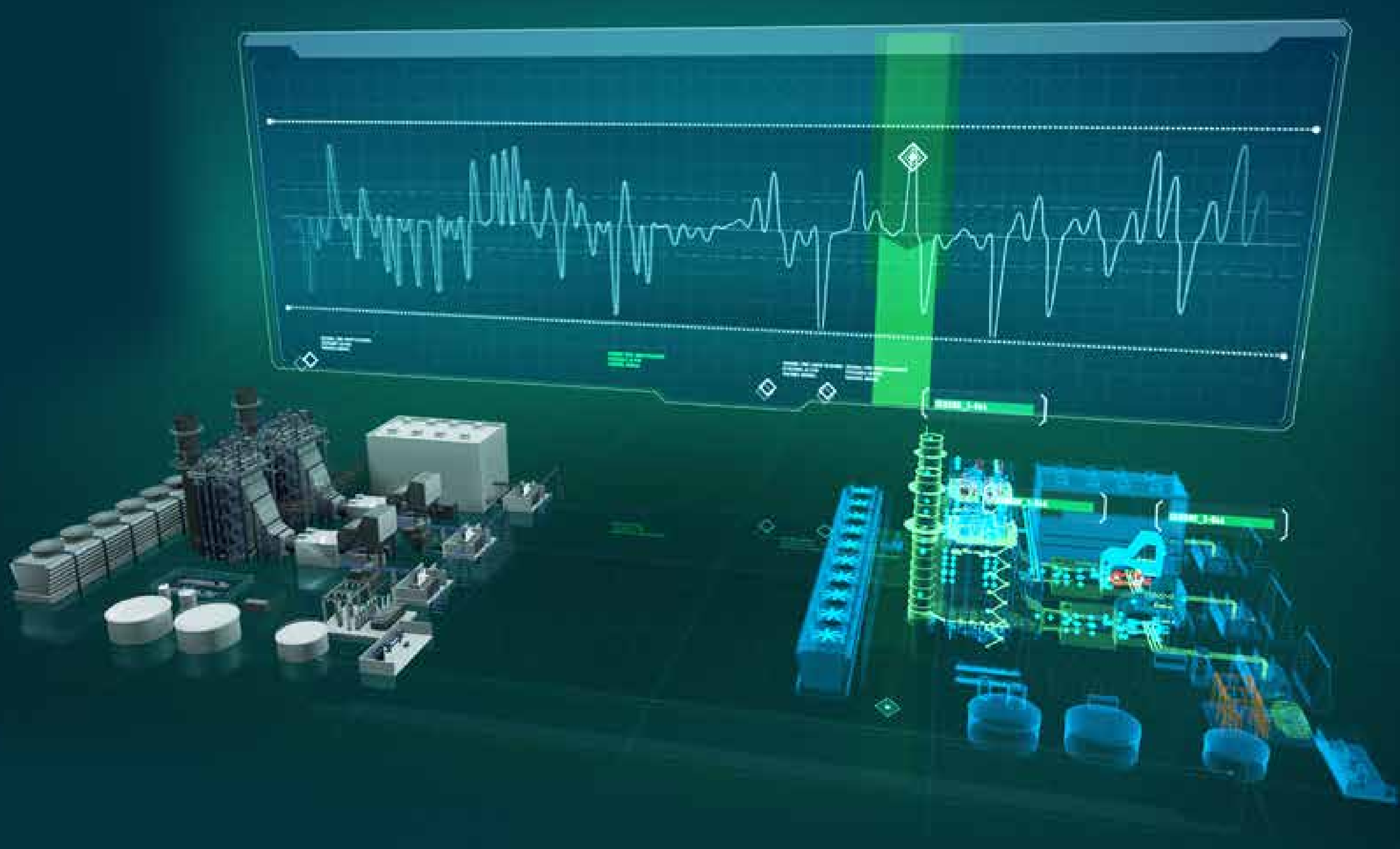
GE Digital Twin

Analytic Engine for the Digital Power Plant



GE Power Digital Solutions

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1. Introduction

Power leaders globally are constantly seeking opportunities to improve operations, reduce unplanned outages and manage variations in market conditions, fuel costs and weather patterns toward greater profitability. However, point solutions have taken operations efficiency only so far. What's needed is a comprehensive answer, grounded in analytic science, that gives power companies the means to transform operations with actionable insights that drive improved business decisions.

Digital Twin is an organized collection of physics-based methods and advanced analytics that is used to model the present state of every asset in a Digital Power Plant. The models start by providing guidance on "design limits" of a power generation unit at the commissioning stage or inferring the design limit for an existing plant/fleet by matching the equipment to thousands of other similar equipment in the database.

Included in the Digital Twin models are all necessary aspects of the physical asset or larger system including thermal, mechanical, electrical, chemical, fluid dynamic, material, lifing, economic and statistical. These models also accurately represent the plant or fleet under a large number of variations related to operation — fuel mix, ambient temperature, air quality, moisture, load, weather forecast models, and market pricing. Using these digital twin models and state-of-the-art techniques of optimization, control, and forecasting, applications can more accurately predict outcomes along different axes of availability, performance, reliability, wear and tear, flexibility, and maintainability. The models in conjunction with the sensor data give the ability to predict the plant's performance, evaluate different scenarios, understand tradeoffs, and enhance efficiency.

As the plant is operated, the Digital Twin **continually improves its ability to model and track the state of the plant.** The Digital Twin allows plant operators to optimize the instantaneous and transient control of the plant for efficiency or performance, make informed decisions regarding performance versus part life, assign loads and lineups through time, and perform the right maintenance tasks at the ideal time.

By implementing a Digital Twin, power leaders suddenly have the capability to balance and optimize trade-offs between important factors over which they prior had minimal visibility or control. The dispatcher sees a much bigger picture, giving them the confidence to make calculated commitments to dispatching energy without unforeseen maintenance or wasted fuel. The Digital Twin will allow "what-if" scenarios to be tested against business objectives creating the most informed decisions possible.

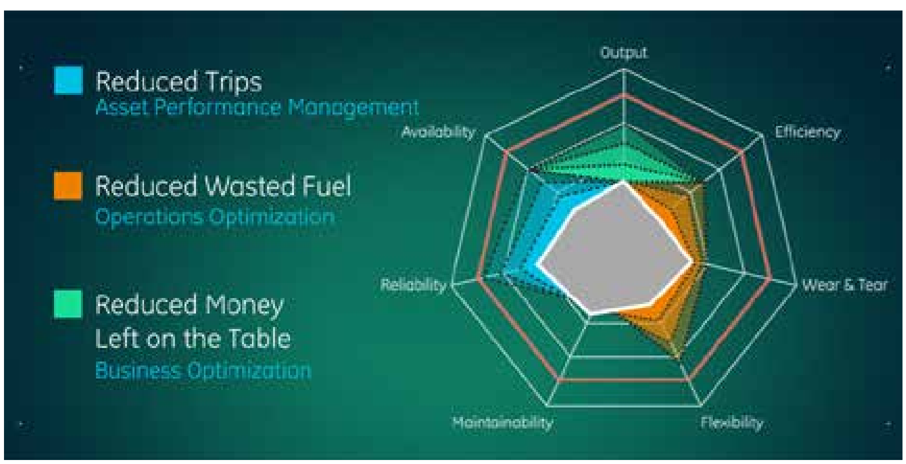


Figure 1: Trade-offs for Business Benefits

GE has created the most advanced and functional Digital Twin that integrates analytic models for components of the power plant that measure asset health, wear and performance with customer defined KPIs and business objectives. The Digital Twin runs on an industrial platform, Predix™, designed to ingest massive volumes of machine sensor data, to manage and execute analytic models, to run a high speed business rules engine and to manage industrial data at scale. Further, this environment is integrated with business applications designed to allow plant executives, plant managers and workers to interact with the Digital Twin in real time.

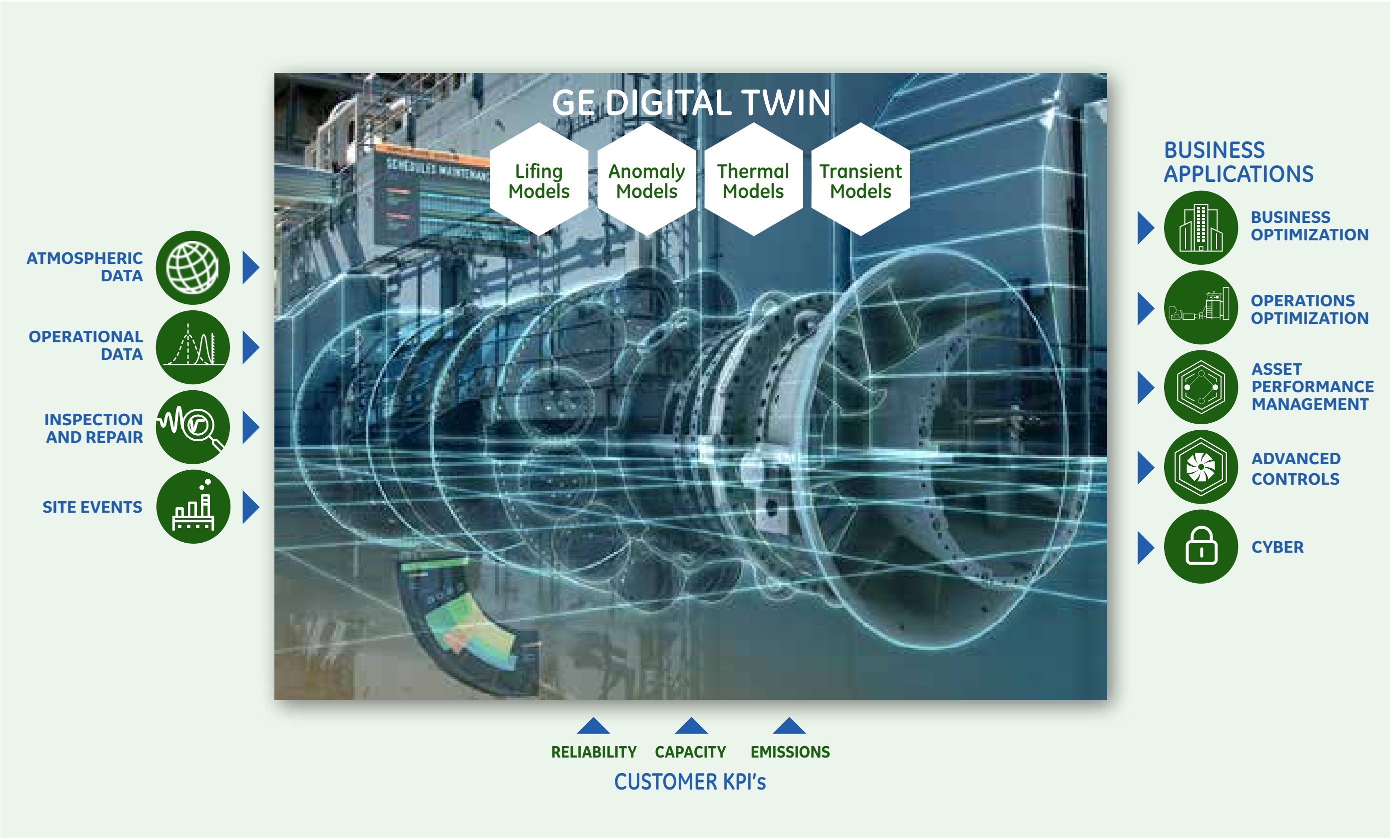


Figure 2: GE Digital Twin

Business applications, shown in the figure above, tied to the Digital Twin provide the window of interaction to take action on insights, to manage the power plant and generation fleet functions to a greater level of control and to be able to react to changing market, fuel price and weather conditions in rapid fashion. These business applications are designed to increase asset performance, enhance operations, and improve energy trading decisions to create additional revenue and cost reduction opportunities. The applications fall into the following categories:

Asset Performance Management (APM): Transform data into actionable intelligence by combining robust analytics with domain expertise. Create a single source of data for all power generation or renewables assets across a fleet, utilizing predictive analytics to identify issues before they occur, reducing downtime and extending asset life while still balancing maintenance costs with operational risk.

