Building Audi's EC4P Platform for Shop floor Virtualization

ARC White Paper
January 2026

Audi's Edge Cloud for Production (EC4P) is a transformative initiative aimed at modernizing manufacturing through the integration of edge computing and cloud technologies. By virtualizing essential shop floor assets—such as HMIs, industrial PCs, and PLCs—EC4P streamlines operations, reduces hardware complexity and costs, and ensures security, while enabling easy and timely upgrades. This new architecture empowers Audi to deploy advanced AI solutions for predictive maintenance and quality control, paving the way for software-defined factories and data-driven decision making. Ultimately, EC4P establishes a scalable, AI-ready infrastructure that supports Audi's vision for efficient, adaptable, and future-proof production.

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CONTENTS

Executive Overview

"Software, not hardware" – this simple tenet is the basis of what AUDI AG calls "IT-based factory automation," a concept that is turning IT/OT convergence theory into practice at the premium automaker. Dubbed Edge Cloud 4 Production (EC4P), the concept is to replace thousands of decentralized industrial PCs with a much more efficient and flexible IT-like architecture of scalable local servers, effectively uniting the cloud and the edge on the shop floor.

Tenets of Audi's IT-based factory automation:

- *Centralized, not decentralized*
- *Local servers instead of thousands of IPCs*
- *Solution delivery in software, not hardware*

What motivated Audi to redesign its traditional shop floor architecture? The automotive industry is changing rapidly in the face of new cost structures driven by the electric vehicle transition and fierce competition from China. In Audi's view, the traditional model of delivering production equipment floor is outdated, and the future is software-driven production.

Audi is part of Volkswagen AG, the world's second largest carmaker that employs more than 600,000 workers. The implication is that a successful project can reverberate companywide with the potential to fundamentally change plant architectures in well over 100 plants worldwide, so a lot is riding on this project.

This ARC White Paper looks at the origins, the motivation, the business drivers, the project goals, and the real outcome of EC4P.

Key Findings

- EC4P is integral to Audi's 360 factory vision, accelerating the shift to software-driven production.
- By consolidating hardware into scalable, local servers within a unified edge-cloud framework over a high-speed, resilient enterprise network, EC4P streamlines shop floor operations, and enhances efficiency in routine OT tasks, such as equipment maintenance and software updates.
- The server solution levels out spikes in demand across virtualized clients, speeding application deployment and recovery in case of failure, and ensuring more efficient use of resources.

- Future production solutions will be delivered as software, optimized for seamless integration with the EC4P platform.
- The adoption of virtual PLCs represents the most recent milestone in Audi's journey toward the software-defined factory.

EC4P: Challenges and Business Drivers

The IT/OT convergence is a powerful force for change in the traditional world of manufacturing. As industrial companies adopt "IT-like" architectures, the potential for cost savings, efficiency gains, scalability and flexibility is enormous. Several years ago, Audi set out to create IT-based factory automation with its EC4P concept that consolidates compute and control hardware and applications over enterprise networks in a cloud-edge architecture. Now that the concept is shop floor-tested, Audi is extending its shop floor digital transformation to real-time control via the first virtual PLC.

Challenges	Strategies
Mitigate High Energy Costs	Lower energy costs by reducing legacy hardware.
Deal with Legacy Hardware	Consolidate legacy compute hardware and software in production. Lower hardware costs and procurement process. Eliminate need for time-consuming shop floor updates.
Ensure Cybersecurity	Protect assets from the ground up with built-in cybersecurity.
Adapt Production Strategy	Fulfill vision of a new platform that provides IT infrastructure for OT applications. Comply with "360 factory" production strategy for a software-driven factory.

EC4P Challenges and Strategies

With its new software-defined approach to automation, Audi expects huge efficiency gains in device and application management and substantially higher flexibility thanks to the scalability of the new architecture. Most of all, the company looks forward to a new process of specifying and deploying software-only solutions for everything from simple functions to complete automation systems.

