Hybrid MES POC Report – Real-Time Edge-to-Cloud Integration

1. Hybrid MES: The Bridge Between Legacy and Cloud

Why It's More Than Just a Trend As industries accelerate toward digital transformation, Hybrid MES is emerging as the most practical and scalable architecture not just a buzzword, but a strategic enabler.

🔹 Why Hybrid MES Is Gaining Ground Real-time control at the edge Cloud-powered analytics and AI/ML Compliance with data residency regulations Resilience in low-connectivity environments

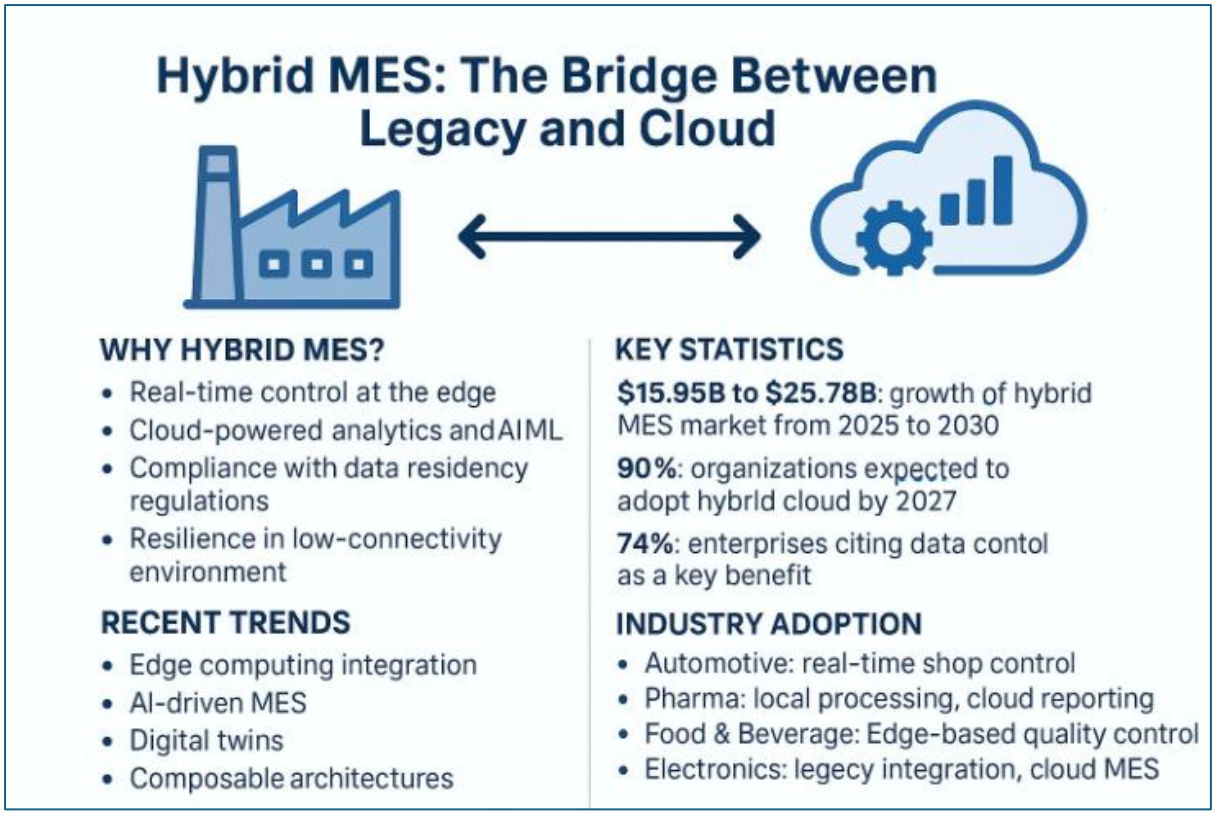
🔹 Recent Trends Driving Hybrid MES Adoption Edge Computing Integration: Enables real-time decision-making and uninterrupted operations. AI-Driven MES: Predictive maintenance, anomaly detection, and dynamic scheduling are becoming standard. Digital Twins: Used for simulation, optimization, and quality control. Composable Architectures: MES platforms are shifting from monolithic to modular, edge-ready designs. Cloud-Connected Intelligence: Vendors like AVEVA and Dassault are enabling centralized analytics across distributed plants.

🔹 Key Hybrid MES Statistics The global MES market is projected to grow from $15.95B in 2025 to $25.78B by 2030, at a CAGR of 10.1%. The hybrid MES segment is expected to grow faster than cloud or on-prem, driven by its balanced architecture. 90% of organizations are expected to adopt hybrid cloud models by 2027, with manufacturing among the top adopters. 74% of enterprises cite improved data control as a key benefit of hybrid cloud MES. Asia-Pacific is the fastest-growing region for MES adoption, fueled by smart manufacturing policies.

🔹 Industry Adoption Examples Automotive: Real-time shop floor control + cloud analytics for predictive maintenance Pharma: Local data processing for compliance + cloud integration for global reporting Food & Beverage: Edge-based quality control + centralized dashboards Electronics: Hybrid integration of legacy systems with cloud-native MES modules

🔹 Is Hybrid MES Just a Phase? Not at all. Until full cloud MES can match the latency, compliance, and integration needs of industrial environments, hybrid MES will remain the backbone of smart manufacturing. Even cloud giants like AWS are investing in edge solutions like Outposts, reinforcing the hybrid future.

🔹 The Future Outlook Hybrid MES is not just the Widely adopted across industries it's the language of transformation. It's the bridge between legacy systems and cloud-native innovation, and it's here to stay.



2. Hybrid MES: Where Edge Meets Intelligence In today's smart factories,

Hybrid MES is a strategic architectural choice it's the optimal architecture for balancing performance, compliance, and scalability.

