DIGITAL INDUSTRIES

Using integrated software and automation to transform fab sustainability

Leveraging synergies to improve energy efficiency, decarbonization, resource efficiency and circularity

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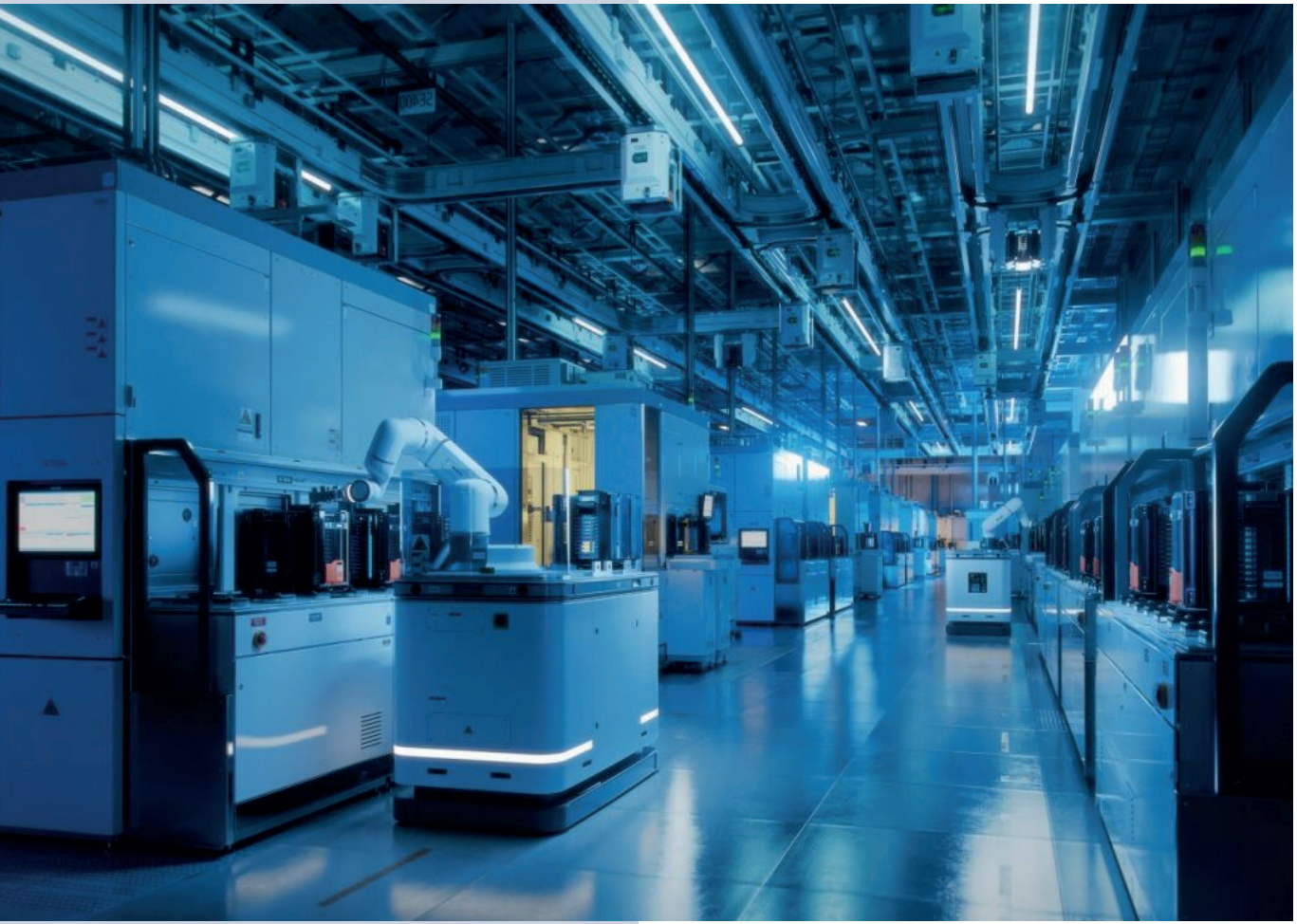
Many complex challenges. One integrated solution.



Today's unprecedented demand is forcing semiconductor plants into continuous, 24/7 operation, generating a significant environmental impact due to high energy and chemical use and elevated water consumption. The resultant waste and byproducts are driving a surge in greenhouse gas emissions.