Key Challenges

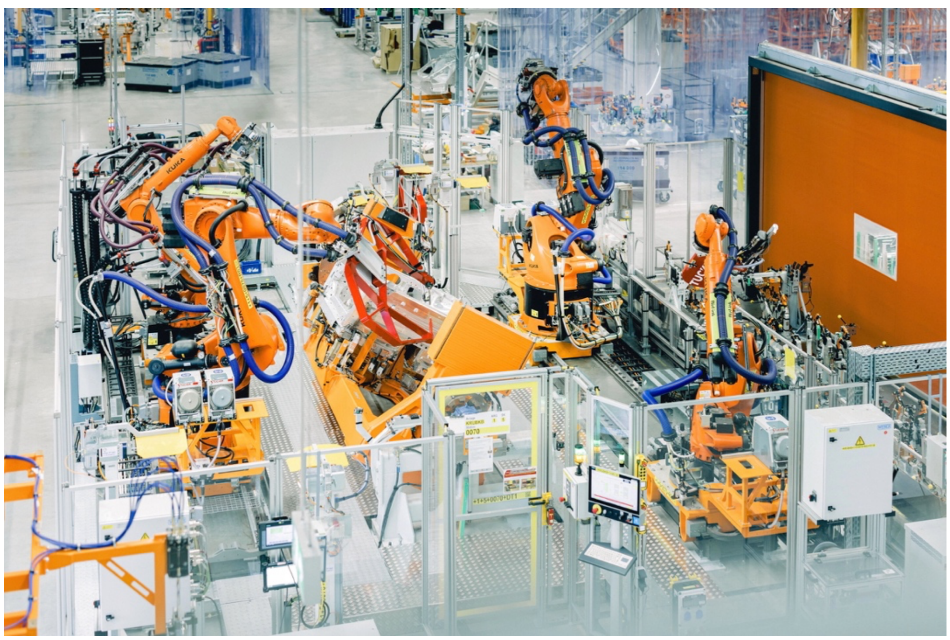
EC4P is a multifaceted initiative designed to address and solve several key challenges, both technical and operation.

Guarantee System Performance

Migrating industrial functions to a software-defined architecture presents several challenges. OT priorities such as equipment availability, real-time performance and guaranteed latency must be maintained for applications such as safety and motion control. Other operational applications such as visualization and production management have less stringent requirements but still benefit from virtualization.

Ensure Functional Safety

Applications with human interaction must be safety-certified via an independent verification that a machine's safety system meets specific international standards, ensuring it operates correctly and reduces risks to people, property, and the environment. Software-defined automation solutions must obtain certification, and together with Siemens, Audi has now embarked on this process with the first safety-certified virtual PLC.



A Body Shop Application is Now Controlled by Virtual PLCs at an Audi Production Site in Germany (Photo: Audi Group)

Maintain System Resilience

A software-defined automation solution must offer the same degree of resilience as a traditional hardware-based solution. Here, resilience refers to the ability of a system to recover from an abnormal situation, such as a power outage or an unexpected disruption to the manufacturing process. On the traditional OT shop floor, this may be as simple as resetting a power supply or hot-swapping a CPU or IO module. In a software-defined factory, the first step may be to pick up a mouse and keyboard rather than the key to an electrical cabinet.

Organizational Challenges

Bringing so much IT into critical OT processes required the creation of the EC4P team, which established a 24x7 operational team with both IT and OT skillsets. The success of this team was key to success of the EC4P project.

EC4P was a multi-company effort right from the start. Audi's timeline was driven by production projects with fixed start-of-production dates, so it was imperative to align the activities of partners, most notably Siemens, Cisco and Broadcom (VMware), to deliver the appropriate solutions at the right time, including successful interoperability testing.

Before EC4P, no carmaker had so boldly created a plant architecture that takes advantage of all the efficiencies and conveniences of a modern IT-like architecture, and yet considers the specific priorities and requirements of the OT environment.

EC4P has reduced complexity on the shop floor despite the addition of layers to the whole solution (virtualization stack, automation tools, monitoring and logging, etc.). New stakeholders were added for networking and servers, as well as the EC4P operations team -- all dedicated to managing the virtualized workloads running on the EC4P platform. New processes were introduced to manage debugging issues in these distributed and connected systems.