🔹 Why Hybrid MES Works Edge Control: Real-time responsiveness on the shop floor Cloud Intelligence: Centralized analytics, AI/ML, and global visibility Regulatory Fit: Local data handling for compliance Operational Resilience: Works even in low-connectivity zones

🔹 Tech Synergy Leading MES platforms are enabling hybrid architectures:

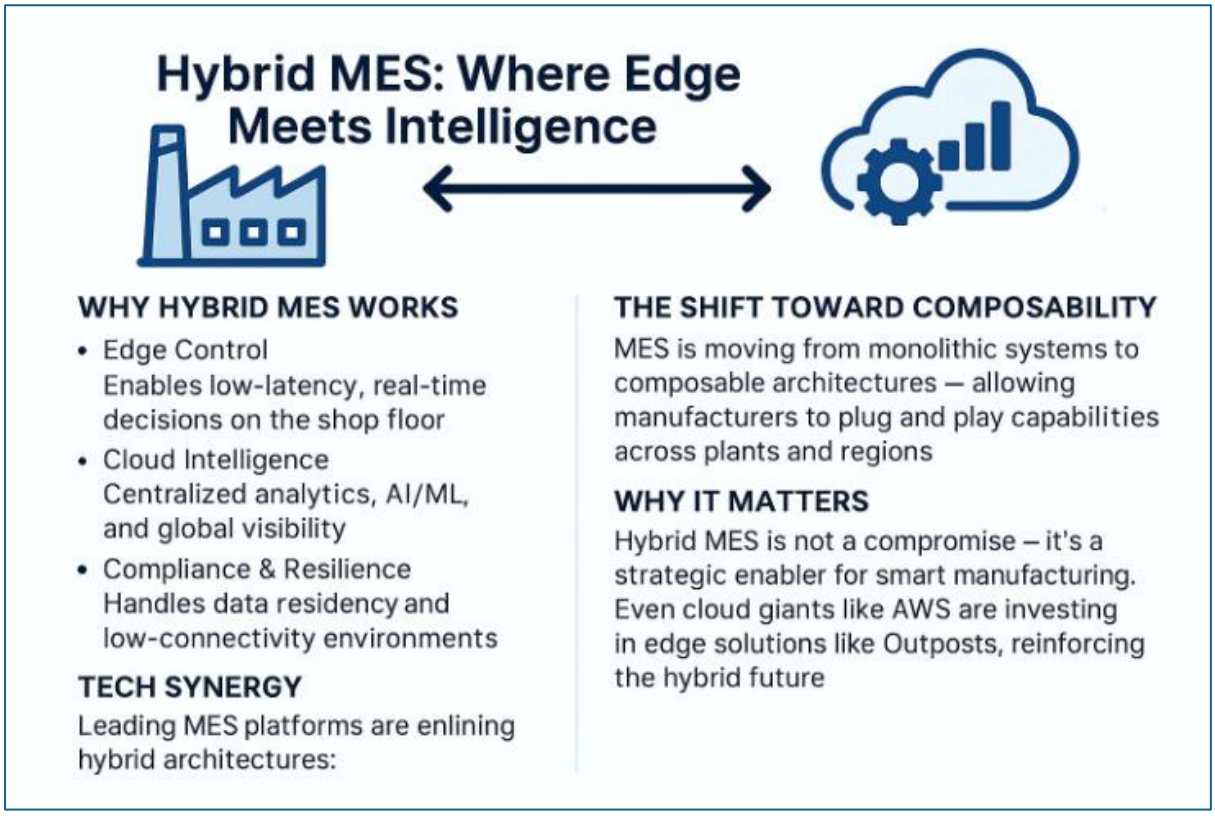
AVEVA: Model-driven MES with edge-ready modules

DELMIA Apriso: IaaS-based MES with cloud integration

Siemens Opcenter, Rockwell FactoryTalk, GE Proficy, Honeywell all evolving toward modular, hybrid-ready designs.

🔹 The Shift Toward Composability MES is moving from monolithic systems to composable architectures allowing manufacturers to plug and play capabilities across plants and regions.

🔹 Why It Matters Hybrid MES is not a compromise it’s a strategic enabler for smart manufacturing. Even cloud giants like AWS are investing in edge solutions like Outposts, reinforcing the hybrid future.



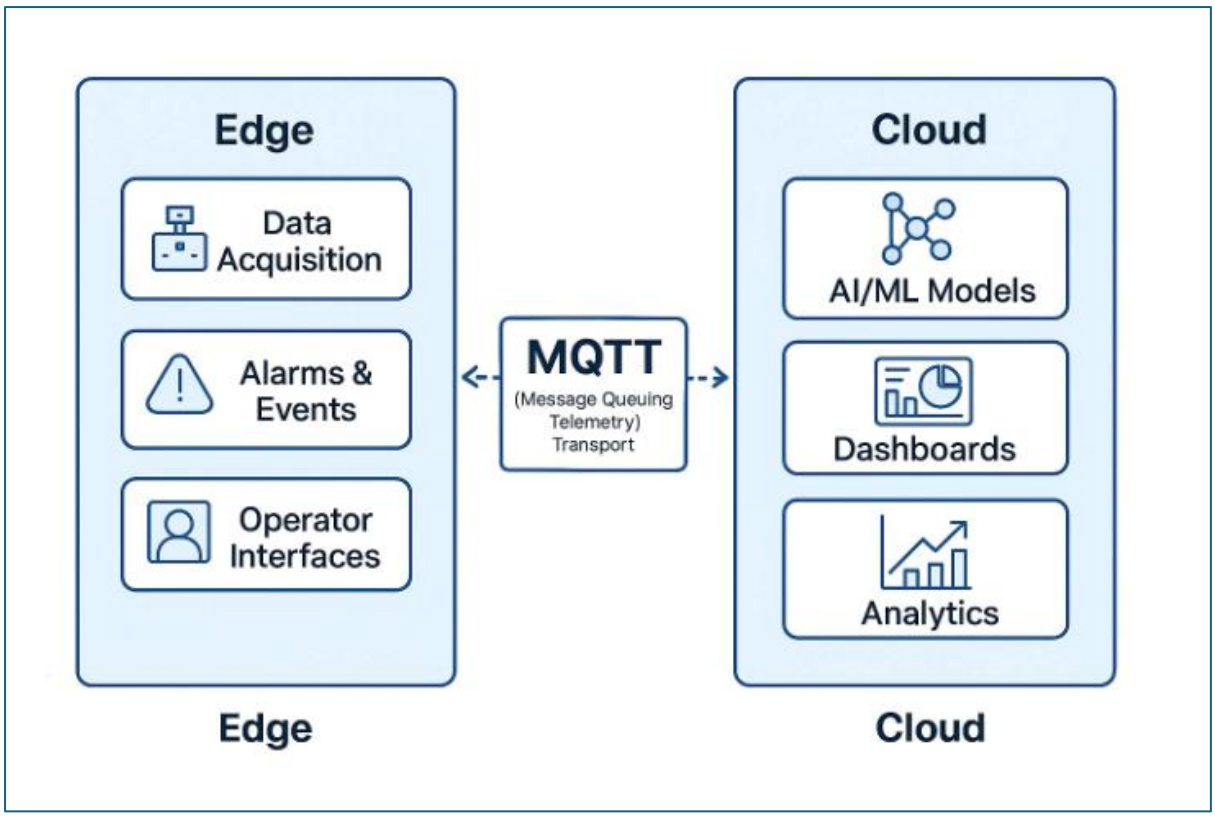
3. Hybrid MES: How Edge & Cloud Layers Collaborate in Smart Manufacturing