Operations Optimization: Deliver enterprise data visibility across power plant and fleet-wide footprints, providing a holistic understanding of the operational decisions that can expand capabilities and lower production costs. Empower operators and plant managers with KPI driven insights to raise overall productivity.

Business Optimization: Reduce financial risk and maximize the real potential of the power fleet toward greater profitability with intelligent forecasting for smarter business decisions.

Advanced Controls/Edge Computing: Control power plant operations with advanced technologies. Analytics based solutions manage grid stability, fuel variability, emissions, compliance and other challenges to reduce costs and maximize revenue.

Cyber: An advanced defense system designed to assess system gaps, detect vulnerabilities, and protect critical infrastructure and controls in compliance with cyber security regulations.

Digital Twin Application Suite: A set of applications interfacing with Digital Twin analytic models and application capabilities of Asset Performance Management, Operations Optimization, Business Optimization and Advanced Controls to bring insights and actions together for business benefits.

The Predix Platform, on which the Digital Twin and business applications run, is a proven industrial environment. Cloud (public or private) based capabilities are closely integrated with an on-premise Predix Machine and Edge Analytics Control System, responsible for collecting, formatting and sending machine data and for executing machine level analytics where real-time responses are required on site. Predix is specifically designed for massive data ingestion, housing and executing analytic models, managing time-series machine data and high speed application execution. The environment, from Supervisory Control and Data Acquisition (SCADA) systems through Predix Machine to cloud and back is a highly secured environment, locked down with the same cyber technology GE has installed in industrial operations globally.

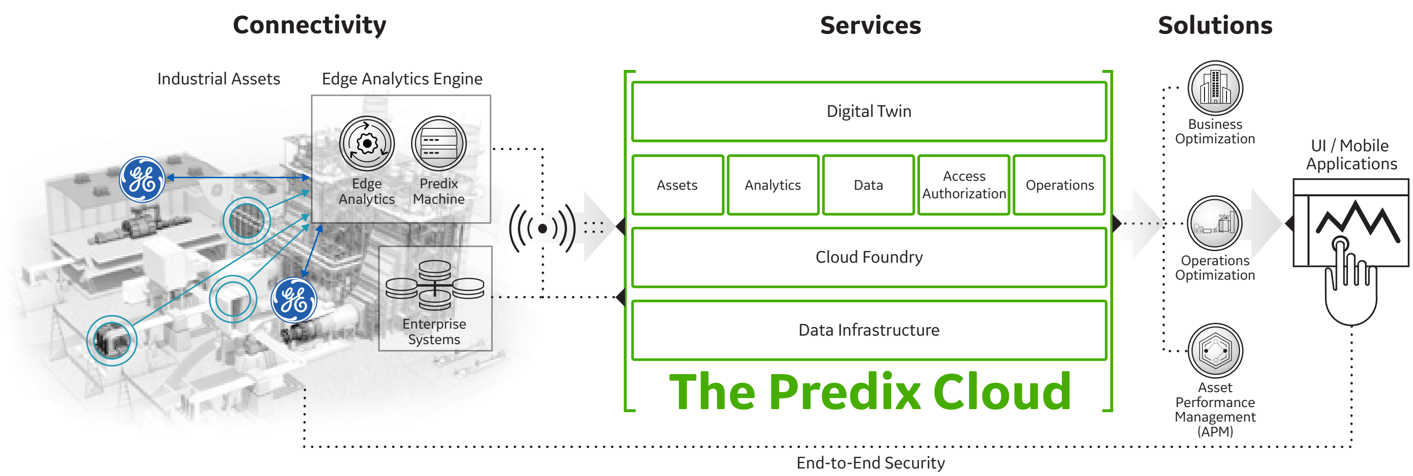


Figure 3: Predix Platform

1.1 GE Digital Twin Analytic Overview

At its core, the Digital Twin consists of sophisticated models or system of models based on deep domain knowledge of specific industrial assets. The Digital Twin is informed by a massive amount of design, manufacturing, inspection, repair, online sensor and operational data. It employs a collection of high-fidelity computational physics-based models and advanced analytics to forecast the health and performance of operating assets over their lifetime. The integration of these models in the Digital Twin and associated business applications is shown in Appendix A.

The **Lifing Digital Twin** is able to assess each asset within the plant and how that asset will age relative to its operation and exposure. Fatigue, stress, oxidation and other phenomena are predictable using this Digital Twin and help optimize the maintenance vs. mission reliability of each asset as well as the entire operating system.

The **Anomaly Digital Twin** uses physics and data-based prognostic models to detect faults for improved asset failure mode management and reduced unplanned downtime. Using fusion techniques with Lifing models, anomaly models can increase the accuracy of production machine life curves and further personalize maintenance needs.

The **Thermal Digital Twin** determines thermal efficiency, plant capacity, and emissions prediction as well as simulation of all of parameters that can affect these outcomes. The technology can be used on all thermal cycles from combined cycle and fossil to cogeneration and district heating. The technology is OEM agnostic and can provide precision to all brands of power plants. However, it best enhances GE-based power plants by integrating with GE's own asset models.

The **Transient Digital Twin** can simulate the plant's ability to react to changes in environmental or control shifts. This would include startup, ramp rate, minimum generation, and regulation performance. The Digital Twin will provide insights into speed, stability, emissions, and stresses as well as predict the limitations of the plant with configuration and operational changes.

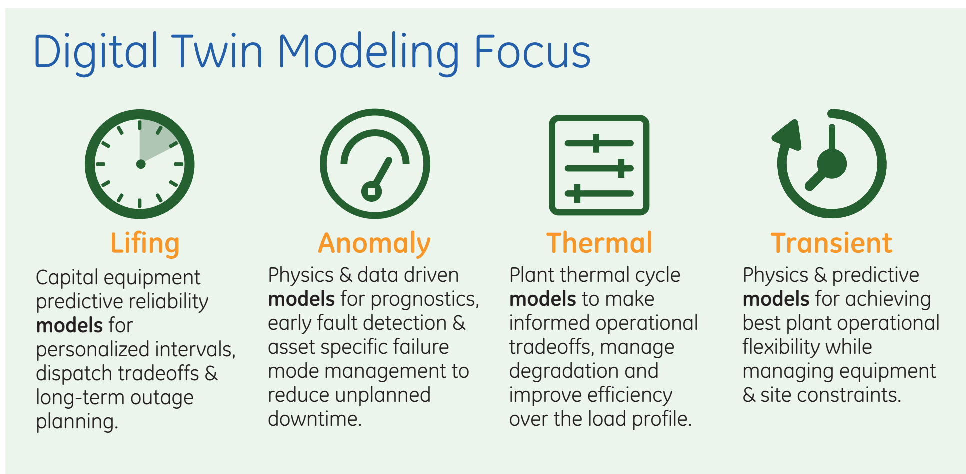


Figure 4: GE Digital Twin Model Categories

1.2 Attributes of GE Digital Twin

GE Digital Twin offers the advantage of incorporating deep domain knowledge garnered over years of production and operations history. Decades of GE research, design, test and operational experience are built into the Digital Twin models. For example, thermodynamics of the individual assets such as gas turbines, steam turbines, generators and even the entire power plant systems are used as core building blocks. Further, GE understands the materials and manufacturing systems used to create GE assets. This knowledge is then used to create detailed part life in Digital Twin that drives reliability and availability.

GE offers additional "dimensionality" or "control knobs" to be used to improve the performance of the asset or system modeled with GE Digital Twin. The fundamental physics of GE systems is built into GE Digital Twin; the steady-state and dynamic behavior and how best to deliver the desired outcome. The footprint of GE Digital Twin extends into the embedded control layer. No other supplier can develop to this level of insight and capabilities for GE assets.

Finally, because GE has built the Digital Twin for multiple industrial segments, cross-integration of technology is a part of the development environment. For example, a sophisticated mathematical process used to tune a thermodynamic model in an aircraft engine Digital Twin is now being investigated for keeping a power plant model up to date with the latest field data. Additionally, GE is investing in powerful analytics used to check data being fed into Digital Twin models and impute or calculate missing sensor values. This capability is fundamental to Digital Twins across all our industrial segments.

The Digital Twin is used to create demonstrable business value along several axes:

Individual: The Digital Twin is applied to individual assets, tracking history and performance over the asset's lifetime.

Adaptable: The Digital Twin infrastructure and models are adaptable. For example, they can transfer to another part or asset class, or adapt to new scenarios or new factors.

Continuous: The Digital Twin models are continuously updated as the physical asset is operated. At any moment the Digital Twin represents a faithful representation of the current state of the asset; the output of the model changes with every fuel burn hour.

Scalable: Benefit is derived when hundreds or thousands of like assets have a Digital Twin. A Digital Twin tracking a single asset learns from similar assets.

2. Examples of Digital Twin Applications

Applications built using the Digital Twin gather information from multiple models and contain advanced solver algorithms to achieve the best possible economic outcomes for power plant processes. The GE Digital Twin is integrated into the business applications of Asset Performance Management, Operations Optimization and Business optimization, providing the integration between the Digital Twin models, advanced technologies and the user facing business applications as follows.

Business Applications Enabled by Digital Twin

		Asset Performance Management			Operations Optimization				Business Optimization	
		Equipment Health	Reliability Management	Maintenance Optimization	Operational Flexibility	Thermal Performance	Dispatch Optimization	Outage Management	Portfolio Planning	Optimal Outage Planning
Digital Twin Model Type	Lifing			• Asset Maintenance Strategy	• Operational Excellence (OE) • Plant Start Optimizer • OpFlex Solutions		• Plant Dispatch Optimizer • Plant Dispatch Excellence	• Plant Maintenance Management • Plant Asset Life Optimizer	• Load Forecasting • Fleet Dispatch Excellence	• Enterprise Maintenance Planning
	Anomaly	• Anomaly Detection • Asset Condition Monitoring	• Predictive Diagnostics							
	Thermal					• OE • Plant Efficiency Optimizer				
	Transient									

Optimizers, as examples of applications that leverage the Digital Twin, are designed to handle many variables, adhere to constraints that are imposed, and seamlessly account for interconnected aspects of the problem to be solved that cannot be grasped on the basis of the individual parts alone. The goal of the Optimizer is to solve large and complex problems with ease, make real-time adjustments to power generation equipment to maximize value, and put more power into the hands of plant personnel who make critical operations, business, and maintenance decisions. The Optimizers are the engines that power the Digital Twin outcomes; they transform a set of virtual plant models into comprehensive economic value tools.