A joint report from the global association Semiconductor Equipment and Materials International (SEMI), the Climate Consortium and the Boston Consulting Group revealed the semiconductor industry, including chip design, electronic design automation (EDA) and ingress protection (IP), wafer fabrication, manufacturing and package, assembly and test) is responsible for 0.3 percent of global carbon emissions. Another 1 percent is produced by upstream and downstream suppliers and users. Sixty-five percent of emissions from semiconductor manufacturing come from using electricity to power equipment and buildings. About 30 percent of emissions result from using process chemicals that enter the atmosphere during manufacturing.[1]

Sustainability is one of today's critical manufacturing challenges

As the demand continues to grow for smart devices, so does the responsibility to ensure their design and production is environmentally responsible.

Unfortunately, legacy systems offer fragmented solutions that fall short of what manufacturers demand today to meet sustainability challenges.

Many legacy systems are unconnected without a common data platform or common language across systems, limiting the secure collaboration, visibility and traceability needed to compete in today's ecosystem. Design, engineering and manufacturing functions often exist in silos where sharing information is difficult, impacting innovation, sustainability planning and manufacturing optimization.

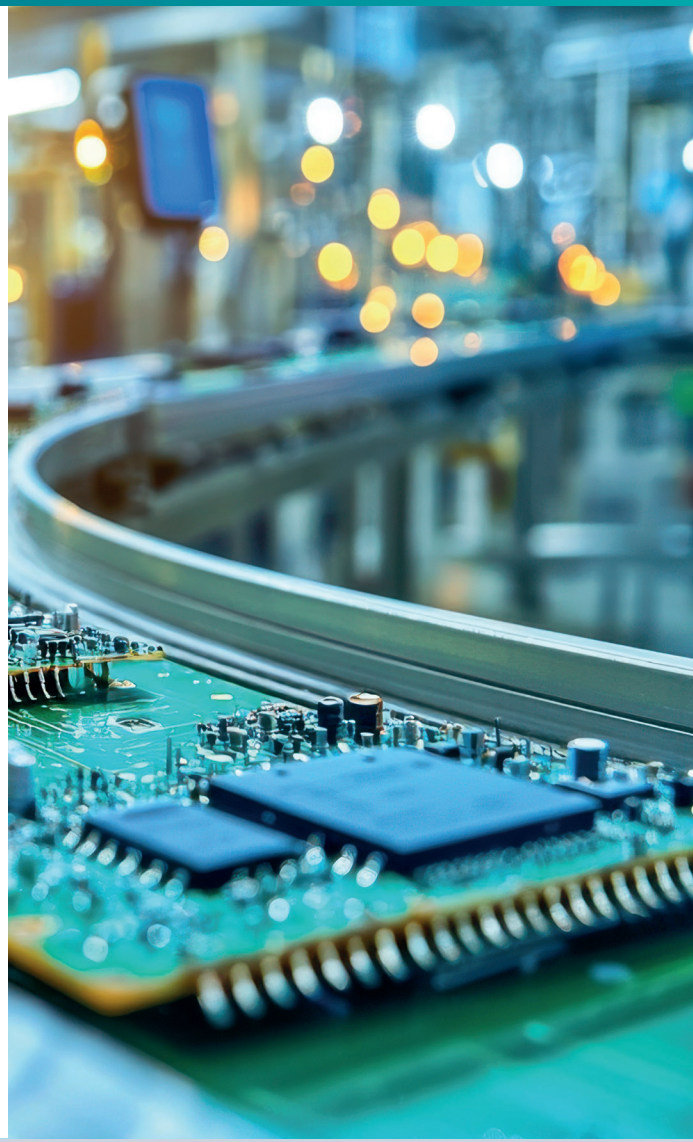
Some limitations of the traditional approach include:

- Disconnection between the fab, subfab and utilities
- Disaggregated data with incomplete and inaccurate data sets
- Data fragmentation that inhibits sustainability planning
- Poor knowledge transfer and collaboration between teams
- Missing flexibility to quickly adapt to volatile market demands and supply chains
- Long-term asset performance that remains unclear
- Cloud computing security risks

Semiconductor manufacturers have now entered a new era, one defined not only by speed and profitability, but by resilience, adaptability and sustainability. To thrive in this future, they must embed sustainability into the core of every decision, process and product to unlock a dynamic, data-driven and artificial intelligence (AI) enabled view of the entire value chain.

Software and automation working synergistically can bring the energy efficiency, decarbonization, resource efficiency and circularity needed to transform the fab.

While software enables process optimization, automation drives operational efficiency. Their seamless integration creates a multiplier effect that delivers predictive insights, self-adjusting systems and real-time optimization that transforms semiconductor manufacturing from reactive to proactive, unlocking new levels of sustainability and performance that neither could achieve alone.



Software and automation work better together

When the enterprise, operating and automation systems are fully digitalized, interconnected and working together seamlessly, productivity, quality and sustainability will rise to new levels.