As industries embrace digital transformation, Hybrid MES is becoming the go-to architecture combining the speed of edge computing with the intelligence of the cloud.

🔹 Edge Layer (On Prem MES) Connects directly to machines, PLCs, and sensors Executes real-time operations like data acquisition, alarms, and operator workflows Ensures low-latency response and local resilience Ideal for environments with intermittent connectivity

🔹 Cloud Layer (AWS or Azure) Aggregates data from multiple plants Powers AI/ML models, dashboards, and historical analytics Enables centralized monitoring, benchmarking, and optimization Scales effortlessly across regions

🔁 MQTT: The Bridge Between Edge and Cloud MQTT (Message Queuing Telemetry Transport) is a lightweight, publish-subscribe protocol that enables efficient, real-time communication between edge devices and cloud platforms.



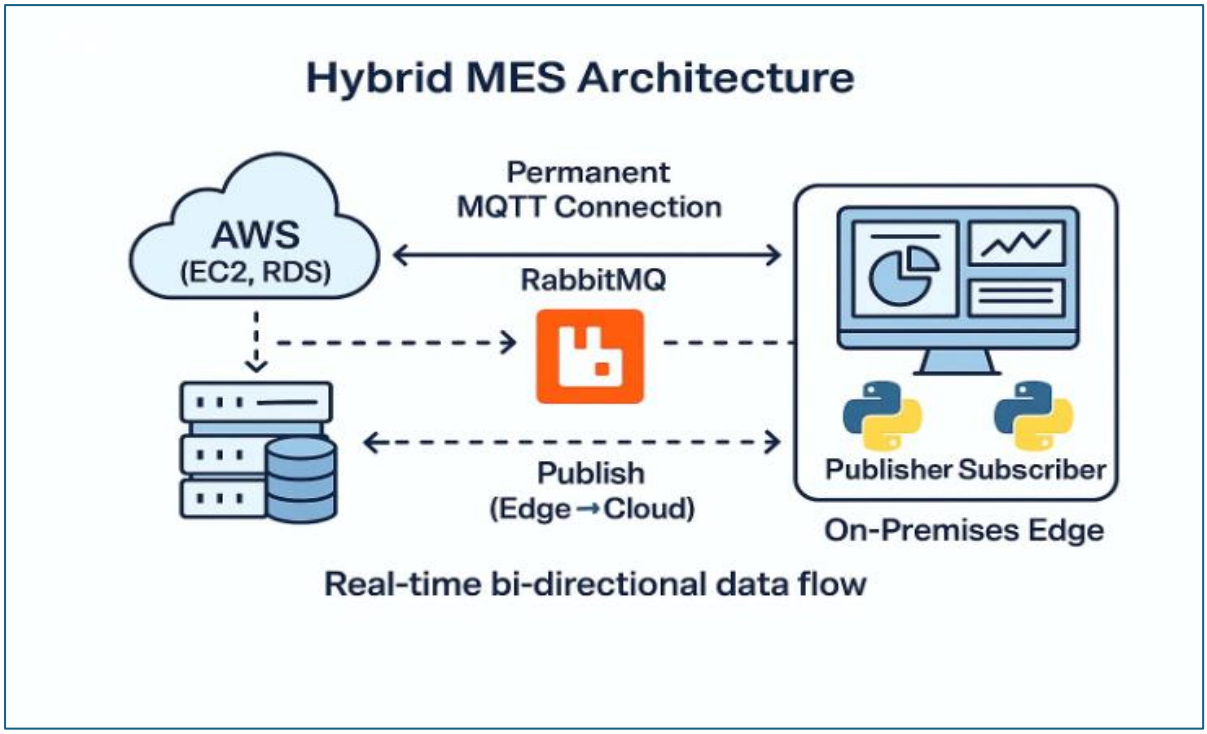
4. Hybrid MES Architecture – Why Real-Time Edge-to-Cloud Integration Matters
Modern manufacturing demands instant visibility and control across distributed environments. A hybrid MES approach enables this by connecting on-premises systems with cloud infrastructure for bi-directional, real-time data flow. Here's an example architecture that demonstrates this concept:

✅ AWS EC2 + RDS (SQL Server) for cloud-side hosting

✅ RabbitMQ MQTT for secure, bi-directional messaging

✅ Python Publisher & Subscriber scripts with permanent MQTT connection

✅ Secure RDS insert for production and quality data This approach aligns with Industry 4.0 goals, enabling scalability, resilience, and closed-loop control.



