END-TO-END AUTONOMOUS PLANT

Honeywell

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LIST OF ABBREVIATIONS

Abbreviation	Definition
PID	Proportional- derivative-integral
APC	Advanced process control
EU	Engineering units
L4	Level 4
Model ID	Model Identification
MQI	Model quality index
MPC	Model based predictive control
DCS	Distributed Control system
EKG	Enterprise Knowledge Graph

A VISION OF THE AUTONOMOUS PLANT

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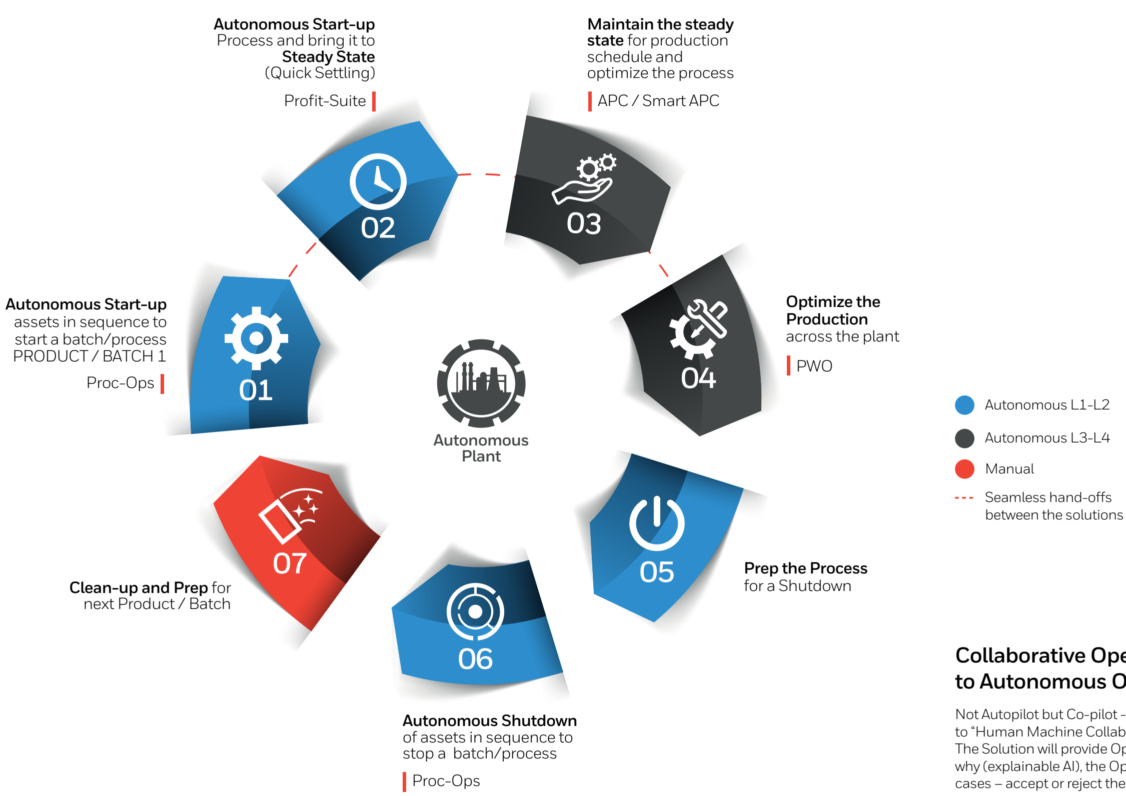
Plant operations in process industries are traditionally the responsibility of both the operational technology (OT) and information technology (IT) teams.

> The former focused on engineering and operations, the latter on the business, managing people, work processes, and technology.

However, over time the way people use technology has changed. Plants have moved towards automated operations through well-integrated and well-applied digital automation technologies. These include distributed control systems (DCS), programmable logic controllers (PLC) and safety integrated systems (SIS). These technologies have not only centralized operations in the control room, but enabled automated start-up and shutdown procedures and higher-level closed-loop solutions like advanced process control (APC) and real-time optimization.

In fact, with further advances in digitalization and ongoing convergence of OT and IT, the process industries are gradually moving from "automated" to "autonomous" operations: With solutions that can utilize predictive maintenance, data contextualization, visualization and analytics as well as systematically execute processes without human intervention and reach predefined goals through independent decisions and adaption to changing conditions by drawing on a whole range of data and intelligence captured across the organization, from both OT and IT systems.

