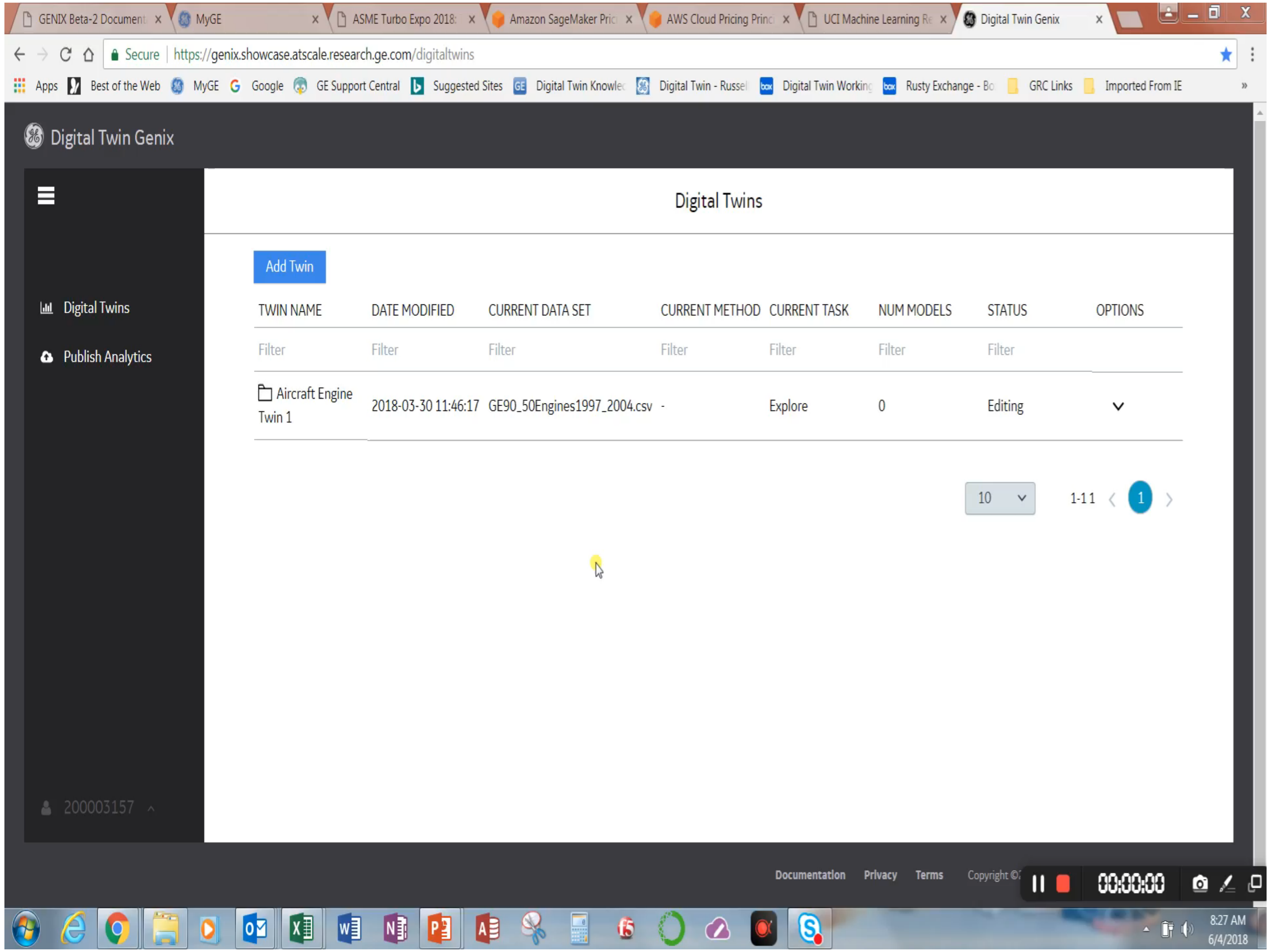
Regression Model

- Lasso Regression
- R-squared 0.958
- Correlation 0.98

Power Predictions

Temp	AmbientPressure	RelativeHumidity	ExhaustVacuum	EnergyOutput_predicted
23.25	1008.05	71.36	71.29	438.7847826
13.87	1007.45	81.52	42.99	466.6762397
16.91	1013.32	79.87	43.96	462.0567857
10.09	1012.99	72.59	37.14	475.563
12.72	1013.45	86.16	40.6	471.8331579
17.77	1020.11	81.51	52.9	456.9463333