5. Hybrid MES in Practice: Real-Time Edge-to-Cloud Communication

Challenge: How can machines at the edge securely and reliably talk to cloud systems in real time?

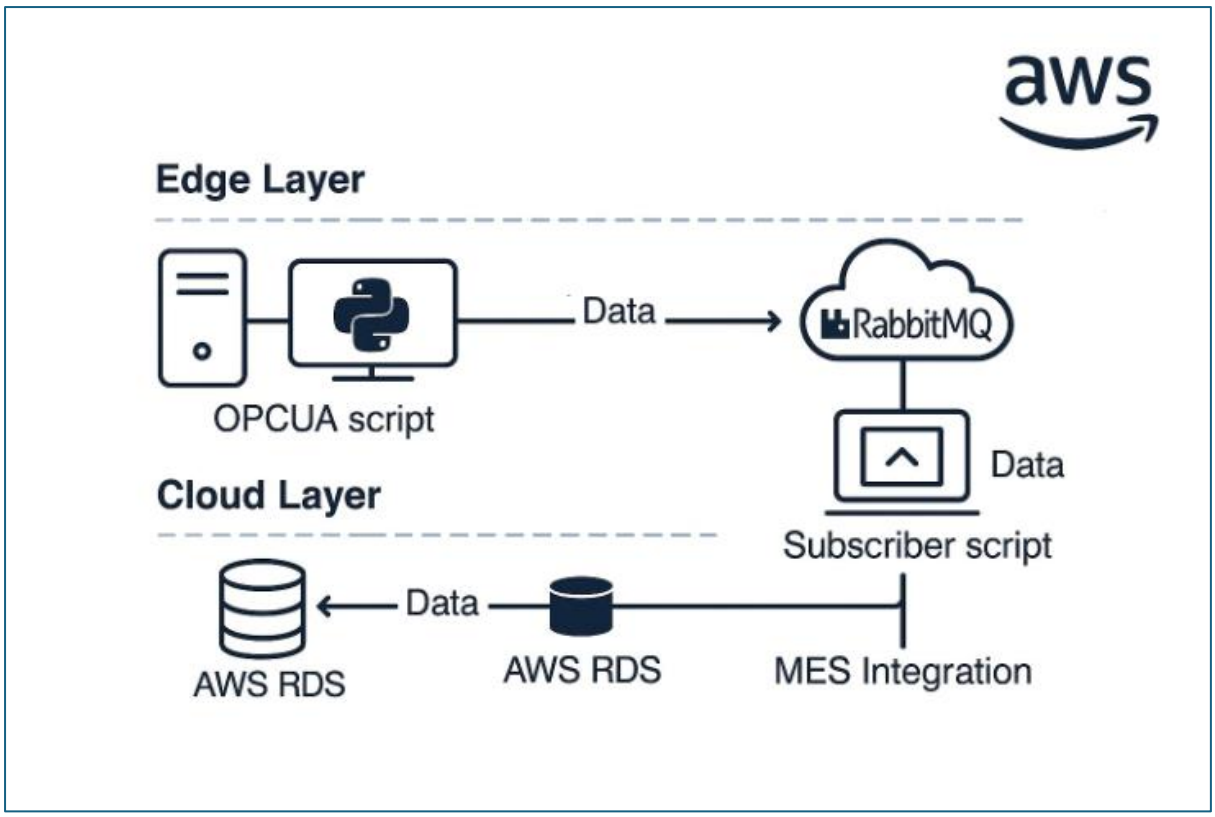
✅ Why OPC UA? It's platform-independent, secure, and supports rich data modeling—perfect for Hybrid MES.

🔧 My Setup: Edge: OPC UA server + MQTT bridge Cloud: RabbitMQ on AWS EC2 + SQL Server RDS MQTT scripts maintain permanent connections for real-time delivery Subscribed data stored with accurate timestamps

📊 Real MES Reality: Control loops stay local Cloud gets filtered/event-driven data Historical data moves in batches Real-time streaming enables OEE dashboards & predictive models

⚠️ MQTT Considerations: Great for lightweight data, but large plants need QoS, throttling, and persistence. For scale, consider AMQP, Kafka, or AWS IoT Core. 💡

Why It Matters: Hybrid MES balances local control with global insights—key for Industry 4.0.



6. Hybrid MES in Practice: Part 2 - RESTful Web API for Enterprise ↔ Cloud Integration Challenge: How can the cloud-side of a Hybrid MES exchange structured, transactional data with high-level enterprise systems (like ERP, PLM, QMS, and CMMS) using standard, secure, and firewall-friendly protocols?

✅ Why RESTful Web APIs? Universality: Widely supported, language-agnostic, and ideal for integrating MES with external enterprise applications. Security & Standards: Uses standard HTTP(S) and can easily integrate with enterprise security protocols (API Key authentication in this case).

Transactional Focus: Perfect for request-response operations like creating work orders (POST), retrieving BOMs (GET), or updating quality results (PUT).