By integrating critical systems using a unified digital platform, software-enabled automation creates an intelligent semiconductor manufacturing environment. This comprehensive approach combines manufacturing execution systems (MES) for production management with advanced process control (APC) for process optimization, seamlessly integrating automated material handling and digital twin technology. Enhanced by AI and machine learning (ML), this holistic solution enables predictive maintenance, yield optimization and real-time control to deliver a highly efficient and adaptive production environment that maintains the highest quality standards.

Advancing digitalization across the fab and subfab
Advancing digitalization at every level transforms your company with unlimited visibility across design, engineering, manufacturing and support domains, connecting everyone from enterprise management to every team at workstations across every area of the fab.

End-to-end digitalization empowers a higher level of planning, optimization and execution. Real-time data sharing powers intelligent automation to equip both fab manufacturing systems and subfab systems for digital transformation. As an example, using the Siemens Facility Monitoring and Control System (FMCS) optimizes the use of water, chemicals and gases in the subfab to simultaneously improve sustainability, efficiency and cost-savings.

In addition, Siemens Industrial Edge installs an open, scalable edge computing system at the equipment level for localized data processing and analytics for rapid decision-making. By processing data closer to its source, fabs can implement faster control loops, detect anomalies instantly and power the rapid optimization of equipment performance.

Smart manufacturing facilitates sustainability
Smart manufacturing, which began as Industry 4.0, combines digital technologies with advanced manufacturing to create intelligent, efficient and connected systems.[2]

Smart manufacturing breaks down traditional production and data silos with a connected workflow engine across the fab to collect and share real-time performance data so the right data is available at the right time and in the right context for successful sustainability planning.

With smart manufacturing, you can simulate operations to continuously optimize your fab planning, processes and systems to increase efficiency while reducing carbon footprints and the use of water, energy, gases and other resources.

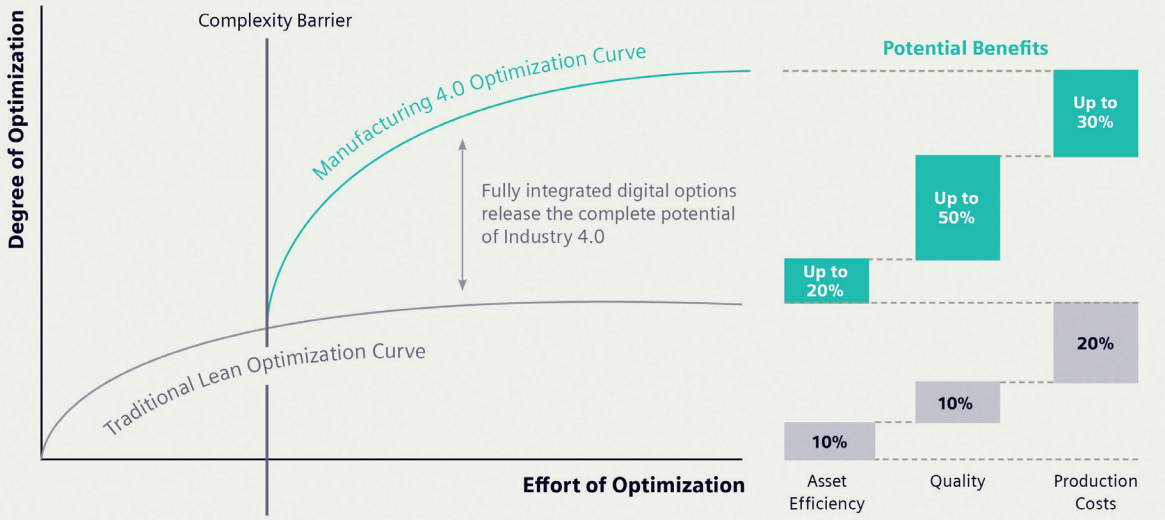
Projections from Siemens and Deloitte show that the potential for smart manufacturing is impressive:

a **20%** increase in **throughput**

a **15%** reduction in **costs**

a **10%** revenue **increase**

a **mitigated risk of cyber-attacks** and noncompliance with regulatory mandates and sustainability targets