Combined Cycle Power Plant (CCPP) Output Prediction Demonstration



Hot Intake Manifold Prognosis (EVO/FDL Locomotives)

(Modular Workflow)

Hot Manifold Prognosis: Objectives

Asset

Locomotives (models EVO & FDL)

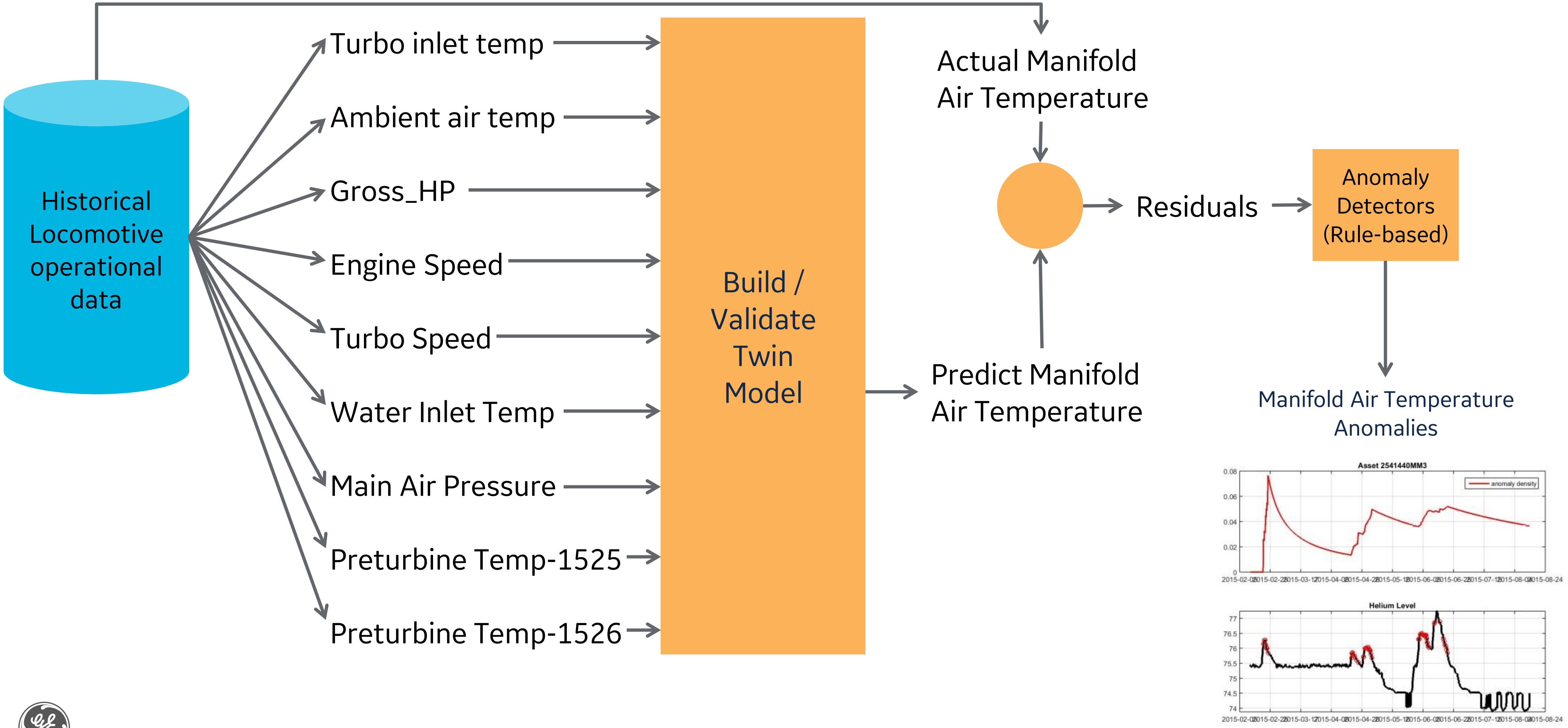
Objective

- Develop a model to proactively predict road failures due to rise in manifold air temperatures.
- Reduce the unscheduled outage & increase the availability to customers.
- Increase coverage of existing RX while ensuring an accuracy of ~90%.