Plant Dispatch Optimizer

- Optimize plant profitability while precisely holding to outage date targets
- Maximize revenue during peak market conditions
- Optimize balance between performance and life

Plant Efficiency Optimizer

- Plant-level performance entitlement with HR AutoTune capability
- Keep plant in optimal state of tune
- Automatic degradation response to maintain plant output or HR

Plant Startup Optimizer

- Ability to select start profiles based on customer desired outcomes
- Predictable, repeatable and reliable plant starts
- Improve day ahead forecasting and eliminate over/under generation

Plant Asset Life Optimizer

- Predictive life curves and synchronized intervals for many machines on plant level
- Anticipate failures with longer lead times; eliminate unplanned outages and penalties
- Adjust life trajectories in near real time

2.1 Dispatch Optimizer

The Dispatch Optimizer enables a plant to make short and long-term economic dispatch decisions. The underlying performance and life models allow for market driven asset utilization for drastically improved dispatch economics. As an example, GE starts with a Digital Twin of the latest Advanced Gas Path and combustion systems. This new software and combustion system opens new opportunities to run the turbine in ways not possible in the past. With Cold Part Load the Digital Twin can calculate accumulated Megawatt hour credits and, when used in conjunction with GE OpFlex* Peak Fire Advanced Controls application software, will maximize profitability. Full visibility and insights enable the customer to examine scenarios to maximize plant profitability.

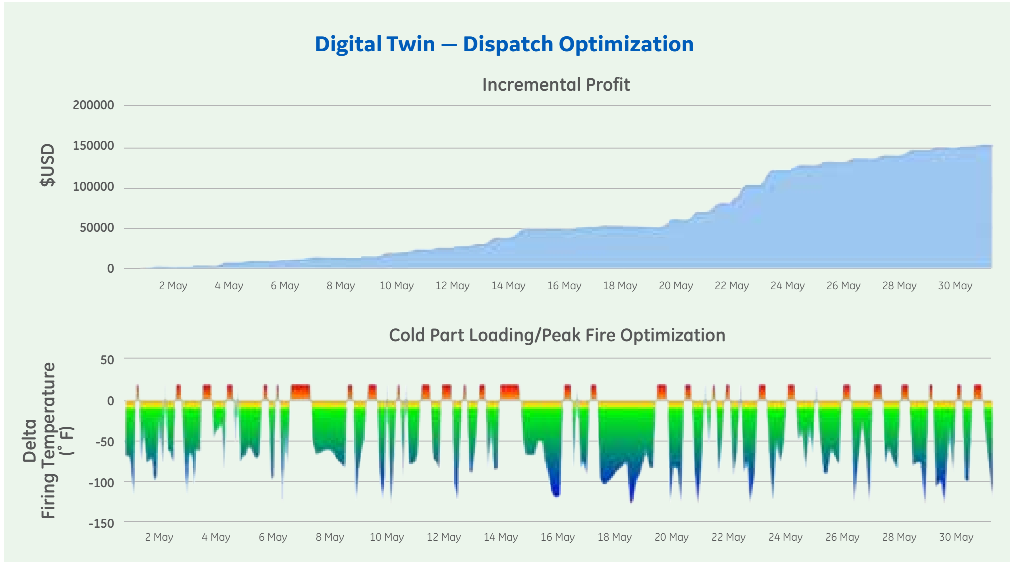


Figure 5: Dispatch Optimization

2.2 Efficiency Optimizer

Efficiency Optimizer defines plant asset operational settings required to achieve best possible steady-state load and efficiency at baseload or partload. Efficiency Optimizer uses an online performance model in conjunction with real-time optimization capabilities to give periodic recommendations for asset operation. Load, IGV, exhaust temperature, attemperation flow and steam admission temperature are examples of settings the Efficiency Optimizer considers. Plant-level heat rate entitlement with GE OpFlex AutoTune capability eliminates operator manual steps. Degradation response is provided with automatic control action to maintain output and heat rate.

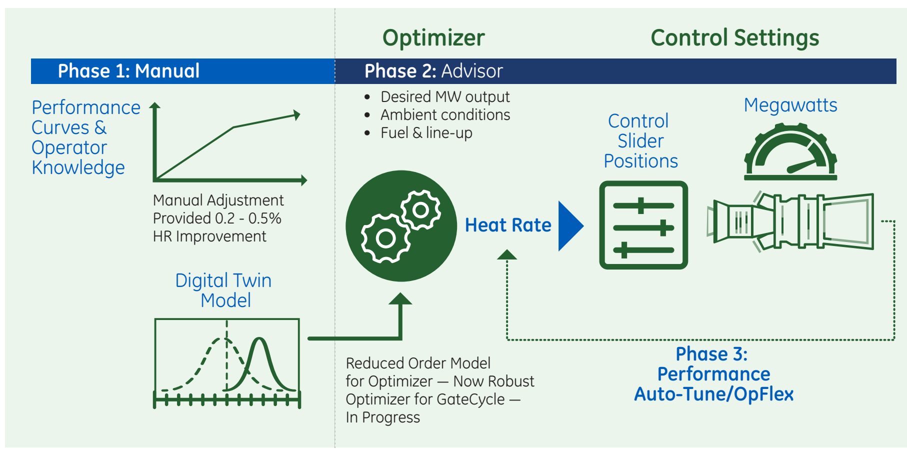


Figure 6: Efficiency Optimizer

*OpFlex is a trademark of General Electric Company

2.3 Startup Optimizer

The Startup Optimizer dynamically analyzes the results of optimization software for faster starts. Using model predictive control (MPC), the application provides the ability to select start profiles based on customer desired outcomes. With MPC, site specific dynamics models are used with customer specific constraints (stress, emissions, time to dispatch, cost...) to generate best possible startup profiles. Startups will be predictable, repeatable and reliable. Day-ahead forecasting capabilities can eliminate over and under generation.

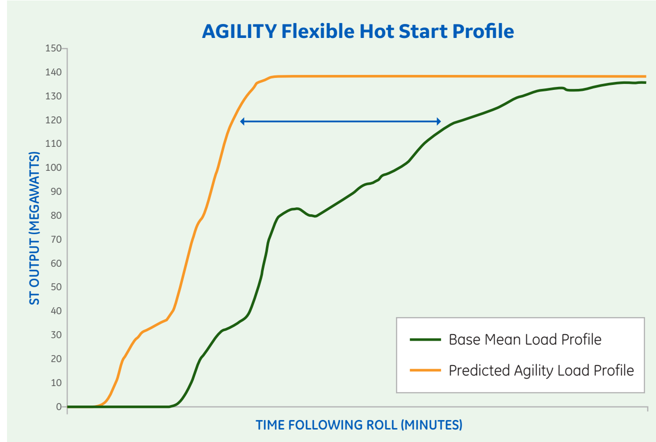
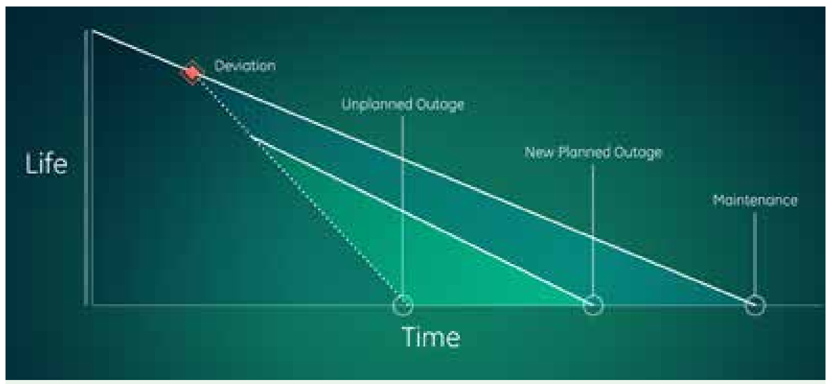


Figure 7: Startup Optimizer

2.4 Asset Life Optimizer

The Asset Life Optimizer is an application built on odometers using Lifing models and Anomaly models to accurately predict the remaining time left before maintenance is required. Every asset in the plant has a planned outage schedule, but every planned outage can turn into an unplanned outage when that asset experiences an unforeseen anomaly. Anomalies can be caused by many factors: operating profiles that deviate from original design, failed components, adverse balance of plant interactions. The Digital Twin is capable of taking these anomalies coupled with OEM data to create the best possible planned outage strategy. The goal is to minimize unplanned outages, on gas turbines, steam turbines, generators and all critical assets. The insights from Asset Life Optimizer provide both asset and plant outage visibility, enabling more refined scheduled plant outages with a focus on critical assets.



- An asset is on a trajectory to a planned maintenance when an unexpected issue indicates a potential disruption.
- With Digital Twin, proactive action can be taken to stop the interruption and impose a new planned outage point.
- In essence, additional life capacity is recaptured, proportional to the time the issue is detected and a new outage is planned.

Figure 8: Life Impact with Asset Life Optimizer

3. Outcomes

Digital Twin applications use continuously matched models and optimization to drive desired customer outcomes:

- **Performance Monitoring and Optimization:** Plant level productivity for output and efficiency:
  - Monitor Plant Performance
  - Optimize Plant Performance
- **Start Operational Flexibility:** Create more predictable, faster starts for flexible objectives (time, output, emissions, fuel burn).
- **Economic Dispatch:** Execute day-ahead and long-term planning for improved economics while respecting plant operation boundaries and lifing. Optimization is integrated with plant and unit controls to address dynamic market and operating conditions.
- **System Availability and Reliability:** Proactively monitor and manage asset specific life through optimization and controls to drive to a desired outage target for the plant. Synchronize outage between machines at plant and coordinate outage across the fleet. Reduce unplanned outage through continuous online monitoring and prognostics.
- **Inventory Control:** Track location, operations and maintenance history of production assets.

3.1 Performance and Monitoring

Monitoring Plant Performance

The Digital Twin technology enables a local monitoring and diagnostics infrastructure to remotely calculate plant performance every day of operation. The plant, asset and/or maintenance managers, using GE's performance operational optimization applications, can view real time thermal monitoring of the Gas Turbine, HRSG, Steam Turbine, and Condensers. Component shortfalls can be isolated, so that quick corrective actions can be made in real time (see Figure 9) The performance monitoring technology is OEM agnostic so that any power generation asset can be monitored or optimized.

Unlock Up to 8–13MW or ~2MM of Capacity from Improved Thermal Efficiency

Driving Plant Performance

Gaining Insights — Performance Optimization will allow fleet operators to determine which site or power asset is the most thermally efficient and has the highest output on any given day by incorporating local weather station information. Operators would have automatic asset performance forecasting for each site. Plant managers will be able to model variable peak firing for local area power demands and shuffle assets accordingly while viewing all assets from one monitoring and diagnostics center. Combined cycle part load performance analytics can be used to determine the most efficient turndown point for lower load asset capability.