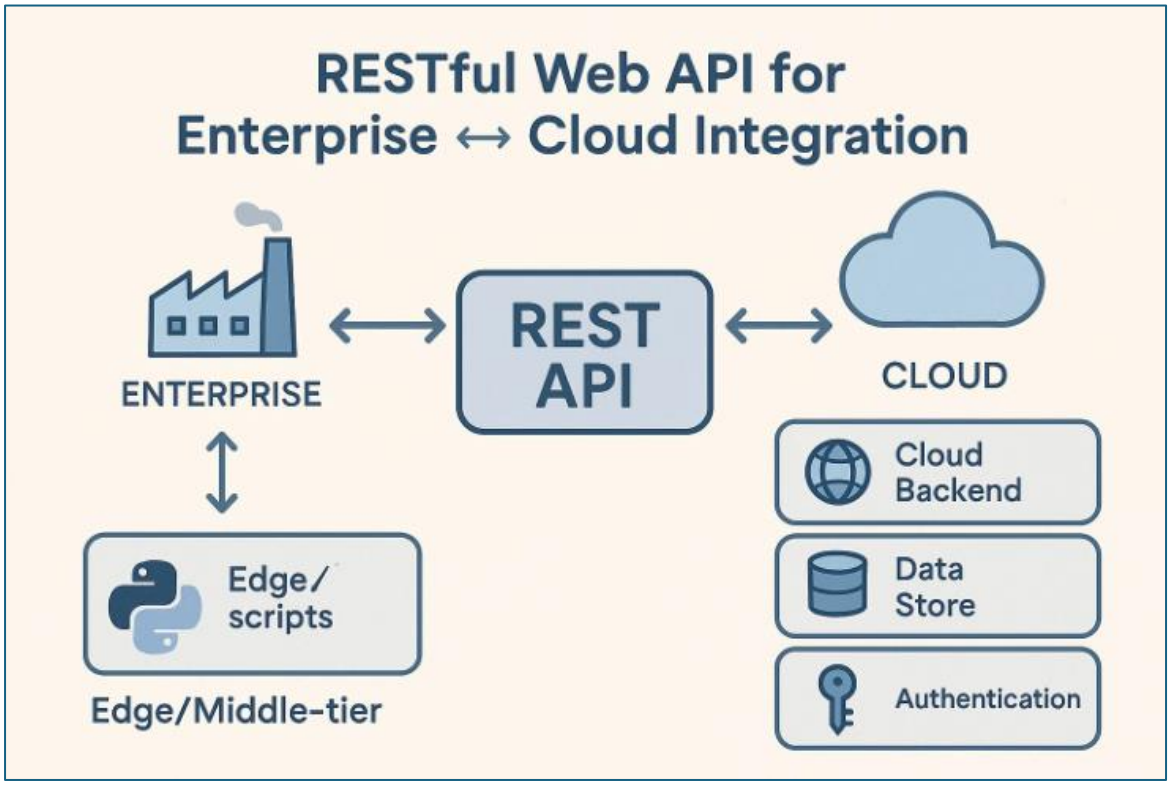
Reference Setup: Edge/Middle-tier: Python scripts use standard requests for robust API calls.

Cloud Backend: REST API endpoint hosted on AWS EC2, managing data access. Data Store: Structured data persistence in SQL Server RDS.

Authentication: API Key for secure access control.

Model: Both Push (Edge sends data) and Pull (Enterprise requests data) models are implemented.

💡 Why It Matters in Hybrid MES: This RESTful approach is key to achieving a robust Digital Thread. It handles the structured, system-to-system communications, demonstrating how Hybrid MES can flexibly adapt to different integration needs from high-velocity sensor data (via MQTT) to structured system transactions (via REST).



7. Hybrid MES in Action: AI-Powered Anomaly Detection with AWS + Grafana

Building ✅ Objective The aim is to move MES beyond monitoring by incorporating AI to help detect anomalies and support proactive decision-making.

✅ What was developed Data Layer: MES production data stored in AWS RDS (SQL Server)

AI-Powered Model Development: Trained an Isolation Forest model on historical MES data Engineered features like Cycle Time, Defects Ratio, and Production Rate Saved model as .pkl for reuse in detection pipeline

Automation: Batch scripts + Windows Task Scheduler to run detection every 8 hours Visualization: Grafana OSS dashboard For Anomaly count (Stat panel) Anomaly trend (Time series) MES KPIs like Avg Production Rate, Defects Ratio, Cycle Time Cloud-

Native Deployment: AWS Lambda for serverless execution of anomaly detection logic Amazon Sage Maker for scalable model training and retraining Docker-based Lambda image for packaging Python scripts and dependencies

✅ AI-Powered Insights This isn't just automation—it's predictive MES intelligence. By leveraging machine learning, manufacturers can anticipate anomalies before they disrupt production, optimize processes, and reduce costs. AI transforms raw MES data into actionable insights, enabling smarter, faster decisions.

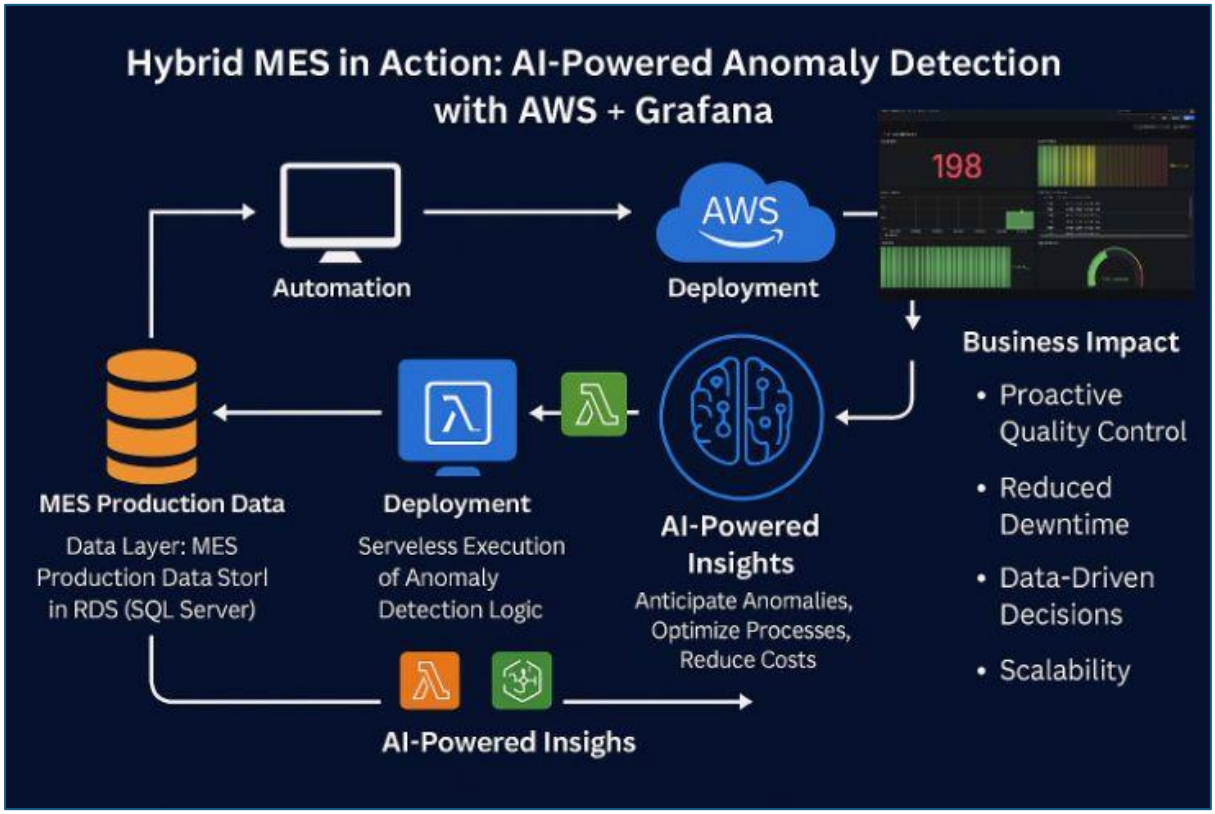
✅ Business Impact Proactive Quality Control: Detect anomalies before they impact production