END-TO-END AUTONOMOUS OPERATIONS



Collaborative Operations leading to Autonomous Operations:

Not Autopilot but Co-pilot - Moving from Human Machine Interface to "Human Machine Collaboration."
The Solution will provide Operator on what action is being taken and why (explainable AI), the Operator will oversee and maybe in certain cases – accept or reject the actions....

Autonomous operation provides potential for greater plant stability, controllability and efficiency – an opportunity to move towards safer, more consistent and optimized operations with less human intervention and more business value. It does not seek to replace human direction, but empower and augment it, enabling effective enterprise-wide decision-making in real-time.

This white paper discusses the move from automated operations to autonomous operations and the critical components that contribute to making the autonomous plant concept a reality and success.

Crucially, we propose that to experience the full benefits of autonomous operations, we should move away from a project-based approach focused on either the plant start-up, stabilization or shutdown. Instead, we should move towards a lifecycle-focused approach that seeks autonomous operations across them, providing a seamless transition through each stage.

- Autonomous start-up and shutdown using procedural automation solutions
- Faster stabilization, control and real-time optimization of process units through advanced process control
- Expanding the scope of optimization site-wide and enterprise-wide and closing the gap between process optimization and business planning through plantwide optimization solutions
- Predictive maintenance
- Visualization and contextualization of data.

AUTONOMOUS START-UP AND SHUTDOWN

2

> The process plant start-up involves a series of activities and procedures enabling a safer and more effective way to bring a plant or facility into operation.

It is initiated by gradually introducing the feedstock or raw materials into the system and bringing online different equipment and sections of the unit according to a standard operating procedure (SOP). It takes equipment, units, or processes from an idle state to their normal operating state while operators closely monitor the process parameters to ensure everything is within the safe operating range.

For some process units, the start-up can involve hundreds of steps and an array of process equipment. It is also not a routine operation, being conducted relatively infrequently, so that operators may be relatively inexperienced in its execution. The process can last days and requires coordinated efforts, effective human-to-human and human-machine interactions, properly documented procedures and adequate operator training to execute it correctly. Failure to do so can increase the duration (reducing efficiency) and may make start-ups more risky than normal operation. According to the Center for Chemical Process Safety[1], process safety incidents occur five times more frequently during start-up than during normal operations.

Automating this process can bring several benefits, including increased efficiency, improved safety, reduced human error, and enhanced operational control.

Honeywell's Automated Procedural Operations solution, ProcOps, for example, provides an autonomous start-up procedure that is fully integrated with Honeywell's Experion® System. ProcOps converts procedures into a sequence program using a structured set of commands, instructions, and verifications. It also creates HMI visualizations to show procedure steps, enable monitoring and control of the process, and facilitate interaction between the automated procedure and the operator.

AN EXAMPLE: START-UP OF A PROCESS BOILER

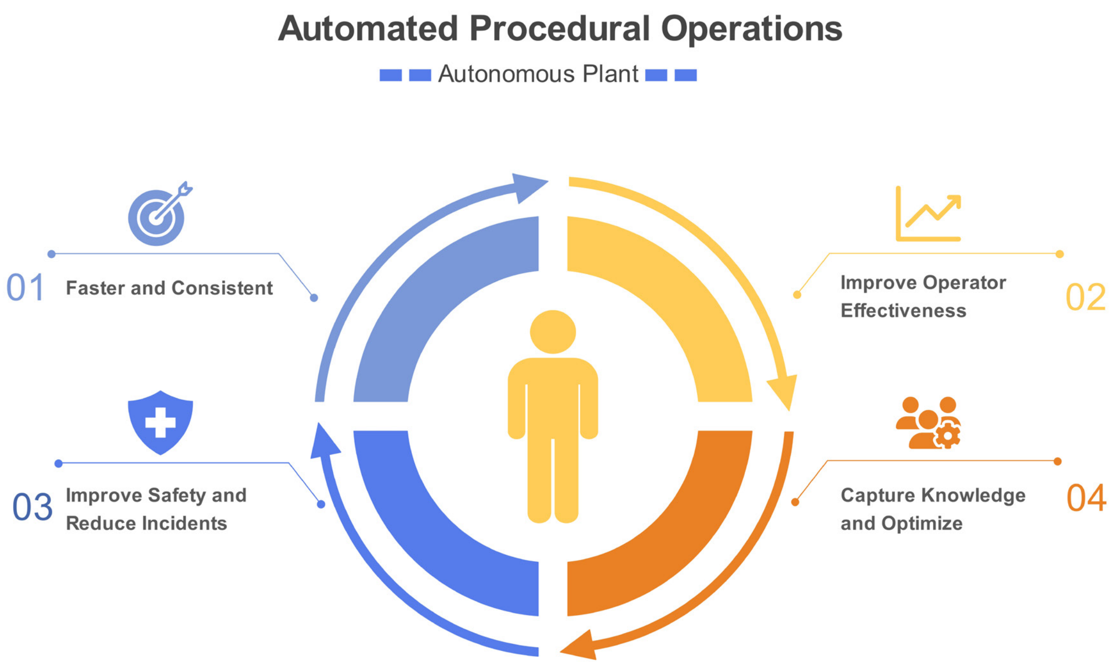
The benefits of an autonomous start-up using ProcOps can be seen in a practical example of a process boiler (although the same concepts can be applied to any other equipment or unit).