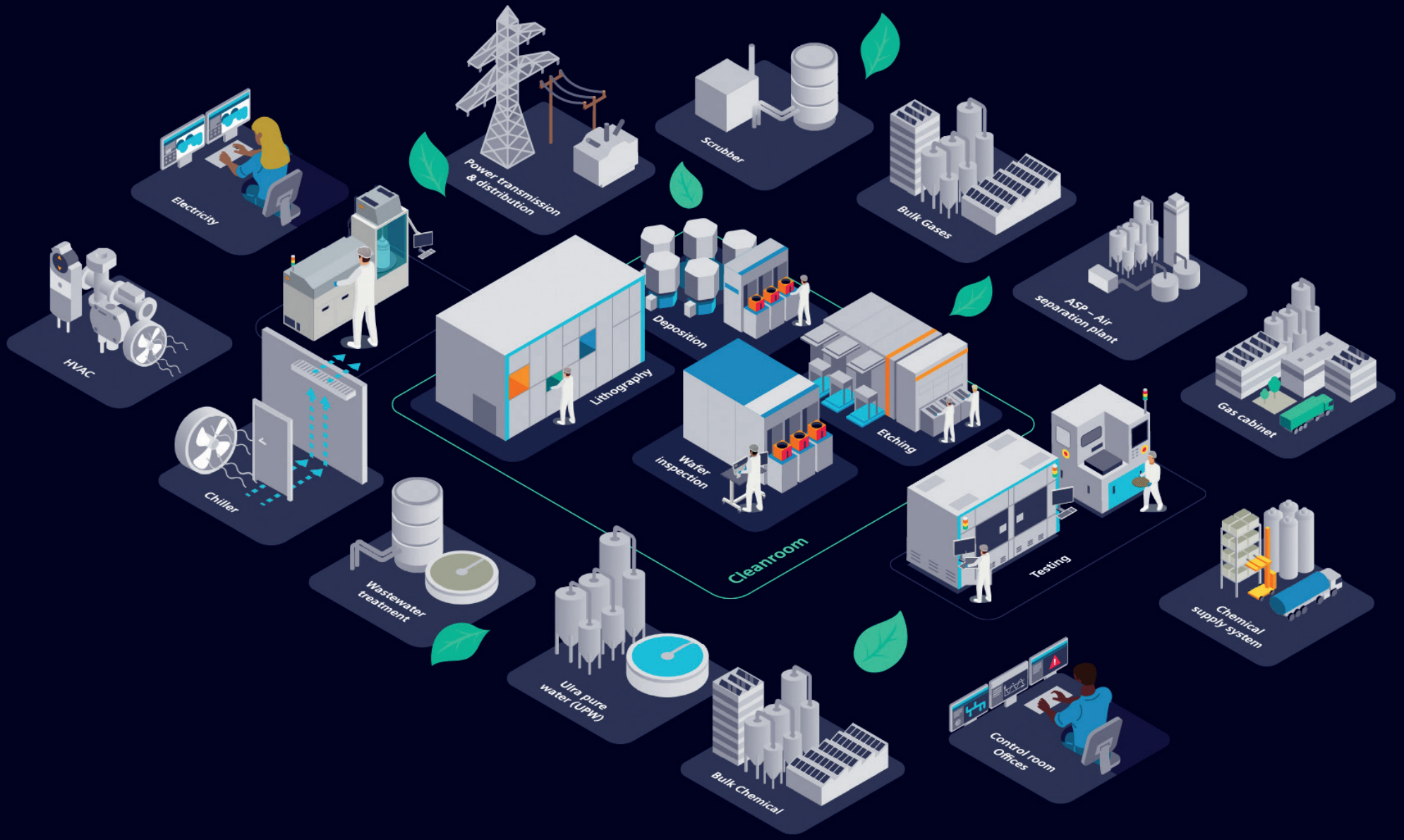


Deloitte Digital Factory

"Data shows you what is going on in your production environment so that you know exactly what levers you can activate to cut emissions. It's about creating a data workflow engine for continuous sustainability improvements."