When OT Meets IT

As vendors from the IT space became stakeholders in EC4P, they needed to learn the special priorities and requirements necessary to support the project that may go beyond the terms of service level agreements. In short, they learned how to react to IT issues in an OT environment.

Initially, EC4P brought together different stakeholders within Audi, from OT maintenance teams to the planning department of the automation business unit to the network and server teams. When external technology partners joined the project, the EC4P had to transfer not just the technical requirements, but also the culture of working with OT people. According to the EC4P team, if you want to bring IT and OT together, you first need to bring the people together.

Business Drivers

When it launched the first ideas in 2018, Audi made the business case for breaking with traditional automation architectures and exploring the potential of the emerging IT/OT convergence. Driving the business decision first and foremost was reducing the cost of the shop floor environment in both capex (procurement of hardware and software) and opex (maintaining disparate hardware in an operational environment). In addition, reductions of required resources in hardware and energy were expected. Finally, the advantage of reduced complexity was anticipated due to the shift from special purpose hardware (PLC, IPC) to standard server hardware.

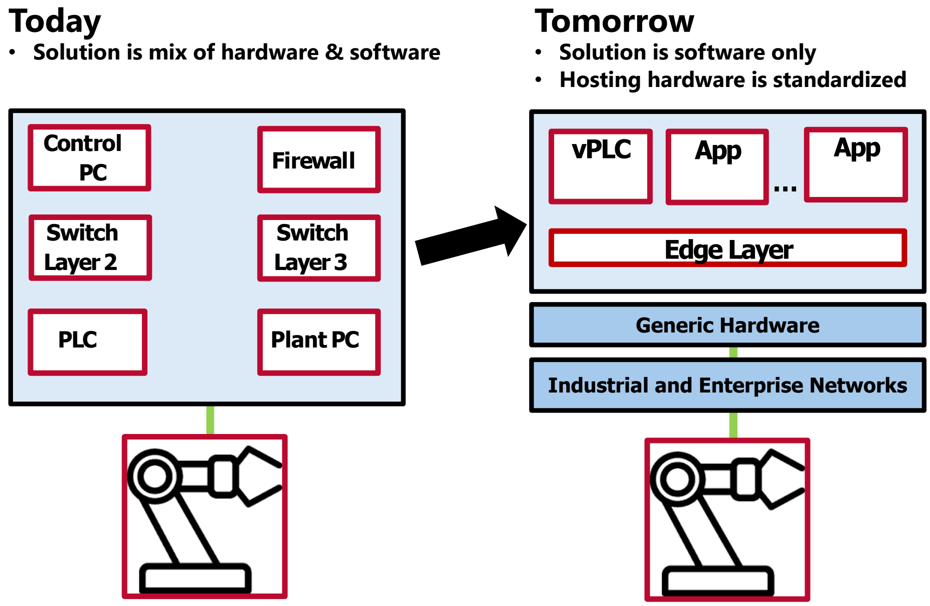
Less tangible drivers that support the business case include an anticipated boost in flexibility of manufacturing assets. Experience from the IT world has shown that applications can be deployed much faster in software-defined architectures. Instead of plant staff going down to the shop floor and physically connecting a PC to each automation device, the platform approach using virtualization allows applications to be updated or scaled up or down much faster, from any location.

Equally important is that a software-defined architecture allows the status and health of production assets, whether hardware or software, to be monitored continuously, opening the door for sophisticated AI-driven predictive maintenance in the future. Finally, the new architecture needs to protect the IT and OT assets with bulletproof cybersecurity.

Key Metrics

An important part of any project is setting metrics by which progress and success can be measured. For EC4P, reducing hardware costs is a top metric that can be easily tracked. In this case it is a trade-off between investments in new servers to host virtualized software versus the elimination of IPCs and PLCs on the shop floor. Legacy hardware is a sunk cost and new servers must be procured, so the offsetting metric must be cost savings derived from having less hardware to maintain on the shop floor.