Among the first activities in the boiler start-up is the Pre-startup safety review (PSSR). This is an important first step in preventing safety incidents, protecting the boiler, and saving costs. Experion®-integrated electronic work instructions and mobile and handheld devices enable seamless interactions to complete PSSR efficiently and create an accountable and trackable record of PSSR inspection.

IN USE, PROCOPS CAN ENABLE SEVERAL BENEFITS IN AUTOMATING THE START-UP OPERATIONS:

- Increased production through faster, safer, and more consistent start-ups
- Reduced operator loads, reducing the operators' work, improving their effectiveness, and helping them make faster, better decisions by prioritizing information, presenting value-added context, and improving situational awareness through effective HMI principles and a philosophy based on Abnormal Situation Management (ASM) guidelines for human factors (HF)
- Capturing experienced operators' knowledge, best practices and intellectual property to enable novice operators to operate like experts
- Improved safety and reduced incidents
- Optimized start-up procedure and improved regulatory compliance
- Improved operator knowledge and experience through a training simulator (OTS).

ProcOps can provide significant flexibility when it comes to automating procedures. For a boiler start-up, it addresses the operation of feedwater systems, fuel systems, forced and induced draft systems, burners, and other interrelated components. Using the built-in equipment modularization and synchronous execution capabilities for these, the boiler start-up can be optimized to reduce the time to reach the rated operating steam pressure and meet other KPIs.



Advanced configuration capabilities in Experion®, meanwhile, enable the automated procedure configuration to be standardized and extended to other boilers using user-defined templates. Custom algorithm blocks extend the functionality for monitoring and control through user-defined algorithms and data structures.

ProcOps is also capable of complex control and alarm management, which can be used to make complex control actions during boiler start-up fully autonomous. These include control of fuel/air ratios, steam pressure, feedwater, draft, purge cycle, and fuel pressure to ignitors. Another key feature is the ability to proactively monitor abnormal events by mining sequential patterns with time constraints and, with the ability to, pre-emptively park the boiler in a safer state to head off a process upset. With ProcOps, intelligent handling of abnormal situations and deviations from normal operating conditions, and recovery from them can be built into the automated boiler start-up procedure.

These benefits can be further built on by leveraging other autonomous technologies. Operator effectiveness, for instance, can be further enhanced with the Operator Advisor functionality in Honeywell's Augmented Lookahead Operations (HALO) solution. HALO uses advanced machine learning and analytics to measure and improve operator performance by allowing them to anticipate and respond pre-emptively and easily to potential failures.

AUTONOMOUS SHUTDOWNS

Much the same principles apply to the shutdown, which, for a boiler, is effectively the reverse of the start-up sequence, taking the boiler from normal operations to an idle state. The same is applicable whether it is a planned, scheduled shutdown or unplanned and unexpected. Whatever the reason, the shutdown must be orderly, safe, and support a quick recovery of normal operations – especially when the cause of the shutdown is an abnormal event.

The same requirements and challenges detailed above for start-ups apply to shutdowns, including the possibility of operators lacking experience and knowledge since turnarounds happen relatively infrequently compared to normal operations. Again, using ProcOps, the necessary procedural steps and operator knowledge can be properly documented and captured in an automated sequence, increasing the probability of operators safely executing a shutdown.