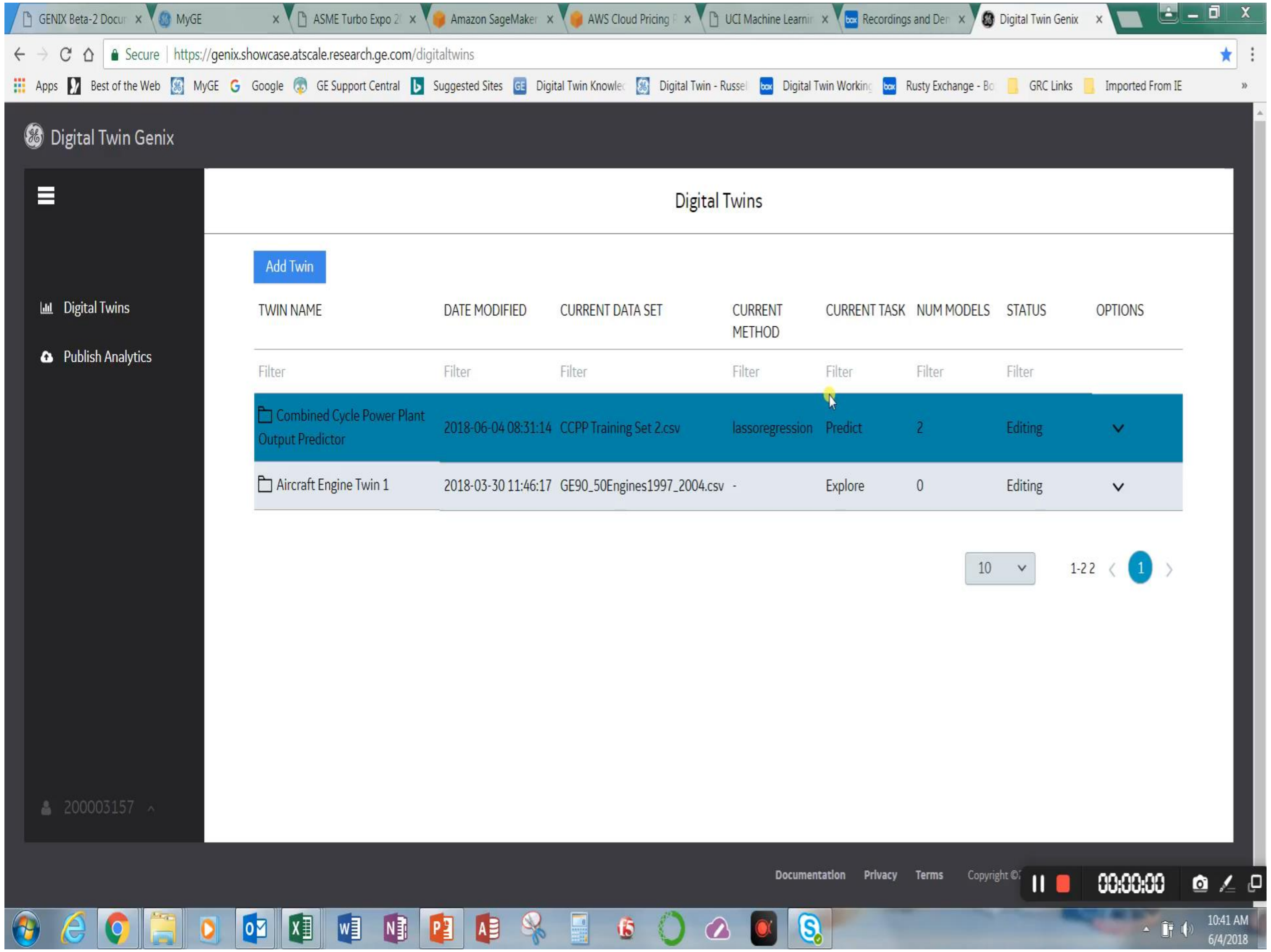
Business Impact

- 55 mission failures EVO Tier 2 & 3 cooling system for year 2016
- 66 mission failures for 2015
- $15K average cost incurred by customer for each failure