Cost savings from hardware reduction will be driven by Audi's "software, not hardware" maxim - a key principle of EC4P. In the future, suppliers will deliver functions as software and not in a "box" (hardware). For example, control or monitoring software that accompanies a new machine will be installed and integrated in the EC4P architecture rather than being delivered in an IPC in an electrical cabinet.



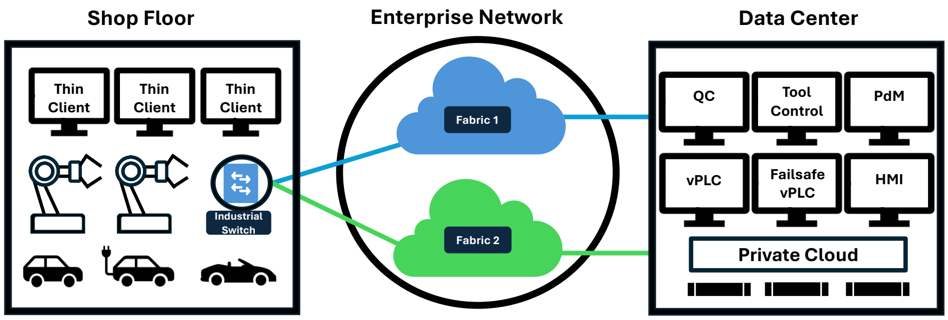
Software-Defined Vision: Equipment Providers in the Future Will Deliver Solutions Realized in Software that Run on Standardized Hardware

On the operational side, equipment availability is a key metric, usually calculated as overall equipment effectiveness (OEE). This is a standard metric that measures the productivity of equipment by looking at three factors: availability, performance, and quality. With less hardware to maintain, OEE is likely to improve thanks to EC4P.

Less tangible metrics include greater flexibility in bringing new features to production equipment. In the past, updates to automation devices were rare because the function of controller software is rigorously tested during commissioning. But the growing sophistication of software in automation solutions exposes plant assets to outside threats. Mitigating these threats requires periodic updates of the IT infrastructure. EC4P expects the new architecture to increase scalability (time to update), speed up rollout velocity (no delays due to lacking flexibility), and improved stability and availability of the system (platform and application).

The Reference Architecture

At the inception of EC4P, Audi began to explore new terrain. No carmaker before had so boldly created a plant architecture that takes advantage of all the efficiencies and conveniences of a modern IT-like architecture, and yet considers the specific priorities and requirements of the OT environment. At the time, the top IT consulting firms lacked domain-specific experience, so to create the future of the automotive plant architecture, Audi partnered with three key vendors: Cisco, Broadcom (VMware), and Siemens. Together, this team created the reference architecture that became the core of EC4P.



The EC4P Reference Architecture (Graphic: ARC)

A reference architecture for the real-time specific aspects of EC4P was developed jointly by the EC4P team and its key suppliers. The reference architecture is made up of three domains:

- **Shop floor:** Manufacturing equipment, automation devices, networks
- **Enterprise network:** Resilient, low-latency/high-bandwidth networking infrastructure connects all pieces in a scalable and secure manner.
- **Data center:** EC4P virtualization platform hosts a variety of applications.

In addition, systems hosted on other private or public clouds may be connected to the EC4P Reference Architecture. This may include monitoring and logging, data engineering, management tools, and databases.

Use Case	Description
Virtual HMI	vBedienPC engineering stations run applications such as TIA Portal (engineering) and WIN CC (visualization) in a virtual machine.
Virtual PLC	Siemens SIMATIC S7-1500V implemented for rear and front axle pre-assembly stations for the Audi e-tron GT, an electric vehicle, at a plant in Germany. Siemens SIMATIC S7-1517VF, TÜV certificated failsafe vPLC for bodyshop robot cells.
Additional Use Cases	OEM software for manufacturing execution systems (MES), and applications for screw fastening and car diagnostics.