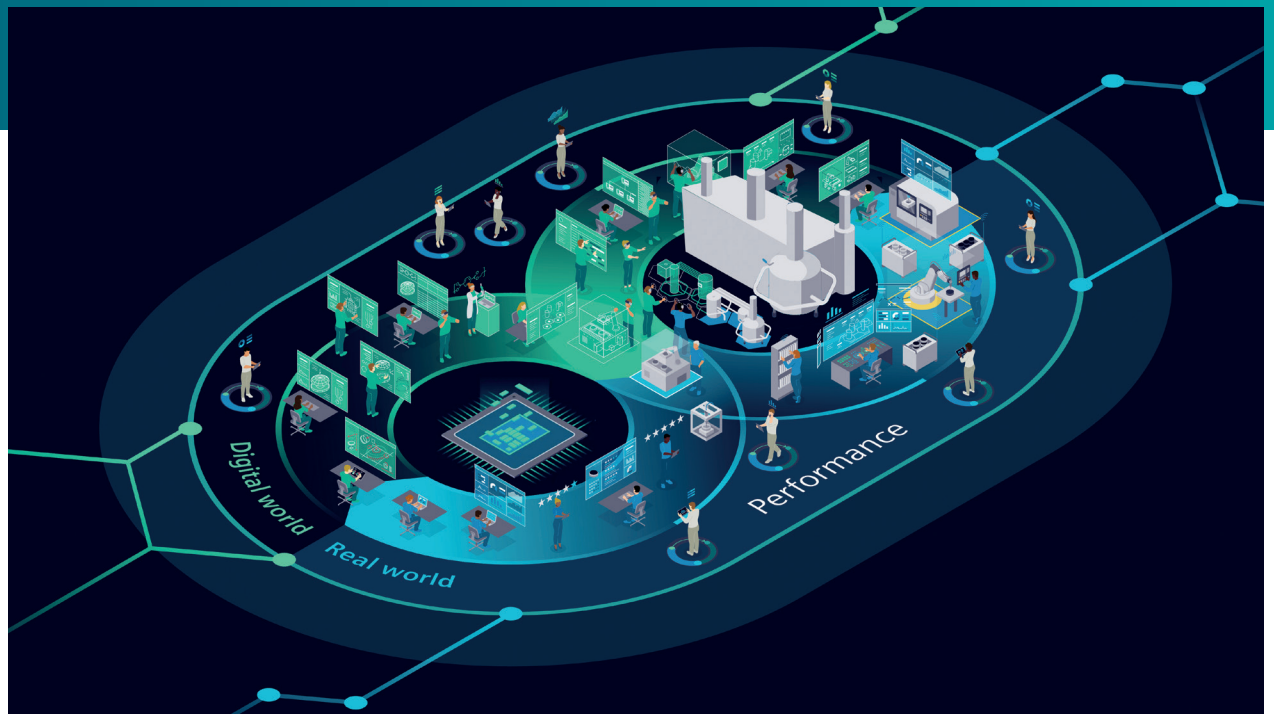
Dr. Gunter Beitinger
Senior Vice President, Manufacturing; Head, Factory Digitalization
Siemens

Connecting smart, secure and sustainable manufacturing processes across the fab



The semiconductor fab presents a complex challenge. Where should the journey begin?
It begins with the digital twin, which is a virtual representation of semiconductor manufacturing processes and systems. It is used to model, understand and accurately predict the fab's production performance.

The digital twin is virtually unlimited in its scope or application for precise modeling, learnings and optimization. It can be used to model either the actual product or manufacturing process. The digital twin can simulate real-world conditions in a virtual model prior to building a semiconductor product or designing actual manufacturing operations.



Virtual fab planning enables data-driven decisions
The validated digital blueprint can be used to orchestrate real-world operations with a seamlessly integrated MES, APC and automated material handling.

With semiconductor manufacturing equipment connected to MES, smart manufacturing can report real-time data collected throughout the fab. This includes data from sensors, actuators and input/output (I/O) modules at the semiconductor equipment level and from subfab facilities and utilities up through every level of product and process recording and tracking. The internet of things (IoT) data and process control data are fed into analytics systems to leverage both historical and predictive analytics to forecast and deliver better future outcomes.

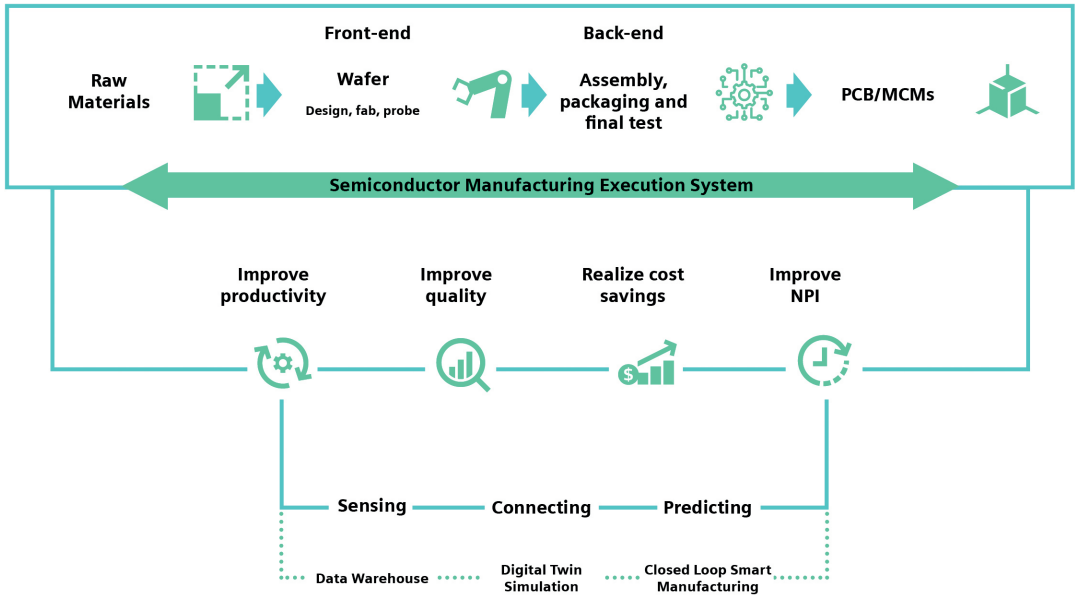
A comprehensive digital twin spanning the entire chip lifecycle can create a powerful feedback loop between design and manufacturing. By simulating production virtually and feeding real manufacturing insights back into design, manufacturers can optimize both chip designs and production processes before physical manufacturing begins.