While many of the same responses are necessary for planned or unplanned shutdowns, the latter can be particularly hazardous and pose serious risks to equipment, environment, and life. Nevertheless, a well-designed automated procedure will help to mitigate the risks. For instance, ProcOps provides multiple execution handlers to automatically address abnormal events and take the boiler to a safe operating state. Again, HALO capabilities can also be leveraged to pre-emptively respond to potential failures.

Both approaches help to prevent process upsets and will enable the boiler to return to a normal operating state quickly and safely.

STABILIZATION AND OPTIMIZATION

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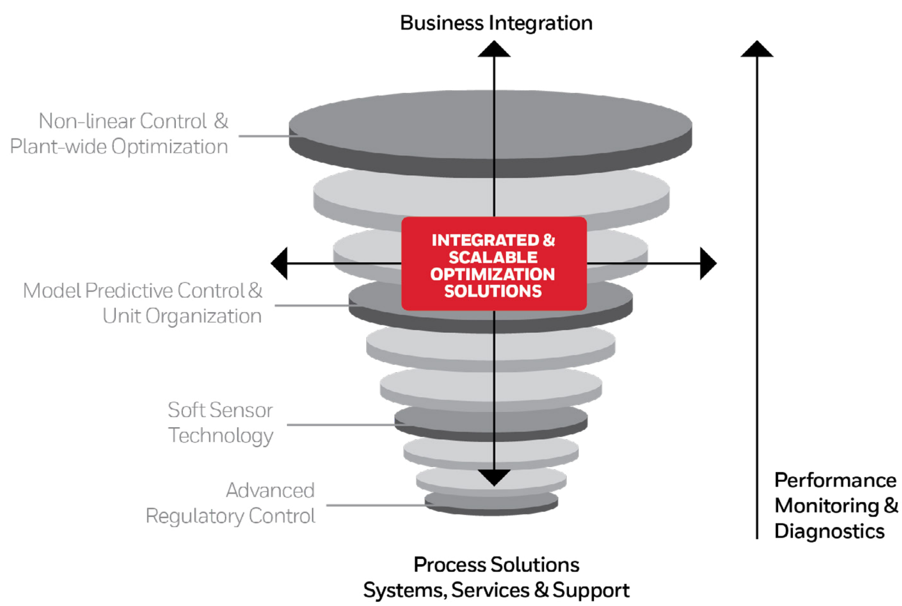
Start-ups and shutdowns are vital to any plant's smooth and safe running. According to a study released in 2010 by process safety engineering associates of ExxonMobil[2], 50% of process safety incidents occur during such transient operations, despite the fact that they account for only 10% of the plant's operational time.

Nevertheless, that still leaves 50% of incidents, according to such study that occur during normal operations. Moreover, these account for the remaining 90% of the running time and will be where the greatest opportunities for efficiency and productivity from autonomous operations can be found.

Once the plant goes through the start-up sequence, therefore, an integrated solution should allow plant operation control to be seamlessly handed over to an advanced process control (APC) application that can ramp up the unit to its normal operating load in a stable manner.



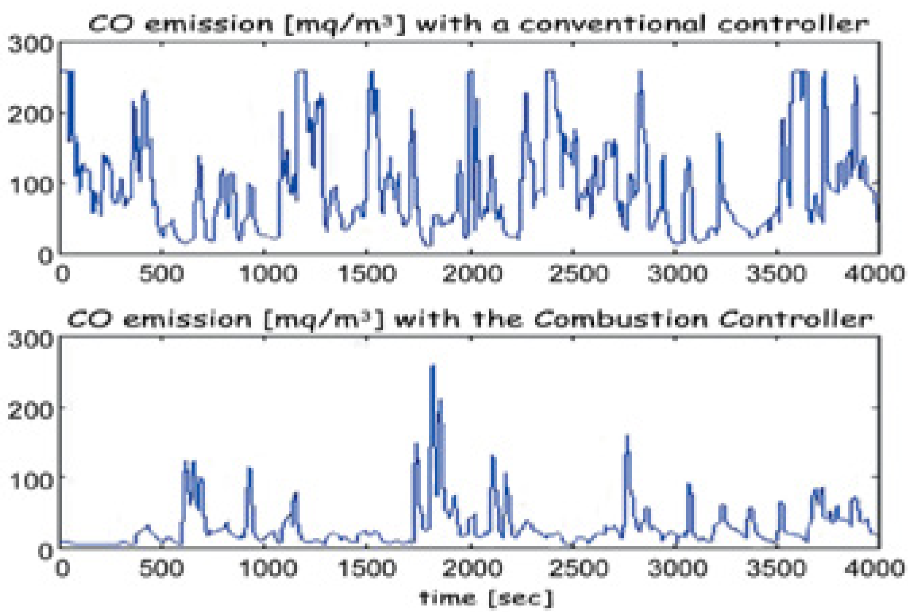
USING AN APC APPLICATION TO STABILIZE PLANT OPERATIONS CAN HAVE SIGNIFICANT ADVANTAGES:

- Reductions in process variations beyond those possible with traditional PID control, resulting in more stability
- Increased automation in normal operation, such that, under normal operating conditions, operators do not need to touch the process at all, helping standardize plant operations.
- Continuously optimized operation, whether that's operating at the maximum throughput, lowest specific energy consumption, highest margins, or a combination of these
- Strict adherence to process limits under all conditions, improving safety and stability.

Again, the example of a boiler is illustrative.

Devising an APC strategy for boilers requires understanding some fundamentals of boiler process modelling. While detailed, first principles modelling of boilers can be complicated, for real-time optimization of an existing system, it is not justified nor required; the usual practice is to use equipment performance curves, such as boiler efficiency curves, to predict their behavior in the normal operating range.

Honeywell's APC Advanced Energy Solution (AES) is a solution set for controlling and optimizing steam and power plants, including boilers. AES comprises a set of function blocks to supplement the capabilities of Honeywell's APC and address the unique challenges in boiler control and optimization. Specifically, it is designed to cope with the fast dynamics, continuously changing steam demand, non-linear optimization, and different kinds of boilers used in power plants.



While the example here is a boiler, the benefits of APC can be realized across a wide range of equipment and units in a process plant.

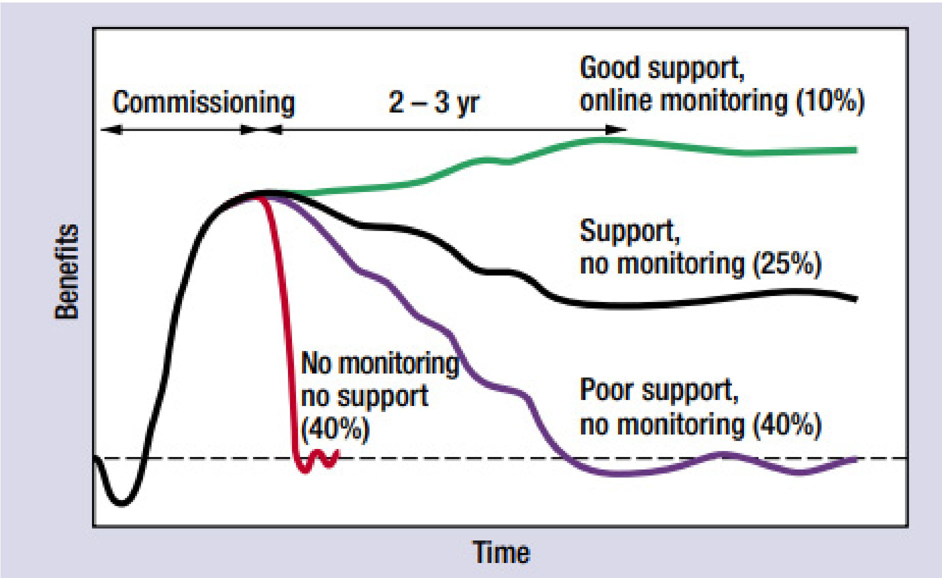
Honeywell's suite of advanced control products includes its flagship process controller, a model-based predictive controller that can provide benefits to a wide range of different process units worldwide. Key features include smart handling of high-frequency dynamics, minimization of the number of control variables (CVs) in an active set to reduce controller moves, condition number minimization offline and online through a well-conditioned matrix, performance ratio tuning for systematic tuning of each CV, and straightforward handling of infeasible solution (using EU give-up high and low). It also features an embedded historian, online integrated trending, historical playback of live data, an L4 user interface, and an online modeler that automates both stepping and model ID for on-the-fly reloading of new models.

THE SPECIFIC AES OBJECTIVES APPLICABLE TO BOILERS ARE AS FOLLOWS:

- Combustion control and optimization of the boilers
  - a. Tight control of the stoichiometric air requirements through control of the air-to-fuel ratio
  - b. Minimizing excess oxygen and optimizing oxygen value.
  - c. Maintaining boiler emissions within operator-defined limits.
- Economic allocation for boilers by minimizing the cost of fuel consumed for a given demand of steam. This is done by distributing steam production between boilers to minimize the total cost of production.