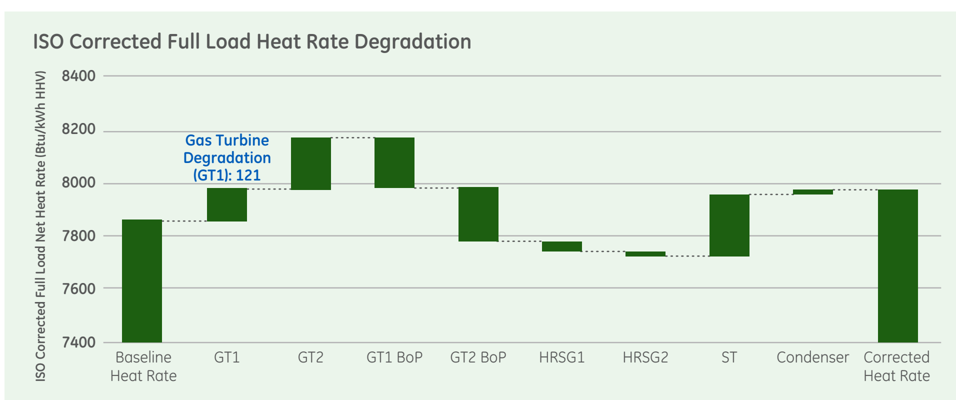


Figure 9: Quantitative performance component waterfall

Improving Performance — Once a matched thermodynamic performance model, or a digital twin of the plant, is available, it can be used as a foundation of model-based optimization of the plant performance in coordination with the unit-level controls. More specifically, as shown in Figure 10, a GE proprietary nonlinear optimizer is used with the matched plant performance model to calculate the optimum settings for the unit control setpoints that meet desired operation requirements and achieve flexible performance objectives like minimized heat rate or maximized plant output.

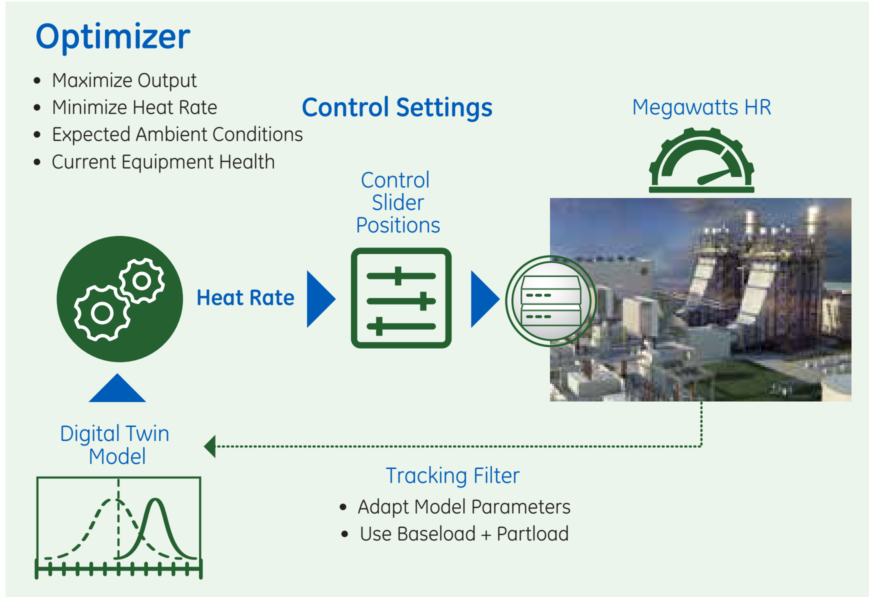


Figure 10: Plant Performance Optimization

For instance, in one configuration, the GE proprietary optimizer can be used to take operator inputs on projected ambient temperatures and total plant MW demand, to solve a nonlinear constrained optimization problem using the matched plant performance model, and calculate the optimum settings for multiple control setpoints in the Gas Turbine or Bottoming Cycle unit controls to achieve minimum fuel use. Typical improvements expected are 1–2% improvement in heat rate at baseload conditions depending on operating conditions.

3.2 Start Operational Flexibility

Reduce Start-Up Time by Up to 50%

Today's power generation market environment is variable in conditions due to fuel cost variations, electricity demand variations, MW/hr price variation, emissions regulation uncertainty, renewables volatility, opening of ancillary markets, and other market factors. Customers are looking for plant-level operational flexibility and agility to better cope with significant cyclic operation, higher number of annual starts, as well as changes in market/contract conditions. Typically, startups have a negative financial impact due to lower electricity sale prices during startup prior to the committed dispatch load and time.

Reducing startup time, costs, fuel burn, emissions, and over/under generation will benefit the bottom line. In addition, combined cycle power plants will have the ability to load the plant as fast as possible and behave like a peaker. These plants can take advantage of ancillary market capability payment as well as high electricity prices that might exist during certain market conditions. The outcome is start up agility on a plant level for fast, reliable, and repeatable starts with less fuel burn and lower emissions.

3.3 Economic Dispatch

Deliver Up to $5MM of Additional MWhr

When dealing with dispatch decisions for plants with a complex configuration, such as multi-unit plants, multi-plants and multi-product trading (ex: fuel, power, emissions, life), finding the operation schedule that is adjusted for market conditions can significantly improve power plant profitability. Examples include: (1) Leveraging the Digital Twin for a plant line-up optimization for a given co-generation steam and electrical demand, and (2) Implementing a generating schedule to financially meet a merchant market bid-award, subject to other constraints such as maintenance or reliability.

3.4 System Availability and Reliability

Reduce Unplanned Outages to Save Up to $150MM/year

Asset Life Optimizer improves both system availability and enterprise level performance. This solution represents a paradigm shift, where maintenance is schedule based on condition rather than on fixed calendar dates. For instance, in one configuration, the customer can drive reliably to a planned outage date by strategically using the available equipment life, while optimizing for maximum profit in a dynamic market. In another instance, the customer can use it to plan and extend the equipment life in a predictable manner while meeting other operation requirements.

The Asset Performance Management (APM) business application fuses anomaly detection techniques, deep domain knowledge, and lifing models to provide both foresight and insight allowing the operator to both mitigate and avoid unplanned outages. Anomaly detection techniques provide early warning with progressively more accurate insight into root cause of failure, enabling the customer to turn the unplanned outage into a planned outage or, in the worst case, respond and recover in minimal time.

Additionally, lifing models give the customer insight to when particular modes of operation are unwittingly damaging hardware, allowing the operator to avoid these modes. In the cases where operation in that mode is required, additional sensitivity to anomaly detection models is given and recommendations are made to maximize remaining life. This additional insight into the damage mechanism allows for a transition from traditional maintenance (manual based scheduling) to true condition-based, predictive maintenance.

Through the APM solution, anomalies and deviations are tracked in a case system and managed by the customer. This approach breaks the paradigm where the customer is notified with little supporting information. Instead, the system shares anomaly data with operations personnel via an online knowledge base to provide the best guidance for rapid and safe repairs.

3.5 Inventory Management

Up to 10% Reduction in Maintenance Costs

The inventory management module can help reduce unplanned down time by tracking location, operational exposure and maintenance history of critical components. This will enable the customer to:

1. Maximize asset and component life,
2. Coordinate system-wide outages and spare parts schedule and forecasting,
3. Optimize enterprise activities involved in strategic capital decisions to improve capital management decisions with more accurate asset operations and repair history.

GE Inventory Management approach enables asset specific evaluation of component age, maintenance, and failure history to accurately determine value and condition. With an accurate catalog of asset information and history, plant managers can more precisely plan capital expenditures, parts replacement strategies and maintenance windows to improve plant financials overall.

4. Enabling Technologies

A high fidelity Digital Twin for power plants/fleets requires an array of advanced technologies and deep domain knowledge in multiple industrial areas. GE is in a unique position to combine deep physics knowledge, engineering design knowledge, new sensing and inspection technologies expertise and the latest artificial intelligence and analytics experience to deliver a Digital Twin of unprecedented fidelity. This powerful combination of digital plus industrial provides the core strength of the GE Digital Twin.

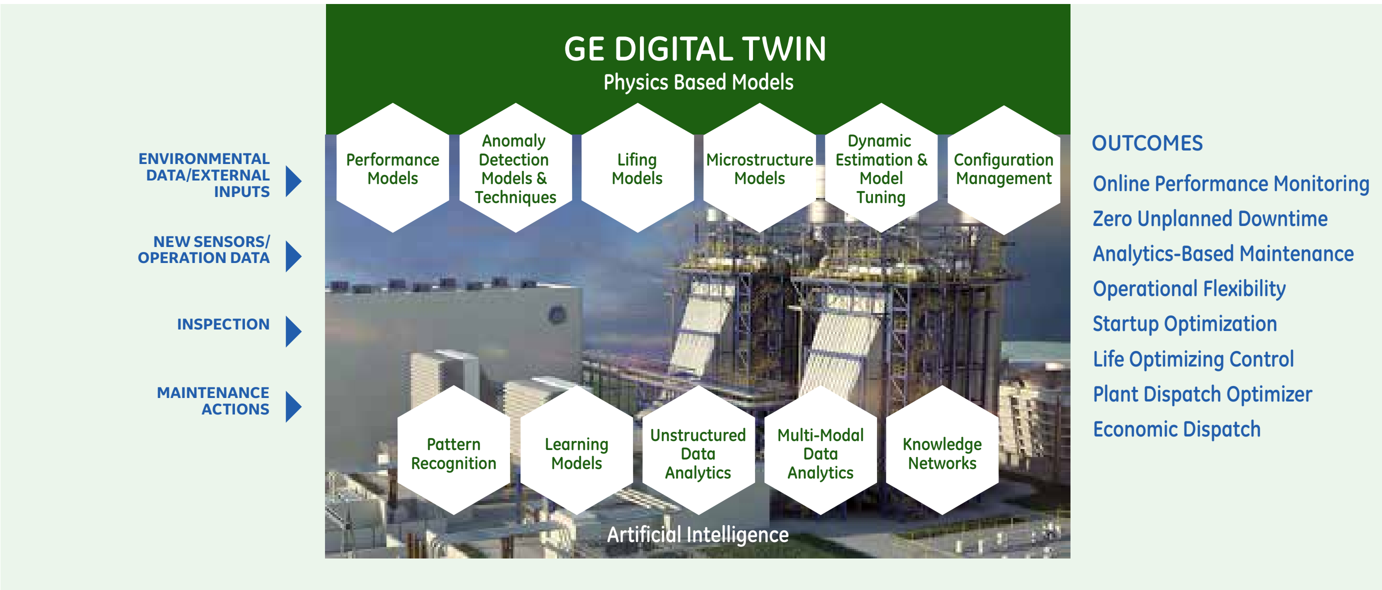


Figure 11: Core technologies for the GE Digital Twin.