Reduced Downtime: Early alerts prevent costly stoppages

Data-Driven Decisions: Real-time dashboards empower operators and managers

Scalability: Cloud-native design supports multi-plant deployments

Cost Efficiency: Serverless execution reduces infrastructure overhead



8. **Hybrid MES in Action (Part 3): Adaptive Workflow & Human-in-the-Loop Automation**

Building on previous discussions around Edge-to-Cloud Integration and AI-Powered Anomaly Detection, this post explores the next frontier in Hybrid MES: Adaptive Workflow—moving beyond predicting issues to automatically acting on them, with dynamic process control and secure human approvals in a closed loop.

✅ Objective

Transform static, rigid workflows into a serverless, event-driven engine that adapts in real time based on machine status, while ensuring Human-in-the-Loop (HIL) approvals for critical events.

✅ What was developed

<u>System Architecture</u>
Data Flow: Edge → MQTT → AWS RDS (SQL Server)
Dynamic Workflow: AWS Step Functions orchestrates adaptive processes using Choice State Logic
Event Trigger: Event Bridge Scheduler invokes Polling Lambda to detect new records (Processed Flag = 0)
Human-in-the-Loop (HIL)
Maintenance status triggers a paused Callback Task
SNS sends approval email with Approve/Reject link

API Gateway resumes workflow instantly using Task Token

Visualization

Workflow status and history displayed on Grafana dashboards

✅ Adaptive MES Intelligence

This is closed-loop control, not just notifications. Step Functions enforce complex business logic automatically, distinguishing between minor changes and critical events requiring immediate redirection—maximizing agility and compliance.