With the integration of software and automation, digital twin capabilities are amplified across the chip lifecycle. Real-time production data automatically feeds into simulation, while analytics drive rapid process adjustments, creating an intelligent, self-optimizing system that continuously improves both current manufacturing and future chip designs.

Applying the power of data to sustainable outcomes

With end-to-end connectivity across systems, shown in the diagram below, real-time data is collected directly from the semiconductor MES to inform the digital twin and semiconductor specific dashboards.

Optimized Semiconductor Manufacturing Execution System (MES)



Siemens MES solutions work with FMCS to help semiconductor manufacturers achieve sustainability goals by optimizing energy use and reducing waste with real-time digital control of fab operations. Digital twin technology and advanced automation enable fabs to maximize quality and efficiency while minimizing environmental impact.

MES can leverage a digital twin to capture real-time performance data, including statistical process control (SPC) and deviations from manufacturing execution, maintenance, testing and scheduling. Continually updated with MES data in a closed-loop manufacturing system, the digital twin is always ready to provide advanced simulation to discover actionable insights not only for predictive maintenance, but also to identify production and sustainability improvement opportunities, which are significant.

Siemens' end-to-end sustainability solutions reduce carbon footprints and optimize the use of water, energy, chemicals and gases, ensuring safer handling of hazardous materials. This supports responsible sourcing and better utilization of materials.

Chipmakers and machine builders can design and build future-proof semiconductor fabs by implementing a wide range of digitally integrated automation solutions, reducing energy consumption, enhancing efficiency and productivity, choosing less regulated materials, reducing water consumption and providing people-centric workspaces in operations.

Empowering predictive maintenance
The digital twin also empowers predictive maintenance capabilities, including equipment health monitoring and predictive process performance. Automated response capabilities are enhanced, including predictive part replacement, preventive cleaning cycles, calibration scheduling, resource optimization and environmental adjustments such as gas delivery systems. Additional predictive capabilities include preventing unplanned downtime, optimizing future maintenance schedules, reducing future operational costs, extending equipment lifetimes and more.

Ai

With the addition of AI, predictive maintenance is enhanced even further
Additional AI capabilities include pattern recognition and anomaly detection, identifying equipment behavior changes, detecting emerging failure patterns, performing root-cause analysis, making risk assessments and preventive action recommendations.

When combined, the capabilities of the digital twin and AI built on a foundation of smart manufacturing and automation, enable semiconductor manufacturers to plan and execute a sustainable business strategy, from design to production to finished chip.

Sustainability KPIs help manage progress
Designing for sustainability begins with the commitment to reduce the carbon footprint, while establishing sustainability key performance indicators (KPIs) to measure progress and guide the process.

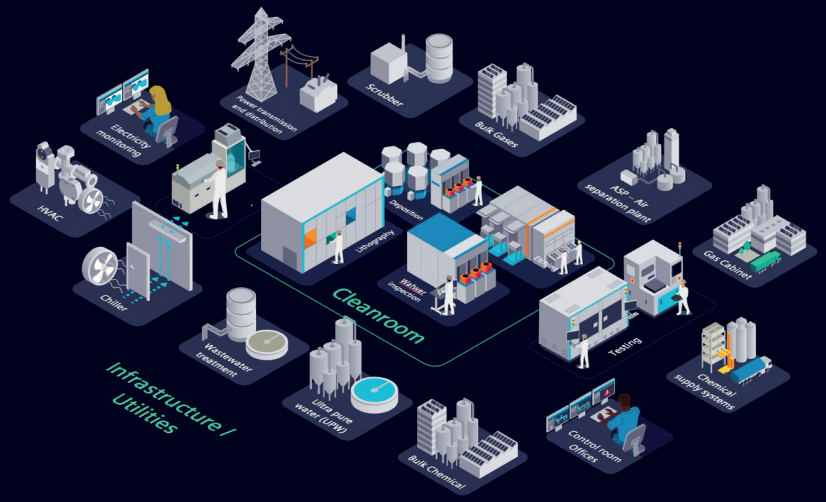
With digital tools such as the Siemens' SIMATIC Energy Suite, engineering managers can establish MES KPIs in energy monitoring and management, power usage patterns analysis, peak demand management, energy cost allocation, resource utilization metrics, energy per wafer metrics, carbon footprint tracking, load balancing capabilities, cost reduction opportunities and more, while tracking sustainability goal progress.