Digital Twin Build for Detection



Locomotive Hot Manifold Anomaly Detection Demonstration



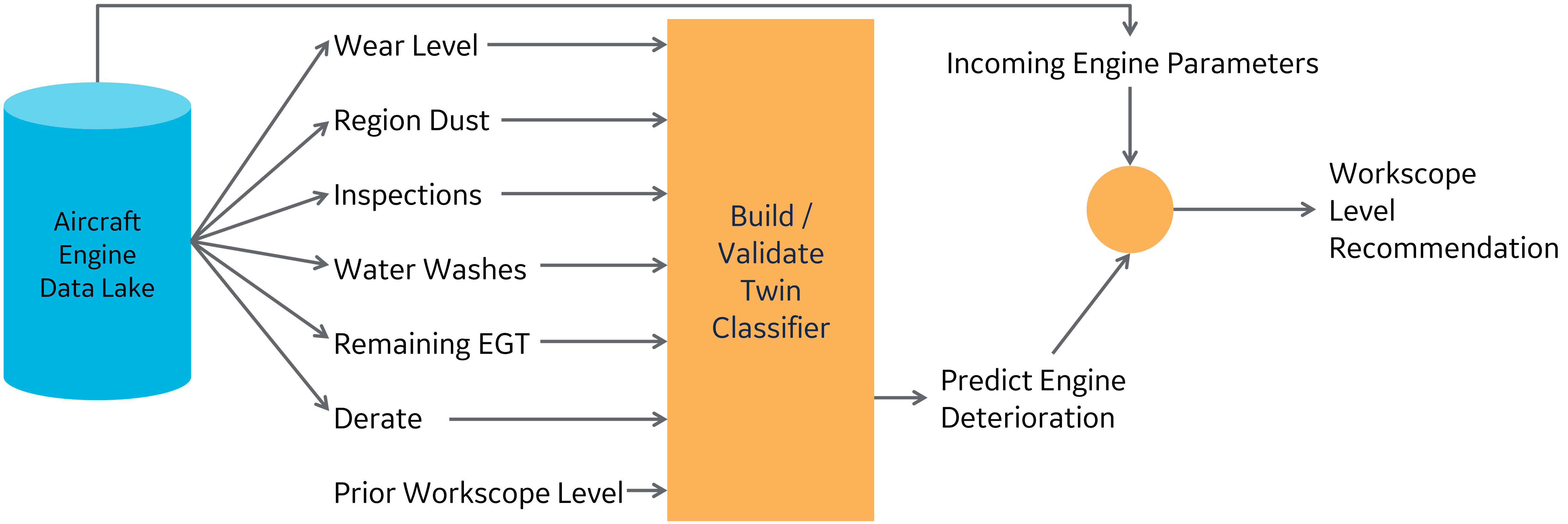
Aircraft Engine Overhaul Level: A Classification Example