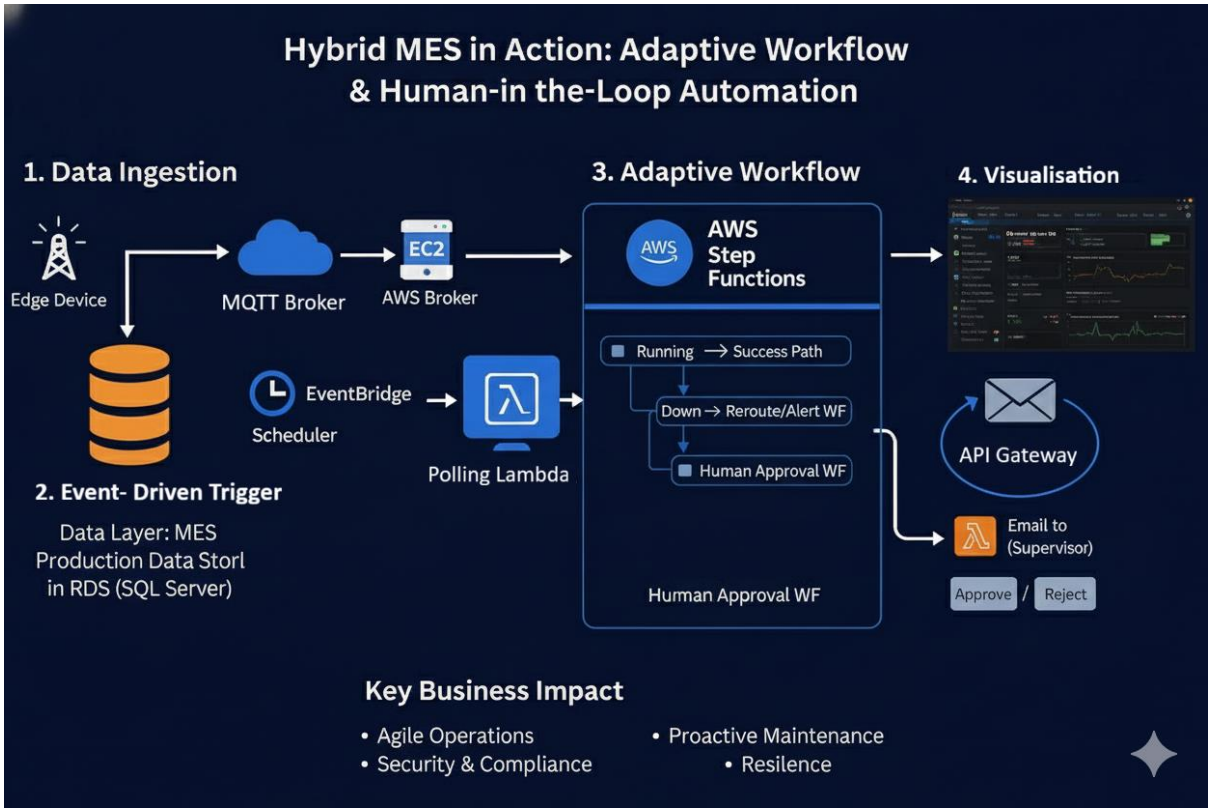
✅ Business Impact

⚡ Agile Operations: Workflows adapt in seconds

🔒 Security & Compliance: Callback Pattern enforces approvals mid-process

📈 Scalability: Cloud-native design supports multi-plant deployments

✅ Resilience: Workflow state maintained during approval wait



9. **Digital Twin in Action: Real-Time Monitoring + ML-Driven Insights**
Building on earlier discussions around **Edge-to-Cloud Integration** and **AI-Powered Anomaly Detection**, this post showcases how we've taken Digital Twin beyond visualization—into **real-time monitoring, anomaly detection, and automated workflows**.

✅ **Objective**
Create a unified Digital Twin platform that combines **immersive 3D visualization**, **graph-based relationships**, and **production health KPIs**, all powered by **real-time data ingestion** and **ML anomaly detection**, unified via the machineID variable.

✅ **What was implemented**
System Architecture

- **Data Flow**: Edge → MQTT / REST API / OPC UA → AWS RDS (SQL Server)
- **Visualization**: Grafana dashboards with a **tabbed layout** for Digital Twin & Production Health
- **3D Model & Real-Time Monitoring**: AWS IoT TwinMaker for immersive scenes and live property updates *(Flask-based video streaming as a Kinesis-free alternative)*
- **Graph Context**: Neo4j for machine relationships, integrated via PyVis + Flask on EC2
- **AWS Services**: EC2, RDS, IoT TwinMaker, Lambda, Step Functions, SNS, SageMaker AI, S3 for storage

ML Intelligence

- Isolation Forest detects anomalies from MES data
- Automated via **Windows Task Scheduler** → Inserts anomaly KPIs into RDS

Workflow Automation

- AWS Step Functions orchestrate maintenance workflows
- SNS sends alerts and **Human-in-the-Loop approvals**
- Maintenance orders auto-created in RDS upon approval

✅ **Why This Matters**
This is not just a dashboard—it's a **closed-loop Digital Twin**:

- **Immersive Monitoring**: Live machine data synced with 3D models

- **Contextual Awareness**: Graph relationships highlight anomalies (red node) and impact zones
- **Predictive Insights**: ML-driven health status integrated directly into visualization
- **Actionable Automation**: Alerts trigger workflows and resource allocation instantly

