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Next-gen digital twins: automating model lifecycle management

Optimising simulation frameworks for enhanced reliability and predictive accuracy

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Refineries depend on process simulation and linear programming (LP) models to support daily operations, long-term planning, and emissions-reduction strategies. As assets become more integrated and operating conditions shift more frequently, keeping these digital twins accurate has become increasingly difficult. Even well-built models can drift from reality as equipment performance changes, feed variability increases, and data quality fluctuates.

This degradation often happens gradually, without clear warning, until planning assumptions no longer match actual operating constraints. The consequences can include reduced optimisation, higher energy use, and diminished confidence in simulation-based decisions.

But what happens when these simulation models or digital twins fall out of sync with reality? When the digital reflection of the plant no longer mirrors its physical twin, how quickly does performance drift, and what does that mean for profitability and sustainability?

Despite growing reliance on digital twins, model calibration and validation remain largely manual in many refineries. Engineers must reconcile data from multiple sources, evaluate deviations, and adjust model parameters to reflect current plant conditions. This work requires time, domain expertise, and coordination across teams. Unfortunately, human resources are becoming increasingly scarce.

At the same time, market pressures are intensifying. According to Wood Mackenzie, more than 20% of global refining capacity is at risk of closure by 2035, based on an analysis of 420 sites.[1] Operational performance will determine which facilities remain competitive. To remain competitive, refiners are accelerating investment in automation and digital technologies. The global digital transformation market in oil and gas is projected to grow by \$56.4 billion between 2025 and 2029. This equates to a compound annual growth rate (CAGR) of about 14.5%.[2] This surge reflects a broader shift. Digitalisation is no longer experimental but a core element of operational strategy.

Divergence of model sophistication and maintenance scalability

As refinery units or assets become increasingly integrated, dynamic, and data-intensive, model sophistication is outsmarting the maintenance of these simulation models affecting scalability. Manual recalibration protocol simply cannot keep pace with the frequency of changes in modern refining. If the models appear to be outdated and do not align with actual predictions, the lag creates a credibility gap, hence diminishing optimisation potential. Without the ability to automate model or digital twin maintenance, these deviations compound.

In practice, model degradation rarely presents sudden failure. Instead, small deviations accumulate over time as equipment fouling, catalyst ageing, feedstock variability, and instrumentation drift alter plant behaviour. Optimisation decisions based on outdated assumptions gradually move operating targets away from true process constraints. Energy integration is becoming less efficient.

Hydrogen management margins are tightening, and planning models are beginning to reflect assumed rather than achievable performance. Since these deviations occur incrementally, they can be accepted as normal operational variability rather than recognised as model inaccuracy. Over time, however, this silent divergence reduces optimisation effectiveness and erodes confidence in simulation-driven decision-making.

> **To overcome the limitations of manual interventions or sudden recalibrations, a new generation of automated maintenance applications integrates process simulation, machine learning, and cloud computing**

Maintaining digital twin accuracy is much like monitoring a refinery's heartbeat. Without regular diagnostics, its rhythm falters. Without timely care, the system weakens. Daily monitoring and quantifying the extent of deviation acts as preventive maintenance, keeping the model's pulse steady and its predictions trustworthy.

Streamlining model maintenance

The integrity of a digital twin is defined by its ability to mirror physical reality through precise predictions. To overcome the limitations of manual interventions or sudden recalibrations,