Virtualization Use Cases on the Shop Floor

Mimicking Layer 2 Connectivity for Real-Time Performance

Profinet RT and similar industrial protocols operate at Layer 2 of the OSI model, using Ethernet frames without IP headers. This means their traffic requires a flat Layer 2 network and cannot be routed across Layer 3 boundaries typical in enterprise networks. VXLAN addresses this limitation by encapsulating Layer 2 segments within Layer 3 IP networks, using VXLAN Network Identifiers (VNI) to create virtual Layer 2 overlays. This allows geographically separated devices to share the same Layer 2 broadcast domain. Cisco Software-Defined Access (SDA) simplifies VXLAN deployment by automating fabric creation and managing Layer 2/Layer 3 boundaries through a centralized controller, enabling seamless Layer 2 connectivity for industrial devices across routed infrastructures.

PRP is a fault-tolerant network protocol for industrial Ethernet systems that ensures high availability and zero recovery time in case of network failures. PRP sends duplicate Ethernet frames over parallel but independent networks. If one network fails, communication continues seamlessly over the other with no switchover delay and no packet loss. Benefits: zero recovery time, no single point of failure, standardization according to IEC 62439-3.

Resiliency with Parallel Redundancy Protocol (PRP)

PRP is a proven protocol widely used in industrial applications to ensure network resiliency. If something breaks, especially with moving workloads to a distributed consolidated platform, increased fault tolerance is needed due to the larger blast radius in the face of a single failure. With this new concept, multiple applications can communicate across the same physical link and nodes.

Where to Put the Data Center?

A key technical challenge faced by the EC4P team was the decision to locate servers for both time-critical and non-time critical application in an off-premises data center. This is the true spirit of cloud computing, and Audi intends to apply this spirit to the manufacturing environments.

The servers are in data centers that serve multiple production sites located at varying distances (currently 6-13 km) from the production sites due to server requirements (cooling, access control, failover batteries). The goal is to make irrelevant the physical distance between data center and production site, without sacrificing performance. According to the EC4P team, achieving this goal was only possible with software-defined networking technologies from Cisco.

It Takes an Ecosystem

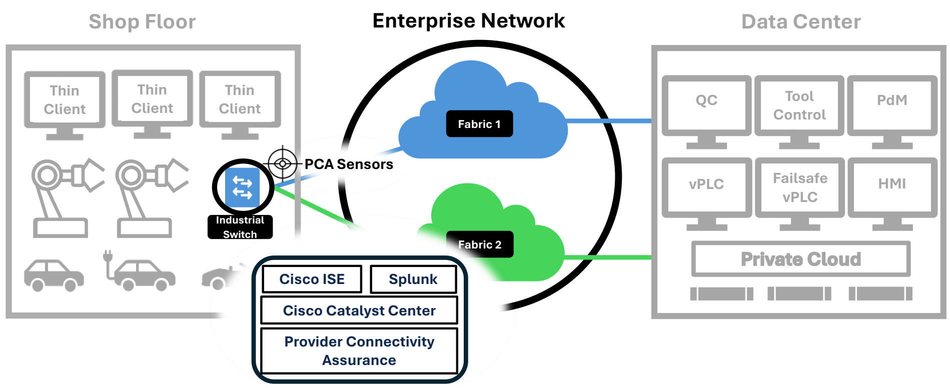
For Audi, EC4P means cooperating with technology partners in a broad ecosystem of vendors, solution and service providers. Production solutions in the future will be delivered in software that is deployed by Audi in a VM/container in the EC4P infrastructure - a paradigm shift in the automation world. For this reason, it is critical to educate the ecosystem on how this new operating model works by sharing important technical information.

The technology contributions of the key suppliers for EC4P are described below.

Cisco

Since the inception of industrial Ethernet 20 years ago, Cisco's innovations have enabled the convergence of IT and OT, laying the foundation for modern, software-driven factories and supporting the deployment of advanced technologies such as virtualization and AI in industrial settings. Cisco's industrial and enterprise networks provide critical security capabilities to segment and protocol critical automation communications.

For EC4P, Cisco provides the critical networking infrastructure that ensures high availability of production and compute resources from the shop floor to the data center. Cisco's industrial Ethernet switches, equipped with Parallel Redundancy Protocol (PRP), provide high availability and fault tolerance, ensuring seamless and resilient communication for critical industrial applications.