SUSTAINING APC BENEFITS AUTONOMOUSLY

While the benefits of APC are well established, so too is their tendency to degrade over time. New feedstocks being processed, changes in the operating envelope, new product mixes, varying energy costs, equipment fouling and other changes to the process not reflected in the APC's assumptions can see its performance deteriorate. APC model predictions no longer match the plant, and inferential properties become inaccurate.



However, the benefits of APC applications can also be sustained autonomously through a two-step process.

First, remote monitoring of APC applications can provide actionable insights and recommendations. This can be achieved using Honeywell's Control Performance Analytics- Unified (CPA-U). This ties together the APC and underlying PID maintenance requirements through an integrated approach. Key performance metrics provided by CPA-U include APC benefits, cost of lost opportunity, overall uptime, a model quality index, attainment index and inferential quality index. CPA-U is hosted on Honeywell Forge and can then be accessed by Honeywell experts, enabling collaboration with customers based on the insights and recommendations generated from the application.

Second, Honeywell's Online Modeler can close loops autonomously, improving models that have a low MQI, as flagged by CPA-U. Honeywell Online Modeler provides integrated data collection, automated step testing, and model identification. It works in a closed loop with Honeywell APC applications to provide updated models based on present plant conditions. It rigorously complies with MV limits and maintains control objectives in closed-loop operation and is also integrated into the operator interface for full visibility.

ENTERPRISE DECISION MAKING THROUGH SITE-WIDE OPTIMIZATION

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While the benefits of APC for individual unit-level optimization units are well established, site-wide or enterprise-wide optimization is expected to add to these substantially.

Moreover, a seamless orchestration between functional silos (the process and the business) to drive common optimization goals has come to be a focus of the move towards autonomous operations.

To stick with the example of a boiler, this would mean expanding from optimization of a single boiler to multiple boilers, allocating the total steam load between several boilers or turbines across the site based on efficiency, and maintaining and stabilizing the steam headers in terms of pressure control, and to minimize steam venting. Coordinating power plant boilers with the process boilers at a site level, and planning utilities production based on plant production, could add huge value.

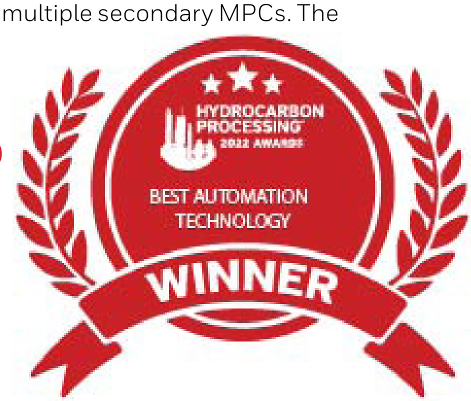
Traditional process control and optimization do not effectively connect key functions across different levels of optimization. Planning and scheduling in the case of a refinery, for example, are not fully synchronized to dynamic operations, limiting organizational agility to shifting market conditions. Optimizing an entire enterprise across units in a coordinated way enables the business to maximize profit and make the most of changing opportunities.

PLANTWIDE OPTIMIZER

Honeywell Plantwide Optimizer (PWO) is an integration layer between business planning and process control. It closes the gaps between the two functions, integrating the planning and execution layers. It defines a simplified wide-scope optimization problem at the top (similar to a planner's model) while respecting constraints within the lower-level APC applications for more effective optimization.

Structurally, Plantwide Optimizer is a 1-to-n model-based predictive control (MPC) cascade: A single primary MPC cascades onto multiple secondary MPCs. The