As part of the GE Digital Twin engine, analytic models and advanced technologies provide the input to the business applications that drive value from a Digital Power Plant. These underlying capabilities that differentiate the GE Digital Twin fall into three major categories: physics based models, artificial intelligence and enabling sensor technology:

Physics Based Models: Deep physics models that model flow, thermal, combustion and mechanical aspects of the Power equipment to provide unprecedented insights into equipment operation. Some examples include:

Performance Models
Anomaly Detection Models and Techniques
Lifing Models
Microstructure Models
Dynamic Estimation and Model Tuning
Configuration Management

Artificial Intelligence: GE Digital Twin employs the latest in Artificial Intelligence technologies that leverage data from equipment to generate insights and deeper understanding of operating environments. They include:

Pattern Recognition
Learning Models
Unstructured Data Analytics
Multi-Modal Data Analytics
Knowledge Networks

Enabling Sensing Technology: Innovations in data sensors, designed to work under harsh and difficult environments, provide the information that drive the analytic models. Examples include:

Printed Sensors
Inspection Technologies
Atmospheric/Weather Data
Plant Component Analytics

4.1 Physics Based Models

GE Digital Twin analytic models are derived from and validated against vast volumes of time series data from GE's install base. The models, used by GE business applications, are designed to predict an array of operating conditions in a power plant environment. While GE employs a wide variety of analytic models for operations efficiency, the following describe those most impactful that contribute to the value of the GE Digital Twin.

- Plant and asset thermodynamic model (Thermal)
- Anomaly models and detection methods (Anomaly)
- Life models (Lifing)
- Dynamic Estimation and Model Tuning (Transient)
- Flow and Combustion Models (Transient)

4.1.1 Plant Thermodynamics Models

Plant Thermodynamic Models predict plant performance under different operating conditions, dispatch modes and grid (or customer) requirements both under steady state as well as transient operation. The model uses GE gas turbine power plant design knowledge, including GT, ST, and HRSG, with advanced computational methods to accelerate the execution time and enables real time decision-making. With GE's deep expertise in combined cycle gas turbine design and the wealth of data gathered GE large fleet of fielded gas turbine plants, the model robustness, accuracy, and agility is unprecedented. GE is currently using GateCycle as our source for a core Digital Twin thermal application. Specifically, GE is using the heat-balance engine within GateCycle ("HBE") and developing an improved version, HBE7.

The model is created using a user interface (UI) that allows an engineer to define each plant component and how those components are connected to each other. The heat-balance engine contains the fundamental physics of each component in the power plant as well as a "solver" that controls how these components interact such that the final result complies with the laws and principles of thermodynamics. This creates the as-designed model of the power plant.

Once a model is created, the model can be used in multiple ways. During commissioning, the as-designed model is critical as this enables the test engineers to confirm whether the plant meets acceptance criteria for thermal efficiency and output. If there are shortcomings, the model helps the engineer identify the root causes and accelerates remediation. After commissioning is complete, the tuned model represents the as-running condition of the power plant. Connecting this tuned model to a Monitoring and Diagnostics infrastructure, allows the plant to be monitored both by the customer and by GE.

The tuned thermal model can also be used within the control system. Building on the work done in creating closed-loop optimal control (CLOC), GE has been able to demonstrate improved regulation performance, optimized load generation balance, and elimination of over generation costs. This can be taken to the next level with advances in signal processing and model-based control combined with GE's DCS-OEM-agnostic APAL platform.

4.1.2 Anomaly Models and Detection Methods

Every day, GE Power collects more than 44,000 operating hours of data from thousands of globally deployed gas turbines, steam turbines and generator assets. Remote condition monitoring and anomaly detection of a power generation asset involves the full spectrum of data collection, data processing, mechanical condition monitoring algorithms, and alarm disposition, diagnostics and recommendations for improvement. The purpose is to monitor the operation status of each asset by using time series data collected and transmitted from the customer site to detect abnormality at near real-time.

Generally, there are two types of abnormalities: (1) the parameter exceeds a predefined limit, which could cause damage to the equipment if operation continues under such a condition, and (2) the anomaly pattern deviates from a normal operational pattern even below the predefined threshold, which could be a symptom of potential failure or improper operation. Therefore, early detection of these anomalies is critical in proactively avoiding forced outages or part damage, thus reducing property loss and reducing maintenance costs.

At GE, there is a multi-generational approach to anomaly detection using a combination of physics-based knowledge, fleet knowledge and collected sensor time series data. Each asset has algorithms that draw from both physics and data, with models constantly evolving as assets move through their life cycle. The five types of technologies employed at GE include:

Domain or physics-based methods. Here, Digital Twin physics based models enable anomaly detection within the physical plant through the comparison of calculated parameters with measured values. By analyzing the expected values throughout the plant with the reported values, GE can determine whether a true physical anomaly is occurring or if a sensor out of calibration. If a sensor issue is identified the physics based models can be used to provide a "virtual" sensor reading based on the remaining valid data. If a true anomaly is detected, then the Digital Twin applications can provide action recommendations to minimize potential impacts.

Statistical process control. Univariate and multivariate control chart techniques are used with thresholds set empirically or from domain expertise. These include algorithms to detect operational regimes so the appropriate filters and control chart limits are applied (ex: to account for steady-state base and part load operations, as well as transients).

Machine Learning anomaly detectors. AT GE, a full suite of machine learning algorithms are used, ranging from multivariate multi-level survival models to baseline asset risk, to classification techniques like logistic regression, decision trees, random forest methods, neural networks and clustering methodologies. These models are usually derived using healthy and fault data using GE's historical database of sensor and configuration data.

Advanced signal processing techniques. There are certain failure modes, especially in gas turbine combustion systems and compressors, where advanced signal processing techniques are needed to detect subtle anomalies in the presence of sensor noise. A variety of algorithms that use wavelets, kernel regression and multi sensor data fusion techniques are used as needed.

Deep Learning Anomaly Detection. GE has invested in cutting-edge artificial intelligence technologies like deep learning neural networks to detect anomalies. GE leads the industry in the application of these methods for anomaly detection for operational sensor time series data.

We measure the impact of anomaly detection methods using metrics like failure mode coverage, probability of fault detection, accuracy of fault diagnosis, false alarm rate, early warning time, etc. These metrics are evaluated frequently by GE's analytic staff and if needed, models are tuned, modified or redeveloped as emerging faults are detected throughout the life of the asset.

4.1.3 Lifing Models

By combining customer data with GE's global fleet data, this robust physics based foundation is augmented by empirical data including operational, part condition, outage and site specific environmental information. This proprietary process allows GE to leverage its breadth and depth of plant understanding to develop scenario-specific analyses for a customer's principal assets, enabling prescriptive solutions for optimal value. Through the synthesis of anomaly detection algorithms and the aforementioned lifing analytics, GE is able to transcend traditional predictive based maintenance and move into prescriptive strategies. This allows movement from traditional maintenance manual based scheduling to true reliability based planned maintenance. In addition, this strategy leads to forecasting the leading failure events driving unplanned downtime, enabling optimal resource allocation.

4.1.4 Dynamic Estimation and Model Tuning

The thermodynamic performance model will be continuously matched with measured sensor data from the plant using a Tracking Filter. In particular, the performance model has key parameters that capture the variation of the health of each unit in the plant (ex: compressor degradation in the Gas Turbine or HRSG superheater fouling). These parameters in the model will be continuously tuned using advanced Kalman filtering techniques that enable a robust estimation of the model parameters using data from the available sensors. A continuously matched model is the Digital Twin foundation that enables monitoring the performance and health of the plant, providing model-based "virtual measurements" (ex: critical unmeasured temperatures for lifing models, and model-based optimization).

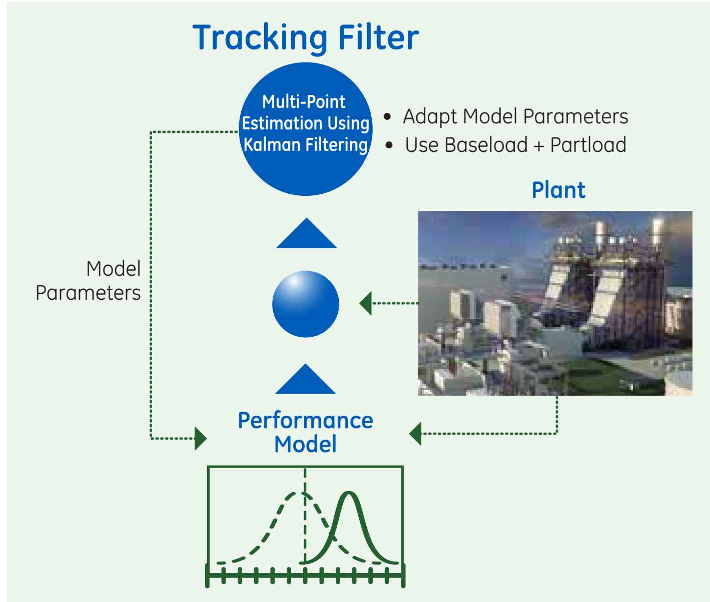


Figure 12: Dynamic estimation used by GE Digital Twin

More specifically, the Tracking filter has key elements: (1) the underling physics-based performance model of the plant, (2) operation data from multiple sensors in the plant obtained at multiple operation points (ex: baseload and partload) on a regular interval, (3) using advanced Kalman filter based algorithms to robustly identify the slowly varying model parameters in the presence uncertainties like errors in sensor measurements that are invariably present or unmeasured variations like fuel quality.

4.1.5 Flow and Combustion Models

GE is the OEM of some of the key equipment in power plants and brings deep domain knowledge of this equipment to design of the Digital Twin. GE uses advanced Computation Fluid Dynamics capabilities to build and optimize the compressor and turbine section. Air foil design, flow, clearances, fluid structure interaction are modeled at individual blade level and as single and multi-stages of blades. Flame properties and combustion dynamics are some of the properties modeled for combustion systems. GE uses high performance computing to run these high fidelity models.

Based on the needs of the fidelity in the Digital Twin, GE brings an understanding for flow and thermal physics through surrogate modeling technology. Understanding of flow-structure interaction is critical to provide an accurate estimate of high cycle fatigue life for compressor blades that have been used for blade health monitoring. Knowledge of combustion dynamics is used for developing lifing capability for combustor components. Use of these deep physics models enables the GE Digital Twin to have higher prediction accuracy that any other models.

4.1.6 Configuration Management

Hardware Configuration Management refers to updated and an accurate Bill of Material (BOM) for all sub components of the gas turbine and combined cycle. The gas turbine's thermal Digital Twin is impacted primarily by out-of-date configuration management due to changes throughout the gas turbine's lifecycle. Configurations can refer to the hardware bill of material, control modifications and performance modeling. They are all linked, but understanding gas turbine hardware configuration is most important.

Modifications, hardware upgrades and outage in kind replacements can change the unit's performance characteristics and modeling accuracy. The configuration management is a dynamic hardware compilation that is updated by the customer and GE to ensure accurate hardware history/model performance and correct firing temperature. GE provides an active configuration management system that is key to the Digital Twin's life cycle of plant assets.

4.2 Artificial Intelligence

Beyond the analytic models described above, other technologies are employed at GE to create a highly functional Digital Twin. Many of these innovations and their uses have been developed at GE research labs, used across multiple business lines and perfected across a wide number and variety of customer implementations.

4.2.1 Pattern Recognition

Pattern recognition capabilities contribute to developing the behavioral Digital Twin of an asset by using various sources of measurement data collected over-time. This is a complementary approach to physics-based models. Massive volumes of asset operation data is combined with the output of deep physics models and domain knowledge in the Digital Twin Pattern Recognition Module. Deep domain knowledge is married with sophisticated artificial intelligence techniques like deep learning, transfer learning and other advanced machine learning methods to identify failure symptoms with lead-time warnings by detecting change from an anticipated behavior or looking for patterns that are known characteristics of a degradation, fault or failure.