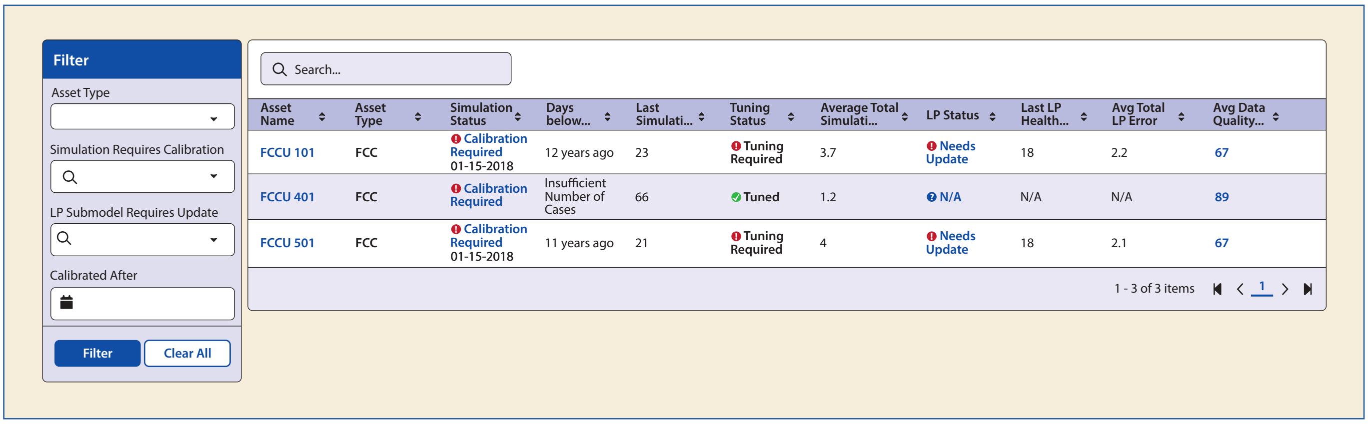

Figure 1 Asset overview dashboard showing model health scores, calibration requirements, and data-quality indicators

a new generation of automated maintenance applications integrates process simulation, machine learning (ML), and cloud computing to ensure that digital twins transform from a periodic, labour-intensive recalibration task into a continuous, self-monitoring lifecycle management system that keeps models remain aligned with live plant conditions.

This automated approach creates a continuous feedback loop that monitors model 'vital signs', such as prediction accuracy and data reliability. This allows engineers to intervene before deviations compromise performance.

Unlike purely statistical black-box tools, this framework applies first-principles rigour. This preserves engineering credibility while ensuring application-guided calibrations accelerate tuning without losing the physical meaning of the process variables. Cloud-based execution further enables this architecture to scale across multiple units and data sources.

As shown in **Figure 1**, the asset overview dashboard consolidates the status of multiple process models to display calibration status, health indices, and data-quality scores. Engineers can quickly identify which units are drifting out of tolerance and intervene before performance degradation occurs.

To complement this high-level view, **Figure 2** illustrates how specific process variables impact overall model health over time. Each colour band represents a key process variable contributing to the health score, allowing users to visualise which parameters are degrading and when recalibration is required.

The automation process follows a structured methodology from configuration to execution, beginning with the configuration of model performance indicators (MPIs), data quality parameters (DQPs), and key performance indicators (KPIs), along with site-specific error tolerances. Once deployed, the system performs two primary functions:

❶ **Autonomous degradation detection**: Health indices quantify deviations between simulated and measured data. When thresholds are exceeded, the system triggers automatic alerts, shifting the engineer's role from data analyser to action taker.

❷ **Automatic calibration and tuning**: Leveraging parameter optimisation, sensitivity analysis, and cross-prediction, the software evaluates calibration quality across multiple datasets. Parallel cloud computing allows rapid tuning cycles, while open interfaces support scalable deployment across multiple units or sites.