Asset
Aircraft Engine

Objective
Develop a model to predict the overhaul level: Light, Medium, Heavy

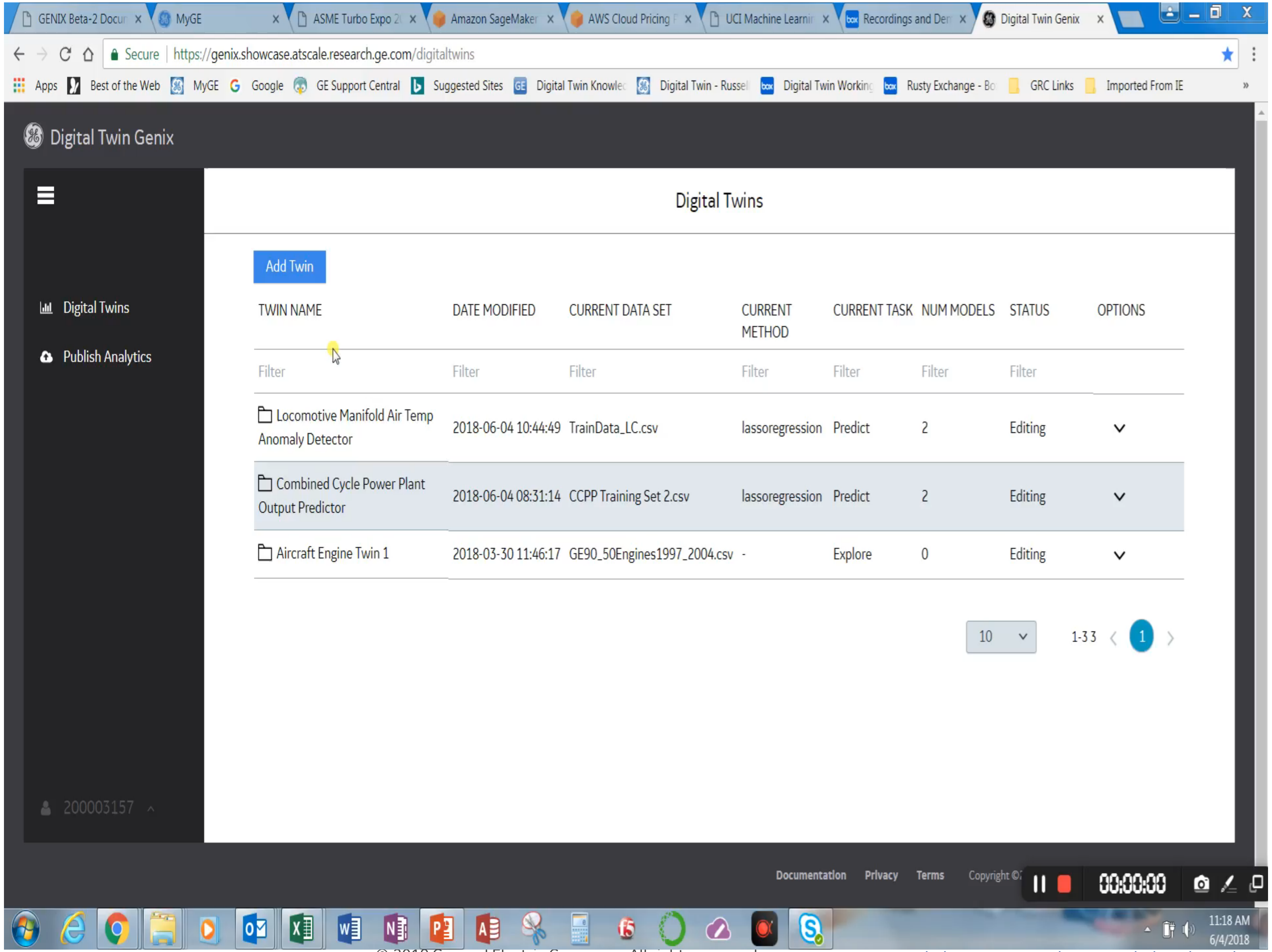
Business Impact
Keep overhaul Turn-Around-Time low by anticipating parts needed based on recommended workscope level

Digital Twin Build for Overhaul Classification



Wear Level	1=vhigh, 2=high, 3 =med, 4=low
Region Dust	1=vhigh, 2=high, 3 =med, 4=low
Inspections	2, 3, 4, 5 (# of inspections)
Water Washes	2, 4, 5 (# of washes)
Remaining EGT	small, med, big
Derate	Low, Med, High
Prior Workscope Level	heavy, med, low

Aircraft Engine Workscope Classification Demonstration



Considerations on Building Digital Twins