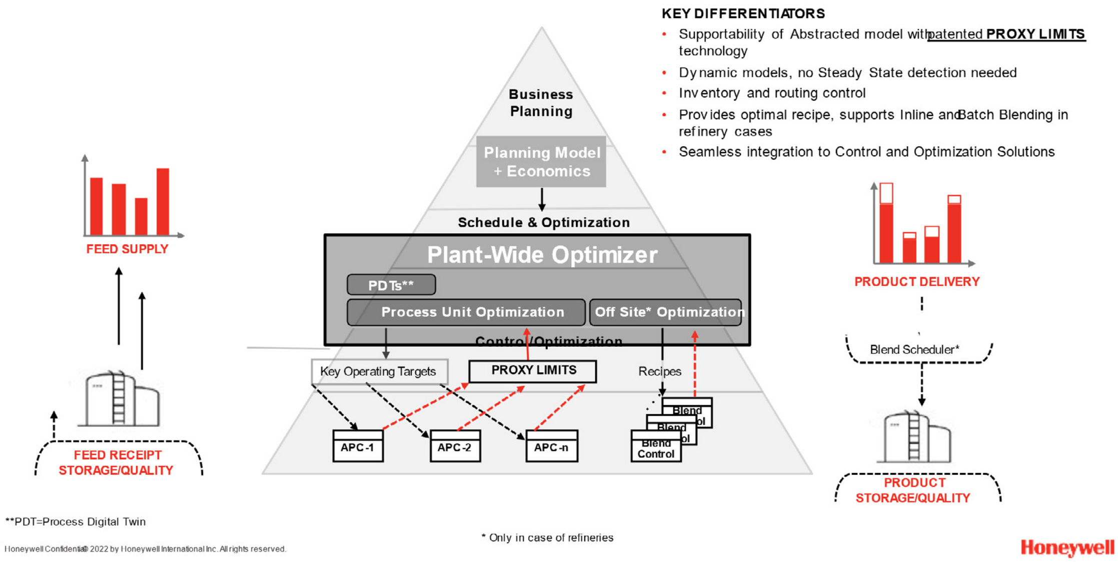
HONEYWELL PLANTWIDE OPTIMIZER IS RECOGNIZED BY HYDROCARBON PROCESSING AS 2022'S "BEST AUTOMATION TECHNOLOGY"



primary MPC employs a dynamic, high abstraction level (coarse scale) model. The secondary MPCs use dynamic, low abstraction-level (fine-scale) regular MPC models. If secondary MPCs are deployed at every process unit, then the primary MPC can solve the plantwide production control problem dynamically in a closed loop.

PWO also uses a flowsheet model to describe the site configuration (i.e., process units, inventory tanks, blenders, splitters, and the routing network) and how

IMAGE OF PLANTWIDE OPTIMIZER
in terms of solution architecture and components



streams can be merged or spitted (or blended in a refinery) to feed the downstream operations. For each unit, a dynamic yield-property model is specified to describe the input-output yield-property relationship. The flowsheet model will then incorporate all unit-level yield-property models to form a global, dynamic hybrid model for online use, similar to the way standard APC models are used online.

Applied to refineries, PWO's scope can be expanded to product blending operations (batch and rundown) and can include inventory constraints for true gate-to-gate optimization.

PREDICTIVE MAINTENANCE

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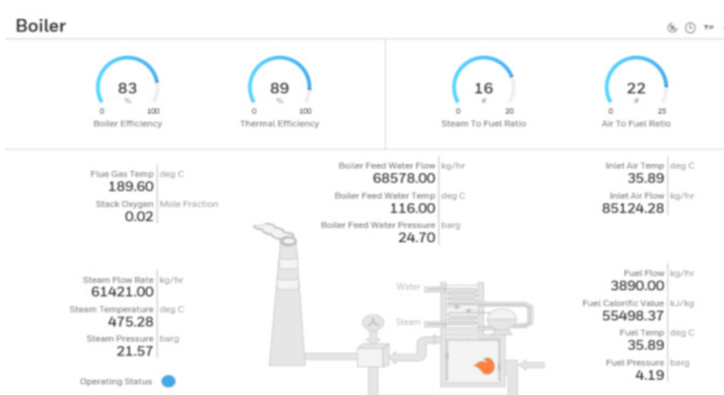
Finally, we should highlight two enabling technologies crucial in supporting the move to autonomous operations and optimization.

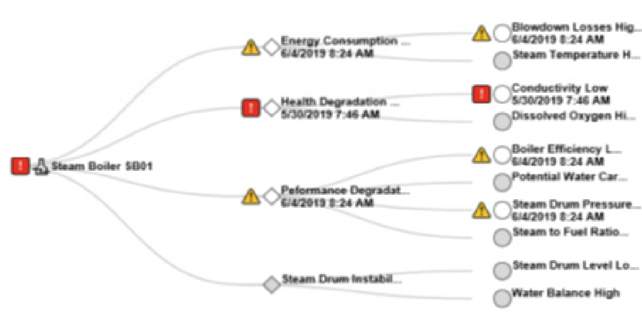
The first is predictive maintenance, which protects the benefits autonomous technologies bring by controlling maintenance costs and ensuring equipment's reliability and performance.