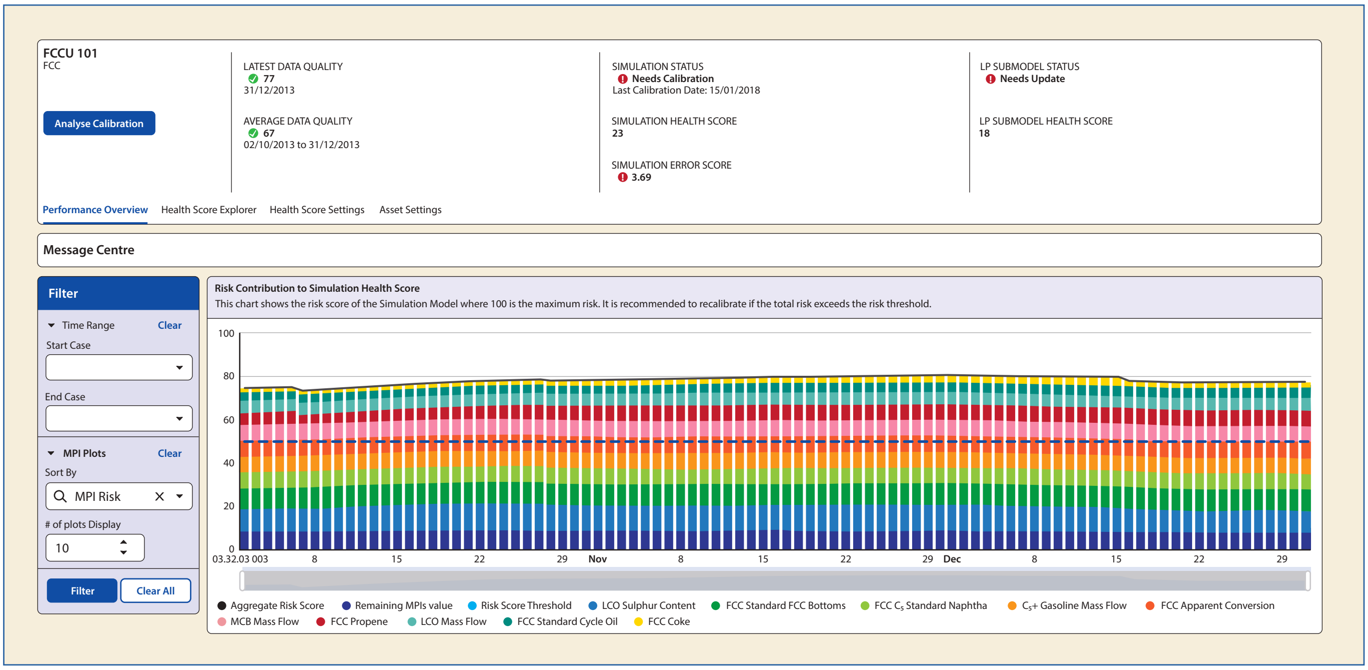

Figure 2 Detailed health-score dashboard showing data contributions to model performance and threshold tracking over time

At the core of the application is the health index, a composite metric combining deviation magnitude, data quality, and calibration history. It provides a single metric that quantifies the 'fitness' of each digital twin. Open REST APIs make this fitness score accessible across the enterprise, ensuring operational digital twins and planning models remain synchronised with the data historian.

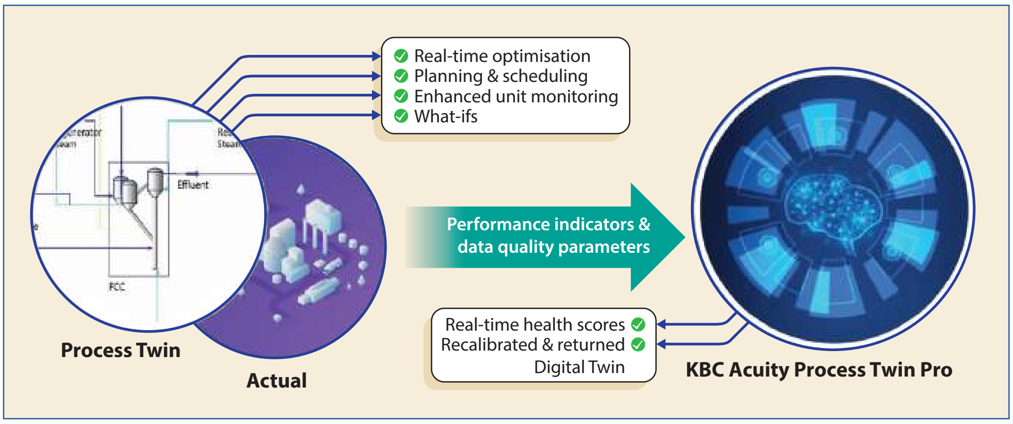

Figure 3 Real-time health scores update

As shown in **Figure 3**, this closed-loop cycle links the new-generation digital twin to the site-based digital twin or the simulation model. The site continuously feeds new, real-time information into the application, and this new information generates updated health scores.

Automating the lifecycle of the simulation models assures model integrity in near real time. It reduces manual workload and improves responsiveness to process changes. Unified dashboards provide enterprise-wide visibility, alerting engineers to emerging deviations and offering actionable recommendations. This approach supports safer, more stable operations and eliminates many of the bottlenecks associated with manual data reconciliation.

Continuous model maintenance at scale

Can automation really sustain digital twin accuracy at refinery scale? While the technology's principles are universal, its impact becomes clearest in real-world deployment. A pilot project in early 2024 at a 400,000 bbl/d integrated refinery and petrochemical complex aimed to find out.

The site operates multiple high-conversion units where accurate process simulation and LP alignment are critical to maintaining profitability and emissions compliance. Using the previously defined MPI, DQP, and KPI configuration, the project established a baseline to measure simulation accuracy, data fidelity, and operational impact across multiple units.

In practical terms, MPIs show whether the model accurately represents plant behaviour. DQPs evaluate whether the input data used for calibration and validation is reliable. KPIs connect model accuracy to operational outcomes. While MPIs and DQPs assess technical integrity, KPIs measure the impact on refinery performance, including energy consumption, throughput stability, hydrogen utilisation, and emissions intensity. In this way, KPIs indicate whether improved model fidelity supports better operational and economic decisions.

For each digital twin, a health index quantified the deviation between model predictions and actual plant data. When this index exceeded thresholds, the system automatically triggered recalibration protocols and notified the engineering team. This action closed the feedback loop between process data and model assurance.