> "By establishing the relevant sustainability key performance indicators early, a business can properly monitor impact and costs in the design process and eventually across the entire value chain."

Eryn Devola
Vice President, Sustainability
Siemens Digital Industries Software

Facility Monitoring and Control System excellence

FMCS – Facility Monitoring and Control System Definition and Scope



The FMCS supports the plant infrastructure and utilities:

- HVAC Heating, Ventilation and Air Conditioning
- PCW
- Water (UPW and WWT)
- Gases
- Chemicals

Low Voltage & Medium Voltage distribution

Office Building

Sub FAB

Live Safety

Particle - Monitoring

By leveraging Siemens FMCS, fabs can streamline workflows, enhance quality control, optimize resource and plant efficiency and boost throughput.

Lowering energy consumption, eliminating waste generation, reducing chemical usage and regulating process cooling water (PCW) are critical points on the sustainability journey. Next steps such as selecting environmentally friendly materials and less regulated substances, properly sizing electrical equipment and sourcing alternatives to polyfluoroalkyl substances (PFAS) can significantly decrease the environmental impact.

Water is the lifeblood of semiconductor manufacturing, with a single chip requiring thousands of gallons of ultrapure water (UPW) during production. Each chip undergoes hundreds of cleaning steps using deionized water that is 1,000 times purer than tap water, since even microscopic contaminants can cause device failure.[3] With fabs consuming millions of gallons daily for cleaning, cooling and maintaining ultraclean environments, water conservation and recycling are critical for sustainable semiconductor manufacturing.

That is why we must safeguard this most essential resource of all, by incorporating water-efficient technologies to minimize high-volume usage of UPW and wastewater creation with wastewater treatment processes (WWP).

Informed by real-time fab and subfab performance data, the digital twin can create highly effective models for use in carbon reduction, material selection, energy and resource management, chemical usage, usage of gases, water conservation and other vital steps to reduce environmental impact and help improve your sustainability KPIs.

Sensors and dashboards are essential

MES and semiconductor specific dashboards provide sustainability analysts with the real-time information they need to both monitor the status of gas levels and to plan any changes in gas usage needed to improve the manufacturing process.

As mentioned above, about 30 percent of semiconductor fabrication emissions result from using process chemicals that enter the atmosphere during manufacturing.

As a result, manufacturing emissions must be carefully monitored and processes that produce emissions must be optimized. A sizable portion of the process chemicals used in a semiconductor fab are gases, which play critical roles in various stages of semiconductor manufacturing, including deposition, etching, doping and cleaning.

Each process gas must be managed carefully. Due to the miniaturization of semiconductor components, most gases must be available at the highest levels of purity. Not surprisingly, some of these gases are potentially hazardous to personnel and the environment.

Gases stored in the subfab and used throughout the fab require stringent safety measures and leak detection systems. Sensors must be strategically positioned throughout the fab and subfab to measure both the purity and security of gases stored in the subfab, while tracking and minimizing the gases used and discharged during the fabrication process.

Emissions from semiconductor fabrication are strictly regulated under international laws, and in the U.S., under both federal and state laws. This is where sensor data, sensor dashboards and Siemens sensor technology become critically important tools for optimizing sustainable processes.

Smart manufacturing puts the right data at your fingertips

Process engineers using AI can leverage the full spectrum of sensor data to fine-tune MES to run more efficiently while maintaining performance and quality.

Fortunately, change scenarios involving gases can be evaluated virtually using the digital twin at a fraction of the cost of testing different scenarios during the actual process.

Ion implementation, a common process used in semiconductor fabrication to implant dopant atoms into semiconductor materials, requires a variety of gases. Typically, gases such as boron trifluoride (BF3), arsine (AsH3), and phosphine (PH3) are selected. Each of these gases must be monitored for safety, since they can be highly toxic and corrosive, and for process control, since a stable and clean process environment is essential.

Fortunately, there is a growing emphasis on minimizing the environmental impact of gas usage, including the reduction of greenhouse gas emissions. For example, the growing use of fluorine, which has a global warming potential of zero,[4] can help to reduce the use of other greenhouse gases currently used to clean chemical chamber deposition (CVD) chambers. In addition, recycling systems for gases like neon are also being implemented, where gases are captured and purified, enabling their reuse in semiconductor manufacturing while reducing environmental impact and ensuring supply chain resilience. This circular approach, which can be modeled during sustainability planning with the digital twin, transforms what was once waste into a valuable resource, demonstrating how sustainable practices can enhance both environmental and operational efficiency.