Early stage pattern recognition allows advance warnings of impending failures, combined with an assessment of the remaining useful life of the asset/component of interest. Pattern Recognition techniques are extensible to multi-modal data such as time-series data, machine-log data, text data and image data, all or any of which can be processed to learn maximum information about the system to build a digital model.

4.2.2 Learning Models

A critical component of the GE Digital Twin is its proprietary modeling platform within which twins of assets are continuously created, validated, monitored, and updated at a speed close to real-time. New data flows in from operational assets in real-time providing a constant window to the instantaneous state of the asset. This data is appropriately preprocessed to improve the signal-to-noise ratio of the relevant information and used to appropriately update the digital model to minimize differences between the physical and the digital personas of the asset. Model performance is used as feedback in Model Updating, where continuous learning technology is used to provide a stream of refinements to the Digital Twin.

In addition to traditional Model Building, GE's Digital Twin also has capability of transfer learning, where a model can be applied to a new asset design based on the knowledge of the existing asset designs, which is in turn based upon the statistical and domain relationships between the two, the source (originating) and target (new) domains. Transfer learning has been effectively applied by GE to develop models between related product lines, related assets and related components.

This approach of transfer learning and continuous model feedback allows for rapid model development and more accurate model redevelopment so the Digital Twin maintains perennial correspondence to the physical asset.

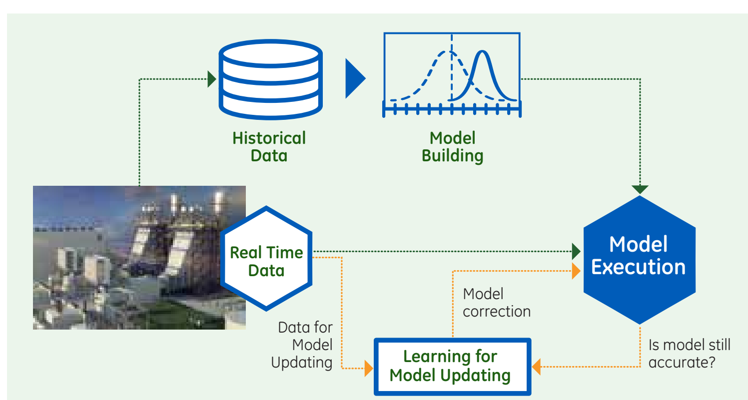


Figure 13: The Machine Learning Ecosystem for the Digital Twin Modeling platform

A critical component of GE's Digital Twin technology is its modeling platform within which Digital Twins of assets are continuously created, validated, monitored, and updated in near real-time. A critical requirement for Digital Twin is the need for the models to have minimal difference between actual physical asset and the Digital Twin. Traditionally, updating and maintaining numerous models is extremely manual and expertise-heavy task. GE has standardized the work flow of updating models using Artificial Intelligence techniques wherein performance of Digital Twins is constantly monitored and both continuous and incremental learning techniques are applied to update the Digital Twin (see Figure 13).

GE's Digital Twin system allows for:

- Automatic detection and correction of drift in the Digital Twin
- Adaptation to changing conditions, both locally (for the asset) and globally (for all assets)
- Highest performance levels when predicting future observations

GE has a unique ability to build and update models using Artificial Intelligence that searches through model libraries to identify the best performing models. This method uses a Genetic algorithm-based evolutionary search algorithm that searches through various Classification, Regression, Clustering and Physics-based models to identify the best new models or model parameters that matche closely with the performance of physical asset. In addition, transfer learning and active learning techniques are applied where domain knowledge and human guidance is required during the model updating process. This approach allows for rapid model development and continuous model updates so the Digital Twin maintains perennial correspondence to the physical asset.

4.2.3 Unstructured Data Analytics

The GE Digital Twin technology leverages advances in Artificial Intelligence in several ways that make it scalable for future challenges and growth:

- AI technology is addressing the massive amounts of unstructured data that enterprises must deal with in the lifecycle of a part and asset. It is estimated that 80% of all data will continue to be unstructured, and AI enables machines to read and understand diverse data, connecting to common and shared semantics, and finding mistakes and quality issues that can be automatically correctly.
- AI is providing semi-automation of complex tasks like configuring models and analytics, and understanding error progation through systems of models.
- AI is the mechanism for "architect to automate": the development of systems with feedback and learning as part of their DNA. Systems like the Digital Twin that are architected in this way benefit by their successes and mistakes, growing smarter and more personalized over time.

Advances in massive scale data storage, computation methods and networking are enabling AI methods to 'train' on Big Data. AI can provide explanation and reasoning using inference and logic that inspires confidence in the systems, creating a virtuous cycle of improvement. AI will then enable a new level of cognitive capability to automate Digital Twin model development and management, particularly as it fuses with GE's strategy to create Knowledge Networks.

Additionally, GE specializes in using the latest in data and text mining techniques for analyzing Industrial unstructured data. Text mining techniques include sentence tokenization, search, industrial phrase matching, vocabulary development, ontology mapping and sentiment analysis. Statistical analysis, clustering analysis and decision trees are used to mine rich industrial data. The extracted information is used to improve the Digital Twin by providing it updated data from maintenance and service records that provide accurate action data performed in the field or in the shop. This information is critical for maintaining the corresponse between Digital Twin and the physical asset.

4.2.4 Multimodal Data Analytics

Analytics for predicting failures and maintaining automated, live, up-to-date asset health scores usually requires data from multiple modalities. The modalities may include:

1. Parametric data (ex: Temperature, pressure)
2. Spectral sensors (ex: Raman spectroscopy)
3. Image Sensors (ex: Infra red imaging, visible light cameras)
4. Free text data (ex: Inspector comments from service records or other forms of communication)
5. Structured database tables (ex: Maintenance databases)

The GE Digital Twin is able to handle data from multiple modalities in a seamless and efficient way, delivering best-in-class performance using the latest fusion techniques. These include Deep Learning, Ensembles, Bayesian methods & Knowledge Representations, used to combine information from different modality and provide new information not possible from each individual source.

For example, the health score of a valve may use sensor data on flow, input pressure, output pressure along with data from an NDE infra-red sensor inspection equipment and also needs to take into account all the text input from maintenance records. The problem is similar for predicting failure of key components in a turbine or the rest of the power plant.

4.2.5 Knowledge Networks

By leveraging Predix, GE is able to quickly connect experts as well as observe how modeling and analytical tools are used to develop Digital Twin models and supporting systems. The action of connecting and building models are digitized and converted into "Expert Twins" that can be used to assist and semi-automate the model building process by helping to promote and create Knowledge Networks across the enterprise.

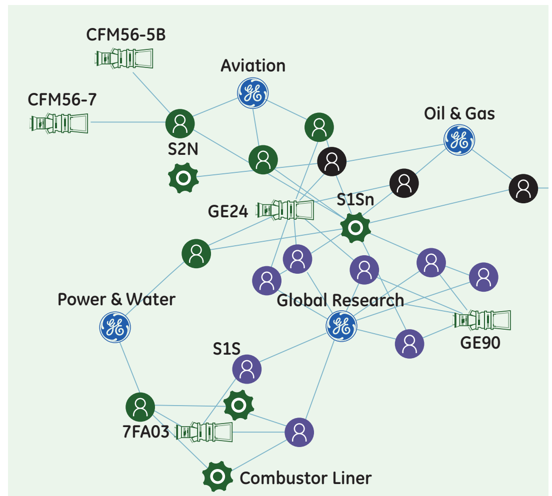


Figure 14: Knowledge Network

Knowledge Networks complement the traditional social networks within an enterprise because they are 'purpose' and 'task' driven: best practices can quickly be identified, shared and then digitized for others. Using GE's unique Knowledge Network capability, experts can easily enter the type of goal they are working toward and find other experts doing the same. Additionally, observed best practices can be quickly found by navigating the Knowledge Network. For example, an expert building a new Digital Twin may have a question about the best data, or how to prepare a Data-driven or Physics-based model. By observing how others have solved similar problems, the expert can take action based on that knowledge directly, or they can contact the other experts for more information. Knowledge Networks enable scale through best practice sharing.

4.3 Next Generation Sensing Technologies

A high fidelity Digital Twin requires high fidelity sensor data. GE is continuously working to apply next generation sensing technologies to gather date from difficult or harsh environments. The following are a few examples of new sensing technologies contributing to the GE Digital Twin:

New Sensor Applications

Advanced sensor technologies for compressor rotor and stator vane health monitoring can help identify issues at both the compressor and the individual blade level. Compressor rotor health monitoring uses magnetic sensing technologies to monitor blades as they are moving at supersonic speeds and uses new technology to estimate blade vibration and resonance in real-time to provide estimates of individual blade health. In addition this technology can be used to improve compressor health monitoring by fusing blade rub and clearance data into compressor efficiency models, thereby providing a unique value proposition to customers.

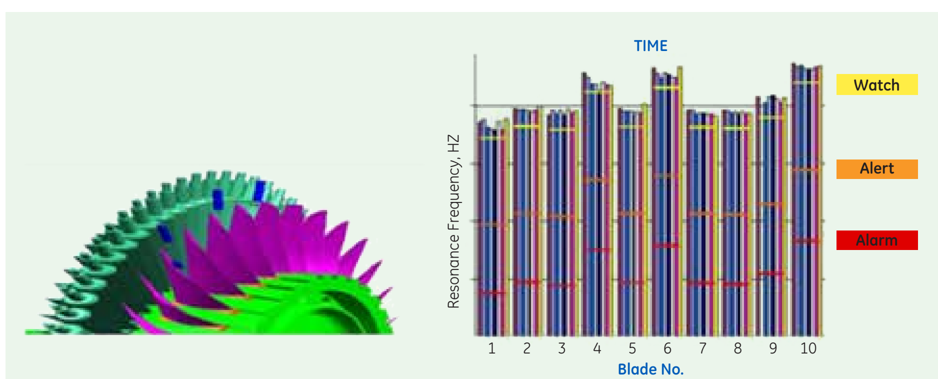


Figure 15: Rotor blade health monitoring technology provides capability to track individual blades in real time through magnetic sensing.

Compressor stator vane health uses high frequency structure borne sound (acoustic emission) to monitor cracking, leaks, rubs and clashing in compressor blades. This technology generates 50 MM samples of data per second and GE employs high frequency data analytics to process this data to build a Digital Twin for monitoring stator vanes.

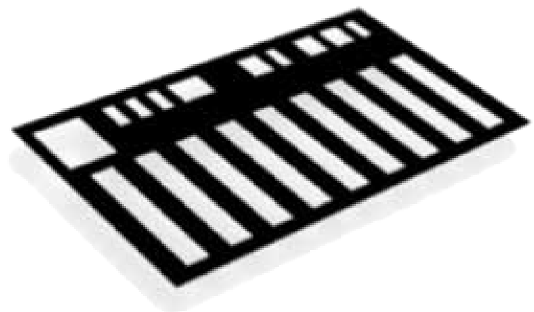


Figure 16: LifeSight sensor printed onto Hot Gas path parts and used to measure creep in blades

Printed Sensors for Creep Detection

A major failure mode that challenges the life of assets is Creep. GE's solution to this failure mode includes installation of LifeSight creep sensors. These sensors are wire free strain/creep measurement devices that are permanently printed to the part surface and scanned for strain measurements. Each sensor is unique with its own bar code. Combined with the digital twin of the asset and full knowledge of the asset's part life, a repair scope is then identified that is specific to that part, indicating how that part was run through it's life. Any deviation from that pattern can be immediately identified. These sensors provide the capability for a high fidelity Digital Twin for hot gas path creep prediction.