Cisco's Critical Networking Infrastructure Includes:
Cisco ISE = Security Policy, PCA = Network Latency Telemetry, Catalyst Center = Software Defined Network Controller, Splunk = Full-Stack Monitoring

Software-Defined Access

Cisco's approach, known as Software-Defined Access, uses controller-based management to simplify and modernize the physical networking infrastructure on the shop floor. This enables easier configuration of network zones and gateways, and supports advanced networking protocols like Virtual Extensible LAN (VXLAN), which allows applications to operate as if they are still physically located on the shop floor. VXLAN allows the stretching of Layer 2 domains, so that applications on the EC4P platform "feel" like they never left the premises, even when virtualized. Industrial Ethernet switches with PRP protocol provide the counterpart to the IVS of the virtualization platform.

Networking Challenge	Solution
Mimic L2 over L3 Networks	Virtualize and extend Layer 2 network over larger Layer 3 network (vPLC thinks it's local).
Resiliency	Zero packet loss redundancy protocol (PRP) and dual fabric to the data center.
Low Latency	High speed connectivity across the network providing deterministic performance (QoS).
Security and Observability	Segment and protect cell/area zones with Cisco TrustSec technology. Monitor latency between vPLC and automation devices with Provider Connectivity Assurance. Gain full observability across the entire technology stack with Splunk. Simplify network management with Cisco Catalyst Center.
IT/OT Aware	Support for industrial protocols (Profinet, Precision Time) to integrate into and support OT tools.

Cisco's Networking Challenges and Solutions

By helping Audi to bridge the gap between IT and OT, Cisco played a key role in Audi's transformation of shop floor operations by providing leading edge technology, a laboratory environment for the testing, and deployment and operational guidance according to a Cisco validated design.

In addition, Cisco provided an end-to-end testing environment for all aspects of the EC4P project from all three vendors to prove that the solution works, iron out any problems, and prepare it for Audi's production environment. Cisco acted as a technology enabler, allowing each vendor to set up and monitor their equipment to ensure full coordination and quicker resolution of problems observed. This lab is now used for testing and proving enhancements to the base setup.

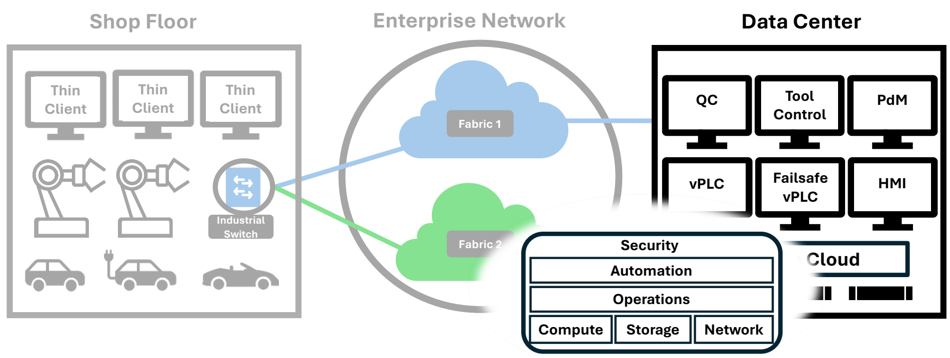
Broadcom (VMware)

Broadcom delivers deployment and management tools for EC4P's wide range of virtualized applications, supporting both time-critical machine control and non-time-critical operational tasks. Their software-defined virtualization platform, VMware Cloud Foundation (VCF), now in version 9.0, provides a unified private cloud solution for the Audi EC4P environment. This includes a comprehensive suite for operations management, logging, and monitoring.

Virtualization Challenge	Solution
System Maintenance	Virtualization enables centralized updates that can be implemented rapidly and reliably, improving system reliability and streamlining updates.
Security	The VCF platform has security built into each layer of the stack, providing encryption of data at rest and data in motion for stronger cyber-defense. Security patches and system updates can now be applied much more rapidly providing faster response to potential security vulnerabilities.
Performance and Reliability	Abstracting the system hardware with virtualization software improves overall performance and availability of the system.
Efficiency	Operational efficiency improves dramatically through virtualization with faster update times, faster implementation of new features through software, improved cycle times, with high availability support through the PRP integration.