Smart manufacturing synchronizes software, data sets and automation

With visibility across your entire semiconductor operation, from design to production to subfab performance, you can make informed decisions using real-time data and insights:

- Catch quality issues early and ensure flawless product consistency
- Collaborate seamlessly across all disciplines with robust data management
- Evolve from reactive to predictive to prescriptive maintenance to prevent downtime
- Analyze sensor, actuator and I/O module data from your equipment
- Anticipate potential problems and schedule maintenance before production disruption
- Improve process efficiency for rapid adjustments to optimize parameters and yield
- Meet quality and sustainability KPIs while optimizing resource and energy management

Future proofing your fab

For operational excellence, you need to harness the power of software-enabled automation to continuously optimize and adapt your semiconductor production to reach new levels of sustainable performance.

The combination of intelligent automation and machine learning algorithms enables fabs to detect and correct process variations in real time, dramatically reducing defect rates while maximizing yield. Furthermore, these smart manufacturing and automation systems provide the flexibility to swiftly reconfigure production lines, allowing fabs to seamlessly pivot between product specifications and respond rapidly to market demands, which is a crucial competitive advantage in today's fast-paced semiconductor industry.

Smart manufacturing also equips semiconductor fabs to make a next-level transformation using a strategic deployment of advanced robotics and AI-driven systems. These sophisticated technologies not only enhance manufacturing precision down to nanometer-scale accuracy but also elevate consistency across production runs.

Smart Manufacturing

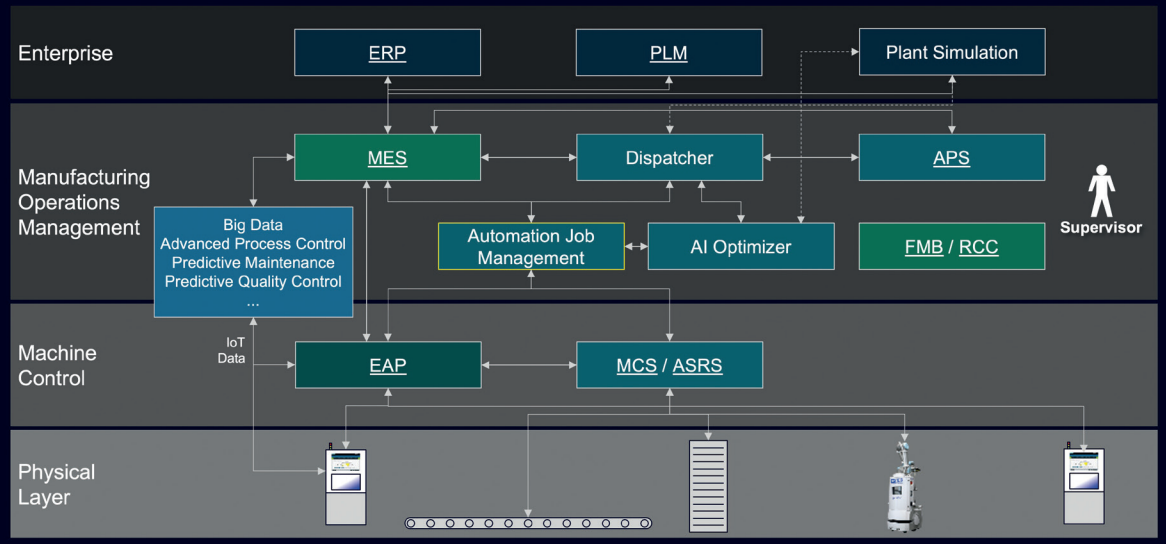


Diagram key:

ERP – Enterprise resource planning system

PLM – Product lifecycle management

MES – Manufacturing execution system

APS – Advanced planning and scheduling

FMB/RCC – Finite model builder/remote command center

EAP – Early adopter program

MCS/ASRS – Material control systems/automated storage and retrieval systems

Enhancing your future with Siemens' integrated software and automation solutions

By integrating Siemens smart manufacturing software and automation solutions, we enable semiconductor companies and equipment manufacturers to achieve greater productivity, improve new product introduction (NPI) yields at higher initial quality, enhance production sustainability, grow your business and stay well ahead of the competition.

Siemens is ready to be your partner with experience in end-to-end solutions in semiconductor manufacturing, automation and sustainable solutions. We're committed to helping your company reach your sustainability goals.

The Siemens mission is also to ensure that you have a successful business outcome from your smart manufacturing and digital twin investment as part of the Siemens Xcelerator business platform of software, hardware and services.

When you're ready to discover more, we're ready to show you the next step.

For more software + automation insights, visit www.siemens.com/us/automation/semiconductor

Siemens solutions empower semiconductor companies to innovate, design and manufacture with precision and efficiency.

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