Embedded Corrosion Sensors

Often local conditions are prevalent that would cause corrosion issues difficult to predict on a global scale. GE's compressor corrosion rate sensor displays real time corrosion rate changes and responses to atmospheric and operational changes from a location inside of the compressor. This sensor is available on a test basis for high corrosion sites identified either through the global model or through site experience. Additional sensors may include an on-site Nephelometer and Dust Collection Station. These technologies allow GE to provide a highly accurate Digital Twin that can more readily predict corrosion issues.

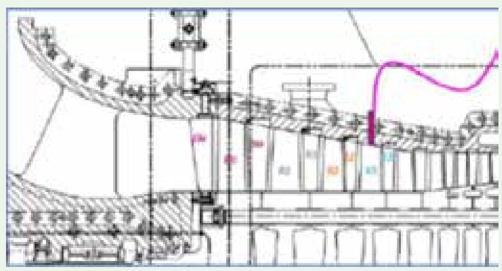


Figure 17: Sensor installation location on the GT compressor section

Figure 18: Probe as viewed from inside the compressor

4.3.1 Atmospheric/Weather

Aqueous corrosion in the compressor and hot corrosion in the turbine section is prevalent in costal and industrial areas. GE has developed an optimized global database of key atmospheric factors in order to manage these failure modes. Many of these factors affect turbo-machinery: SO2 gas, sulfate aerosols, sea salt aerosols, dust, volcanic ash, soot, organic aerosols, humidity, temperature, pressure, wind speed and direction. This is fed into the Digital Twin models to improve their accuracy in predicting asset conditions that are significantly dependent on the atmospheric and weather conditions.

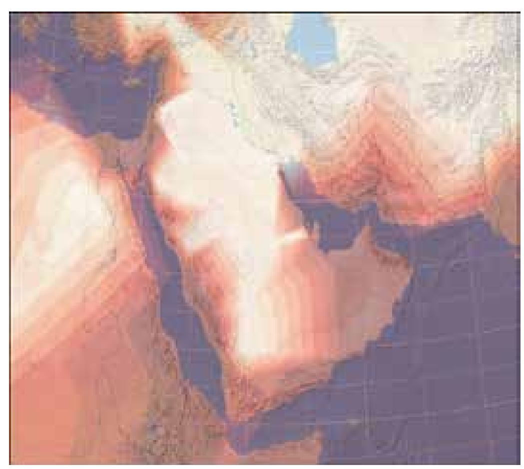


Figure 19: Corrosion heat map of Middle East

4.3.2 Inspection

Foundational to the Digital Twin is sufficient understanding of the configuration of the asset and its history of equipment and parts. This data collection is unique from sensor data in that it involves personnel at outage to record condition of hardware on site. In order to secure this data in a uniform manner and to minimize outage time, GE has developed a suite of applications and peripherals that are linked to mobile devices intended for field engineer or craft technician use. These devices serve the following functions:

- **Part Tracking:** Parts are marked with 3D markings that are read into the application through a scanning device (manual entry backup). These parts are then inventoried and managed throughout their lifecycle — either within the asset, in the repair shop, or in a warehouse. The entire lifecycle of the part tracking is then possible.
- **Wireless Measurement:** Asset and part condition field Inspection enabled through Bluetooth gauges that wirelessly take inspection data adjacent to the asset.
- **Condition Tracking:** Condition information is communicated from a tablet to Predix, ensuring accurate condition data capture, verification of model numbers and condition history recorded.
- **Issue resolution:** Quickly resolve asset issues through Service Now, a GE offering that incorporates web-based issue tracking with GE service personnel interaction, online learning and case management/resolution.

4.3.3 Plant Component Analytics

The imperative for the most accurate Digital Twin possible is component level visibility. GE is constantly updating component level analytics to diagnose current state and predict future performance degradation and failures. Working with suppliers of components such as Gas Control Valve, Pumps, Atomizing Air compressor and other critical plant parts, GE is developing analytics to diagnose current condition, provide prognostics of future performance and prediction of failures.

Real-Time Status Analysis

During normal operation, high speed, low amplitude movements of the component such as driver/actuator/valve system can provide insight into performance and life of the component while still maintaining full functional operation. The following is an example:

- Lost motion within the mechanical powertrain.
- Friction Observer within the mechanical powertrain.
- Power Consumption, which translates into mechanical changes.

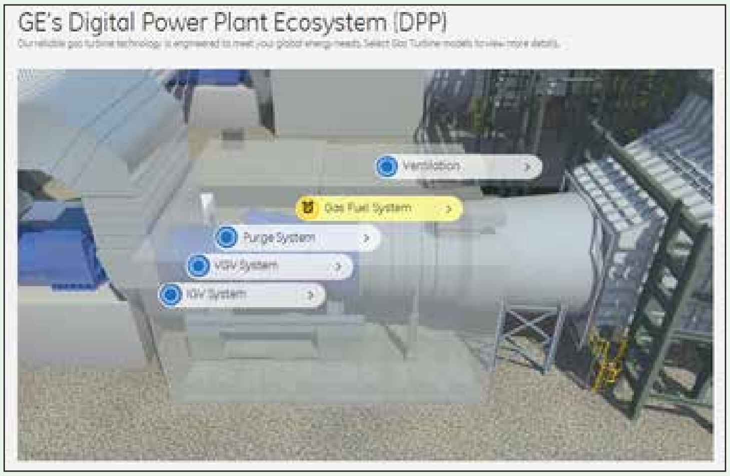
DIGITAL POWER PLANT USER INTERFACE

Shown: Digital Power Plant user interface displaying current plant condition.

Over the next 12 months, there are 2 alerts in both the cooling system and the Stem Seals life

The user can click on Gas Turbine 1 to see more details

SYSTEM LEVEL DIAGNOSTICS

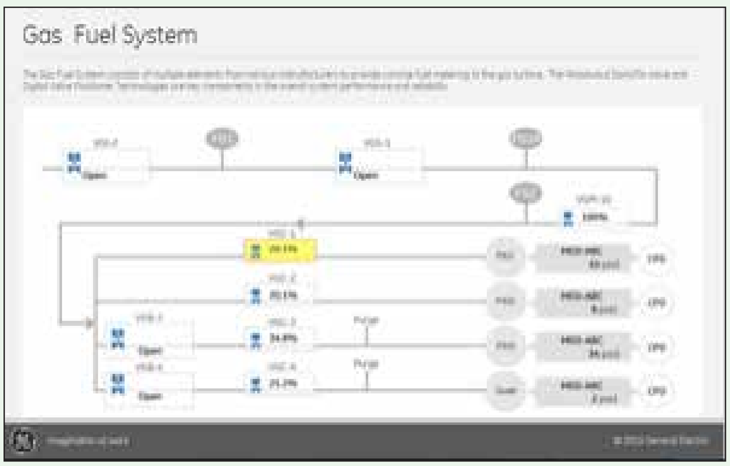


One level below:

An alert in the Gas Fuel System.

The user can click on the Gas Fuel System to see more details

SYSTEM LEVEL DIAGNOSTICS

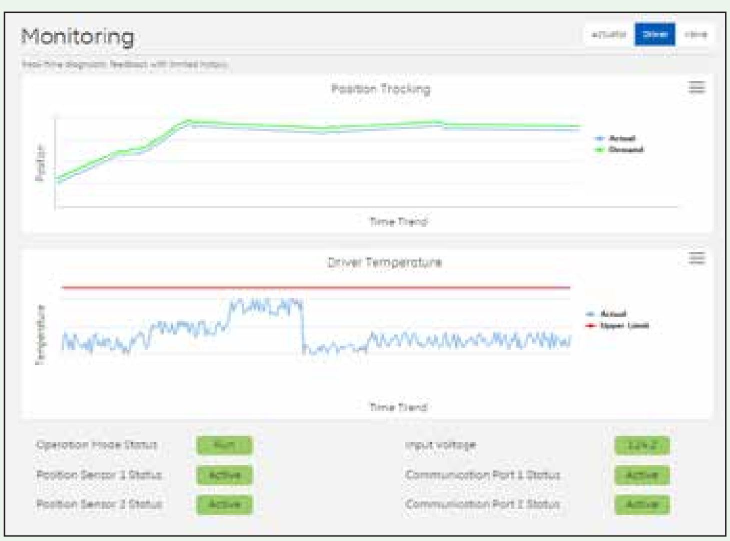


Another level below:

The detailed system level is showing alert in VGC-1.

The User can click on VGC-1 Valve to see more details

COMPONENT LEVEL DIAGNOSTICS



Finally, at the Component Level performance diagnostic is showing the VGC-1 valve's current condition

Prognostics

The GE Digital Twin is able to project component performance based on current condition, operation history, and accumulation of operating hours. A learning curve of component performance is developed using the Predix platform analytics to provide the plant operator with future failure and performance degradation of the component. This is critical in preventing forced outages and creating a better plan for component maintenance.

COMPONENT LEVEL PROGNOSTICS

Component level prognostics screen showing the areas of expected issues in the driver card and valve components.

COMPONENT LEVEL PROGNOSTICS

Component level prognostic screen for VGC-1 valve displays the learning curve of the component performance, degradation, expected point of failure, and recommended outage date.

4.4 Digital Thread

Foundational to the configuration of the asset is the Digital Thread. This data collection is unique as it connects the design process to the services provided to that unit through one continuous Digital Thread. To secure this data in a uniform manner, GE has developed a suite of applications and peripherals that link across the entire life cycle from design to retirement.