Broadcom's Virtualization Challenges and Solutions

VCF is designed to handle mixed criticality use cases, including real-time applications. Its industrial virtual switch (IVS) ensures deterministic latency and jitter, and supports the parallel redundancy protocol (PRP). The platform also runs Profinet, a widely used Ethernet-based industrial network in automotive, and Profisafe, an industrial safety protocol.



Broadcom's VMware Cloud Foundation (VCF) Provides the Deployment and Management Tools for EC4P's Vast Array of Virtualized Applications

With VCF, Audi can virtualize compute, networking, storage, and management, all with integrated security across the shop floor. Infrastructure automation enables Audi to optimize performance and reduce operational overhead by abstracting physical devices like PLCs and IPCs, simplifying deployment, operations, and maintenance. The implementation, in collaboration with Siemens, Cisco, and Audi, required no process changes or retraining for factory teams and is TÜV-certified for safety. As an Infrastructure as a Service (IaaS) platform, VCF is extensible to virtual machines, containers, and AI workloads, supporting future application flexibility.

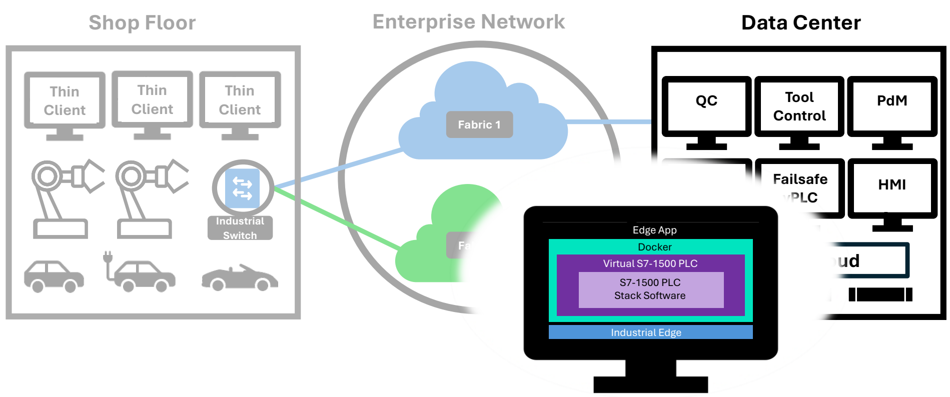
Siemens

The Siemens SIMATIC S7-1500V is the virtual PLC used for the rear axle assembly of the Audi e-tron GT series, as well as in a body shop application for a Lamborghini model whose chassis is built at an Audi plant in Germany. According to Siemens, this vPLC is a drop-in replacement for the classic hardware-based PLC previously used. That means that legacy code developed over many years can be used seamlessly in new vPLC projects.

Automation Challenge	Solution
Minimize training	vPLC uses same engineering tool (TIA Portal) as classic hardware PLCs.
Reuse legacy PLC code	vPLC accepts legacy code written for generations of classic hardware PLCs.
Connect to existing IO	Decentralized IO topologies connect to the vPLC via Ethernet without any special mapping.

Siemens' Automation Challenges and Solutions

SIMATIC S7-1517VF is Siemens' first-ever TÜV-certified virtual failsafe PLC. This vPLC is functionally equivalent to its hardware counterpart, the 1517F, the current PLC of the VASS standard. The 1517VF supports failsafe applications, a necessity in body shop, assembly, paint shop, and most automated production cells. With the introduction of the virtual PLC, the borders between IT and OT are disappearing as the flexibility and usability of IT applications come to the Industrial Edge ecosystem while still fulfilling the priorities and requirements of the OT side.



The Siemens Virtual PLC is a Drop-in Replacement for Classic Hardware-based PLC, Ensuring that Legacy Code can be Used Seamlessly in EC4P Applications

Audi extended the EC4P concept to virtual controllers to enable the rapid introduction of software and new functions that can be updated and managed centrally.

EC4P: How did Audi Get it Done?

While the EC4P architecture is up and running, Audi hardly considers the project to be finished. Instead, the team is busy with optimization, enhancements and daily operations. Several key success factors helped the team reach its goals.