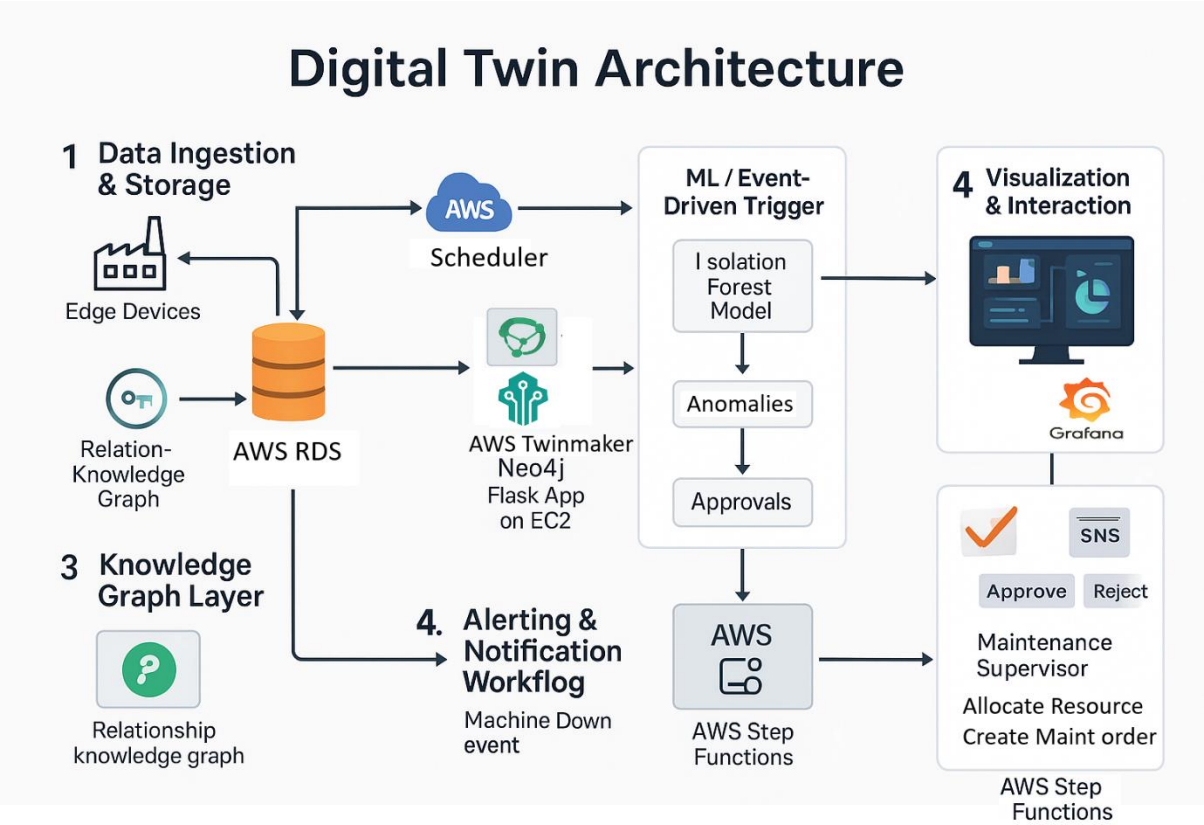
✅ **Business Impact**

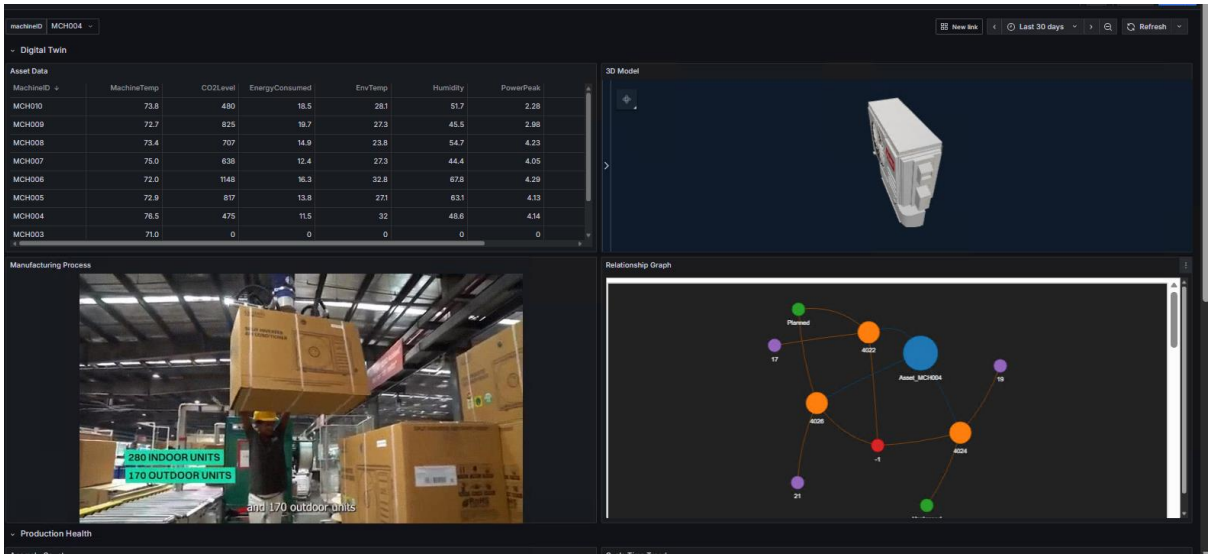
⚡ **Agility**: Operators act on anomalies in seconds

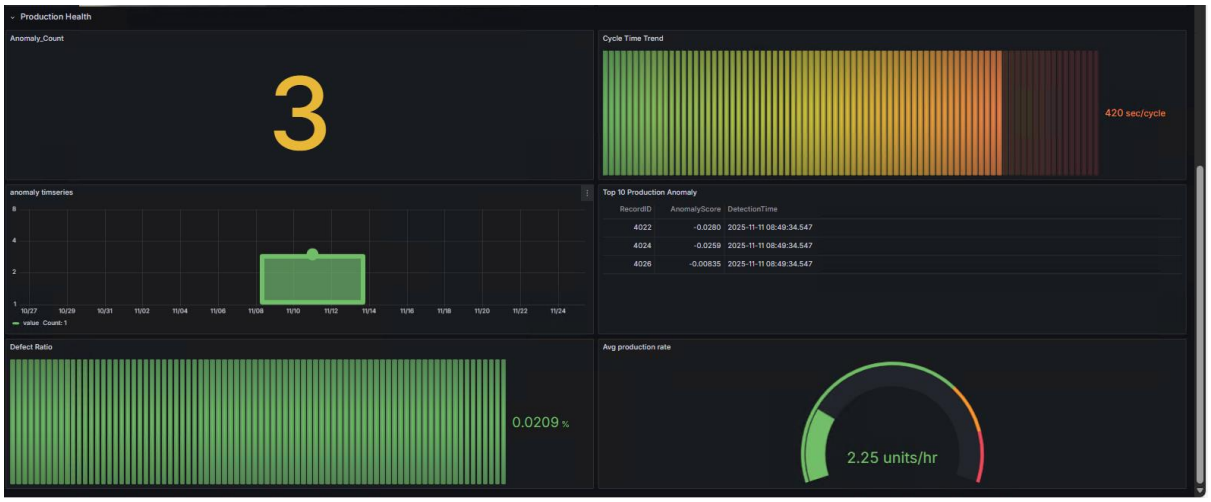
🔍 **Visibility**: Unified view of machine health + process context

📈 **Scalability**: Cloud-native design supports multi-plant deployments

🔒 **Compliance**: Human-in-the-Loop approvals for critical events




machineID
MCH004
New link
Last 30 days
Refresh
Digital Twin
Asset Data
MachineID
MachineTemp
CO2Level
EnergyConsumed
EnvTemp
Humidity
PowerPeak
MCH010 73.8 480 18.5 28.1 51.7 2.28
MCH009 72.7 825 19.7 27.3 45.5 2.98
MCH008 73.4 707 14.9 23.8 54.7 4.23
MCH007 75.0 638 12.4 27.3 44.4 4.05
MCH006 72.0 1148 16.3 32.8 67.8 4.29
MCH005 72.9 817 13.8 27.1 63.1 4.13
MCH004 76.5 475 11.5 32 48.6 4.14
MCH003 71.0 0 0 0 0 0
3D Model
Manufacturing Process
280 INDOOR UNITS
170 OUTDOOR UNITS
and 170 outdoor units
Relationship Graph
Planned
17
4022
Asset_MCH004
19
4026
4024
-1
21
Production Health


Production Health
Anomaly_Count
3
Cycle Time Trend
420 sec/cycle
anomaly timseries
8
4
2
1
10/27
10/29
10/31
11/02
11/04
11/06
11/08
11/10
11/12
11/14
11/16
11/18
11/20
11/22
11/24
value Count: 1
Top 10 Production Anomaly
RecordID AnomalyScore DetectionTime
4022 -0.0280 2025-11-11 08:49:34.547
4024 -0.0259 2025-11-11 08:49:34.547
4026 -0.00835 2025-11-11 08:49:34.547
Defect Ratio
0.0209 %
Avg production rate
2.25 units/hr