In the case of the boiler, for example, monitoring machine health data in addition to boiler operating conditions helps maintain reliable boiler operations. Honeywell's Forge Asset Performance Management integrates process and asset data with wide-ranging standard asset libraries. It combines performance monitoring with machine learning and predictive analytics, enabling industrial facilities to predict and prevent asset failures, improve operational performance, and manage reliability and maintenance efficiently.

The standard boiler model for the solution includes process condition, energy, and performance monitoring. These help monitor boiler performance to increase availability and decrease energy costs. Key performance indicators, such as boiler efficiency, steam-to-fuel ratio, and built-in multi-variate advanced pattern recognition functions, continuously compare observed behaviors to those expected. This can identify very subtle changes and anomalies. Working in conjunction with embedded fault models, it enables predictive maintenance and root cause analysis.

The image below shows an example "Fault Tree" graphical display of assets and associated faults and symptoms. This provides a single view that can be used to quickly locate the source of a fault.





DATA VISUALIZATION AND ANALYTICS

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The second key enabling group of technologies for autonomous operations that should be highlighted is visualization and data.

This provides real-time data insights to enhance operational efficiency, reduce manual intervention, and support proactive decision-making to optimize performance and address operational challenges.

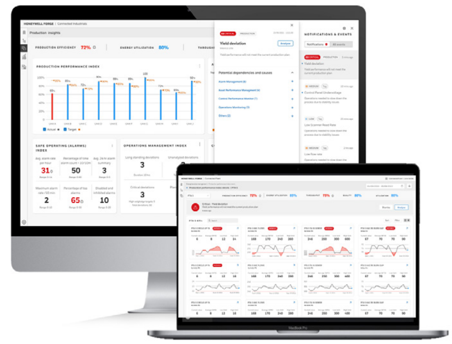
Honeywell's answer is two-fold: First, its next-generation visualization solution for the control room, the Experion Orion Console. With an ergonomic design to improve operator comfort and reduce fatigue, it features large ultrahigh-definition screens for flexible layouts of overview and detail displays, as well as related applications and video. The console enables the operator to become more efficient, respond faster to abnormal situations and handle greater scope and responsibility.

Honeywell's Forge Performance+ for Industrials – Production Intelligence solution, meanwhile, is a cloud-based product that provides enterprise intelligence. It draws on cross-functional, multidimensional data from the process, control, assets, alarms, and operations limits. By unifying this traditionally siloed and complex data, users gain insights to streamline operations and extract additional business value through data collection, contextualization, relationship synthesizing and OT analytics.

THE WORKFLOW ILLUSTRATES THIS:

- Collect & Prepare Data – Extract Base Relationships. This extracts base plant data items and relationships from the DCS and historians to help users understand data's context.
- Contextualize Overlay Application Knowledge. The platform overlays relationships and knowledge from siloed applications to create the Enterprise Knowledge Graph (EKG), which enables cross-functional collaboration.
- Production Intelligence-Synthesize Relationships. The root causes of plant issues are automatically identified through events, cross-correlated data and metrics based on logical clusters identified in the EKG.
- Future Recommendations-OT Analytics. The solution provides users with actionable insights and analytics-driven recommendations to help maximize production operations and achieve meaningful KPIs.

HONEYWELL FORGE Performance+



Built in partnership with Microsoft

CONCLUSION

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Automation has already revolutionized the industrial landscape, and autonomous plant operation is ushering in a new era of efficiency, productivity, and sustainability.

Advanced technologies for autonomous start-ups, shutdown and normal operations enable plants to operate with minimal human intervention, streamline processes, and optimize resource utilization for better safety, reduced downtime, and increased profitability, as well as improved sustainability through minimizing waste, energy consumption, and emissions.

The various field-proven solutions detailed in this paper offer a compelling return on investment. However, the value they bring can be amplified through an even more integrated approach: First, we are already seeing operators take proven plant-level approaches to optimization and autonomous operations and applying these across sites and enterprises to achieve new levels of efficiency, reliability, and safety.

Second, industrial operators will increasingly look beyond individual solutions for the plant start-up, shutdown and operations to a holistic vision and strategy for autonomous operation across the lifecycle. Working with their technology partners they will seamlessly transition from start-up through to stable production, shutdown, and turnaround. This embrace of autonomous operations will open opportunities to take performance to new heights, and help reshape industries across the globe.

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