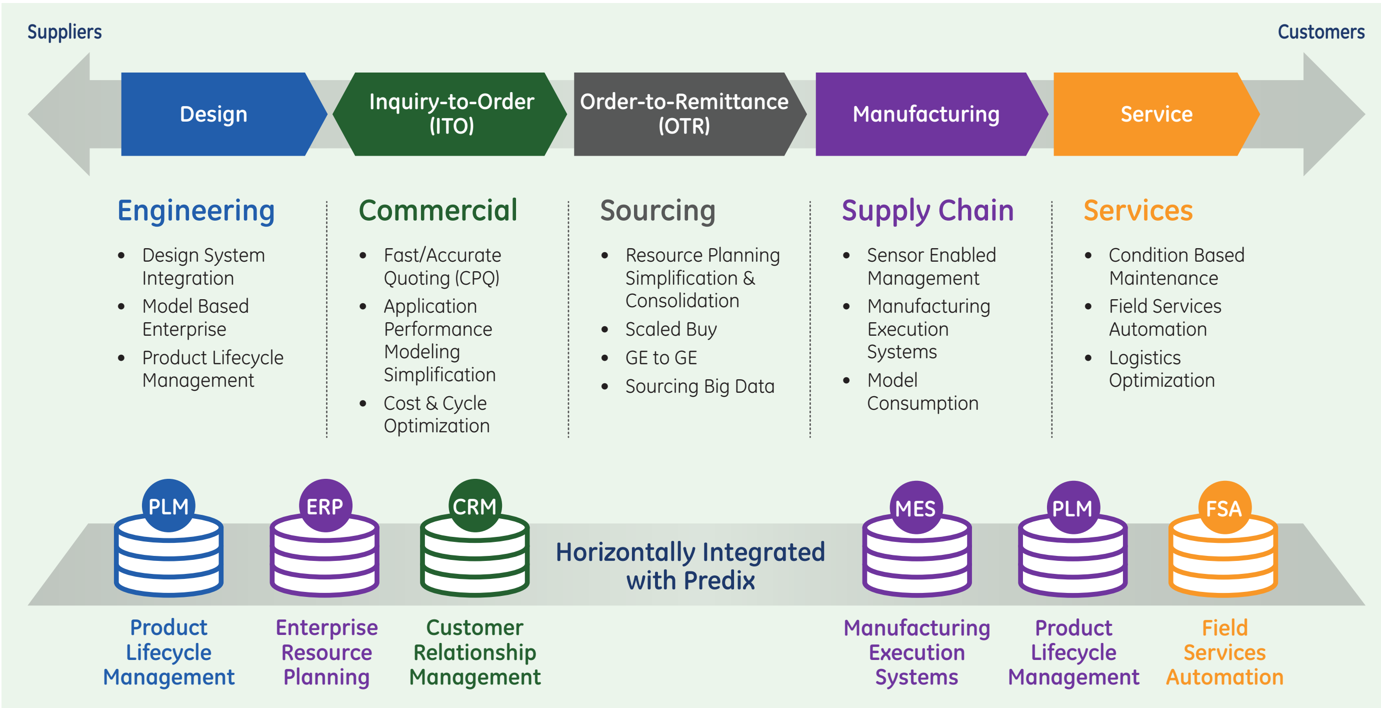


Figure 20: GE Digital Thread

- **Design:** The design platform is integrated into a suite of applications to build a model based enterprise.
- **Commercial:** Critical customer attributes can be understood and specific configurations can be selected to optimize needs.
- **Sourcing:** Big data architecture can be leveraged to improve quality and reduce installed cost.
- **Manufacturing:** Predictable, sensor enabled, model based manufacturing is enabled to deliver consistent optimized products.
- **Service:** Digitally connected supply chain to minimize customer downtime and maximize performance.

5. Edge Analytics Engine for Digital Twin

The GE Industrial Internet environment spans the whole power value chain from managing cross-fleet applications, delivered via mobile and desktop, to device and instrumentation solutions for on-site personnel in power plants. The infrastructure to enable this level of comprehensive coverage dictates both edge and platform environments, integrated and working seamlessly as a single operating environment.

Predix, the platform for the Industrial Internet, is specifically designed to ingest vast volumes of machine data, for analytic processing and for delivery of application results — across multiple power generation and delivery locations. However, equally important are the edge capabilities for real-time analytics, data formatting and communications. Components of the GE Digital Twin will reside in both locations and used where it makes the most sense for the application leveraging the analytic models.

5.1 The Predix Platform

The Predix platform is at the heart of GE's software portfolio. It leapfrogs traditional enterprise IT solutions with a native architecture that augments industrial operational technologies (OT) for both GE and non-GE assets. Predix is purpose built for large-scale machine data processing, data management and analytics.

The key Predix services can be broken down into the following categories:

- Industrial Services (Asset Services/Modeling)
- Data Services (Time Series Data, Modern Hadoop Database, Data Lakes)
- Analytics Services (Catalog/Orchestration/Execution)
- Security Services (User Account and Authentication (UAA)/Access Control Service)
- Software/Configuration Services (GE App store)

5.2 Edge — Predix Machine

The primary responsibility of Predix Machine is to provide secure, bi-directional connectivity to — and management of — industrial assets, while also enabling applications (analytical and operational services) at the edge of the Industrial Internet. The latter is particularly important to delivering near-real-time processing in controlled environments.

Predix Machine also provides security, authentication, and governance services for endpoint devices. This allows security profiles to be audited and managed centrally across devices, ensuring that assets are connected, controlled, and managed in a safe and secure manner, and that critical data is protected.

Furthermore, Predix Machine enables:

- **Device Provisioning,** when a device 'calls home' to the Predix infrastructure and register itself for further management and software upgrades.
- **SW/Configuration management,** with remote configuration of the Predix Machine and the related apps, tracking modifications and changes over the lifetime of the machine.

5.3 Advanced Controls/Edge Computing

Advanced Controls/Edge Computing is the next generation architecture for controls developed by GE and is the intended host for many execution components of the Digital Twin. It consists of a set of scalable, software-defined and integrated components specifically designed to provide the advanced capabilities and analytics required to fully leverage the power of the Industrial Internet.

At the most general level, a control server integrates three top-level sets of functionality into a single configurable product:

- Thin-client Human Machine Interface (HMI)
- Predix-based edge applications
- Supervisory (L2) controls

This is achieved through a hypervisor-based architecture that allows safe coexistence of the different components on top of a single server blade hardware.

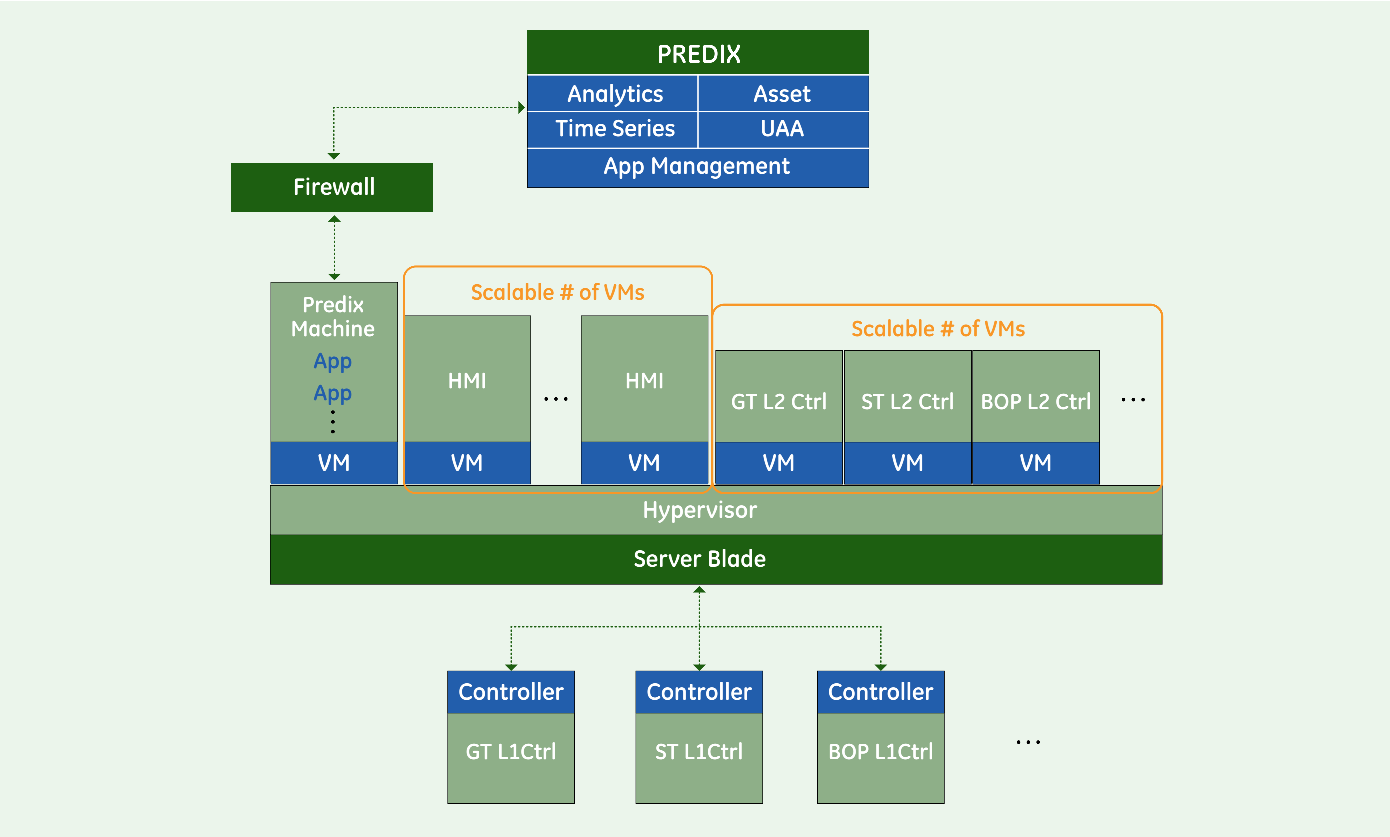


Figure 21: Advanced Controls/Edge Computing Architecture

The applications running in this environment will be capable of interfacing to GE as well as non-GE control platforms/assets given the vendor agnostic nature of the Predix Platform that allows interfacing through generic industrial protocols like OPC-UA and Modbus. This also enables connectivity with the various generations of GE controllers (Mark V to MarkVIe).

6. Summary

With decades of investment in analytic data science, operations software, hardware manufacturing, user interface, and artificial intelligence, GE has created the Digital Twin that essentially becomes the backbone engine of the Digital Power Plant. From the ground breaking of a new power plant through its long-term upgrades and life use, the GE Digital Twin not only mirrors the operating environment digitally, but provides the insights and basis for better decision making at every level of plant and fleet operation.

The GE Digital Twin technology can be used on all thermal cycles from combined cycle and fossil to cogeneration and district heating. The technology is OEM agnostic and can provide precision to all brands of power plants. The benefits are however amplified with GE-based power plants by integrating with GE's own asset models. The GE Digital Twin technology links to GE's Monitoring and Diagnostic Center(s) infrastructure to remotely evaluate the plant KPIs and true capabilities continuously through daily operation. The application of advanced analytics enables precision beyond what the station instrumentation can provide alone without the cost or risk of adding or replacing existing sensors.

The Digital Twin technology embodies the heart of the Digital Power Plant by combining domain expertise with big data analytics and a large-scale network infrastructure, providing value for power leaders from many perspectives. Fewer unplanned outages, more refined maintenance strategies, better managed asset life and the ability to balance plant production against variable factors of market pricing, weather and fuel costs can lead to bottom line benefits of up to millions annually.

Power leaders who understand how data and analytics can help them finally control their operations, financial decisions and market strategies to a level not yet seen understand the competitive and business growth advantages of the Digital Twin.

Appendix A

		Digital Twin Business Applications								
		Asset Performance Management			Operations Optimization				Business Optimization	
		Equipment Health	Reliability Management	Maintenance Optimization	Operational Flexibility	Thermal Performance	Dispatch Optimization	Outage Management	Portfolio Planning	Optimal Outage Planning
Digital Twin Model Type	Lifing			✓	✓		✓	✓	✓	✓
	Anomaly	✓	✓	✓	✓		✓	✓		✓
	Thermal	✓			✓	✓	✓	✓	✓	✓
	Transient				✓				✓	

For information on GE Power Digital Solutions:
www.ge.com/digital/power

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www.predix.com

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