Getting Buy-in

For the initial rollout, the EC4P team needed to get the buy-in of various stakeholders in the Audi family – all those connected to the future use of the new architecture. It was especially important to get the OT maintenance teams on board with the practical side of the EC4P concept. These are the staff most affected by this fundamental rethink of shop floor automation hardware who later will be responsible for ensuring its reliable, daily operation. To achieve this, it was also important to have a close connection with and deep understanding of the planning departments from the automation BU and clear collaboration with the Audi network and server teams.

Joint Architecture Sessions

On the external side, it was necessary to transfer both the technical requirements as well as the cultural requirements to Audi's ecosystems of suppliers and technology partners. The Audi team worked closely with technology partners with deep domain knowledge and a focus on finding creative solutions without fear of being wrong in the initial stages.

What's Next?

Now that EC4P has proven itself in the body shop (and final assembly), the next step is to roll out the architecture within Audi's production sites. This includes members of the Brand Group Progressive (Bentley, Lamborghini, Ducati), as well as different product entities such as paint shop and logistics. The implementation of the new architecture will be different in each production branch, so the first step is to identify the specific areas where it applies and to develop and onboard each new use case. This may require minor to major modifications depending on local requirements.

Post-implementation management of the EC4P platforms worldwide will be handled by EC4P operations team via its Remote Operations Center located in Germany.

Next Step: AI

Audi currently applies AI in many areas of production and is always exploring new use cases. As a next step, the EC4P team plans to add support for AI workloads to the platform, assisting production engineers with the implementation at each site. Examples of AI workloads include data analytics, anomaly detection, and computer vision (quality).

Conclusion

Audi's Edge Cloud for Production (EC4P) initiative marks a transformative milestone in the evolution of industrial automation, setting a new standard for IT/OT convergence in manufacturing. By replacing thousands of decentralized industrial PCs with a centralized, scalable cloud-edge architecture, Audi has demonstrated the tangible benefits of software-defined factories—greater efficiency, flexibility, and readiness for advanced AI applications.

The EC4P platform's core tenet, "software, not hardware," has enabled Audi to consolidate legacy systems, reduce energy and hardware costs, and streamline maintenance and updates. This shift not only simplifies the shop floor environment but also accelerates the deployment of new features and applications, empowering Audi to respond swiftly to changing production needs. The successful implementation of virtual PLCs, including safety-certified solutions, underscores the platform's ability to meet stringent real-time and functional safety requirements, bridging the gap between IT innovation and OT reliability.

Key challenges remain, particularly in ensuring resilience and maintaining critical functionality during migration. Audi's experience highlights the importance of cross-disciplinary collaboration, transparent communication, and ecosystem education. The project's success depends on buy-in from both internal stakeholders and external partners, fostering a culture of openness and shared purpose.

Looking ahead, EC4P is poised to expand across various production sites, with the next frontier being the integration of AI workloads to further enhance predictive maintenance, quality control, and data-driven decision making. The EC4P remote operations center will support worldwide management, ensuring consistent performance and continuous improvement.

In summary, EC4P exemplifies the future of manufacturing—where software-defined architectures, open standards, and robust ecosystems drive innovation, efficiency, and scalability. Audi's journey offers valuable lessons for any organization seeking to modernize its production infrastructure and embrace the possibilities of digital transformation. Manufacturers in all industries will profit from the carmaker's pioneering work if methods created at Audi develop into industry best practices.

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Acronym Reference:

EC4P	Edge Cloud for Production
ERP	Enterprise Resource Planning
HMI	Human Machine Interface
IaaS	Infrastructure as a Service
IIoT	Industrial Internet of Things
IoT	Internet of Things
IPC	Industrial PC
IT	Information Technology
IVS	Industrial Virtual Switch
MES	Manufacturing Execution System
OT	Operational Technology
PLC	Programmable Logic Controller
PRP	Parallel Redundancy Protocol
SLA	Service Level Agreement
VCF	VMware Cloud Foundation
vPLC	Virtual PLC
VXLAN	Virtual Extensible LAN

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