The core of tuning leverages ML algorithms to execute parameter optimisation and cross-prediction. The application framework evaluated calibration performance across datasets and recommended parameter updates based on historical tuning behaviour. Sensitivity analysis identified variables with the greatest influence on accuracy. This step ensured recalibration focused on high-impact parameters, resulting in faster convergence and increased confidence in model adjustments.

Operationally, continuous model maintenance improved planning accuracy and responsiveness. It allowed the LP model to remain synchronised with current constraints, such as energy integration efficiency and feed variability. From a workforce standpoint, automation reduced dependence on scarce domain expertise. It enabled fewer engineers to manage more complex systems while maintaining confidence in model integrity.

Quantifiable performance and safety outcomes

Refinery studies have begun to quantify the operational impact of digital twin deployment beyond conceptual benefits.[3] Reported results include measurable reductions in unplanned downtime, energy consumption, and maintenance labour requirements following digital twin implementation, demonstrating that improved model fidelity and predictive capability translate directly into operational and financial performance improvements. These findings reinforce the importance of maintaining digital twin accuracy over time, as the economic value of the technology depends on sustained alignment between the digital model and physical asset performance. As shown in **Table 1**, early deployments show projected measurable benefits.

Continuous monitoring of health indices prevents small misalignments from becoming major operational upsets. Automated recalibration minimises flaring, maintains stable

Projected performance improvements from continuous automated model maintenance based on early refinery deployments

Metric	Projected result (per large refinery)
Engineering hours saved	More than 4,000 hours per year
Model-tuning speed	10 times faster model tuning
Margin improvement	$0.5-2 million per asset per year
CO_2 reduction	≈2,500 t per asset per year

Table 1

control, and reinforces risk prevention across high-intensity units. Data integrity underpins these capabilities. Cloud deployment on secured industrial infrastructure ensures that calibration data and simulation outputs remain consistent and traceable, preserving model credibility for both engineering decisions and compliance audits.

Simplifying complexity and sustaining expertise

Automation helps bridge a widening workforce and skills gap across the energy and chemicals sector. Deloitte notes that the need for science, technology, engineering, and mathematics (STEM) talent, particularly in advanced engineering, operations, and analytics, already exceeds the available supply. At the same time, a significant portion of this workforce is preparing to retire, which intensifies the challenge of maintaining complex models and sustaining institutional knowledge.

According to Deloitte, more than 1.2 million workers, representing roughly 60% of the energy and chemicals workforce, will require upskilling in digital technologies, processes, operations, and analytics to meet emerging operational demands.[4] As digital systems become more deeply embedded in asset management and optimisation, refiners must balance this growing skills requirement with tightening labour availability.

> **Automating model maintenance represents a decisive step toward the industry's vision of autonomous, digitally optimised operations**

By automating routine calibration tasks, continuous automated model maintenance applications enable smaller teams to manage larger, more complex operations. Junior engineers can focus on analysis rather than manual reconciliation while experts apply their knowledge to refining optimisation strategies. In essence, automation preserves process knowledge, prevents institutional 'drift', and promotes data-driven discipline.

Standardised dashboards and guided workflows democratise access to model data. They make digital twin maintenance accessible across disciplines, from process engineering to planning and energy management, and support more integrated decision-making.

Conclusion: towards the autonomous refinery

Automating model maintenance represents a decisive step toward the industry's vision of autonomous, digitally optimised operations. By integrating domain expertise and automating a simulation framework powered by cloud computing, refineries can develop next-generation digital twins that evolve in step with their physical assets.

This transformation turns process simulation from a periodic engineering task into a continuous performance system, one that strengthens decision quality, reduces emissions, and enhances safety without adding complexity.

As digital twins mature, their role also evolves within refinery operations. Historically, simulation models were used intermittently to validate design assumptions, support troubleshooting, or evaluate capital decisions. Continuous lifecycle management changes this paradigm by allowing simulation frameworks to participate directly in day-to-day operational decision-making.

Planning, optimisation, and operational teams can rely on a shared and continuously validated representation of plant behaviour, reducing the disconnect that often exists between assumed optimisation and achievable operating conditions. Over time, this convergence enables more consistent decision-making across planning, scheduling, and operations, improving both responsiveness and confidence in model-driven outcomes. Rather than replacing engineering expertise, automated lifecycle management amplifies it by ensuring that institutional knowledge is continuously embedded within the digital representation of the asset. In this way, next-generation digital twins become not only analytical tools but operational systems that support sustained performance improvement across the refinery lifecycle.

Ultimately, the move toward automated lifecycle management ensures that the digital twin remains an asset rather than a liability. As refining becomes more data-intensive, this framework provides the necessary bridge between human expertise and computational power, securing a competitive and sustainable future for the process industries.

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