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Sustainability in Smart Manufacturing for Semiconductors

Towards a smarter, more sustainable semiconductor industry

www.sw.siemens.com/en-US/solutions/manufacturing-execution-system-mes

Evolving to a smarter, more sustainable semiconductor manufacturing process

Semiconductors are the backbone of today's technology, powering the performance of the electronic devices and systems we use daily, from smartphones to smart watches to smart grids, AI and cutting-edge manufacturing. Today's unprecedented market demand for higher performance in increasingly more compact devices requires both design innovation and resilient manufacturing.

Innovative approaches such as 3D IC Design, which stacks multiple active semiconductor devices, and the integration of modular semiconductor components such as chiplets, have emerged to meet the demand for higher performance in less space. Other innovations such as high-performance chips that enable AI capabilities are driving new levels of market demand, with McKinsey forecasting an annual growth rate of 18% for AI-related semiconductors over the coming years.[1] But it is the growth of the entire category, with projections for total chip production nearly doubling by 2030[2], that is causing a looming environmental challenge.

**Why is sustainability crucial to the future of semiconductor manufacturing?**

Unprecedented demand means that most semiconductor plants are operating continuously, 24/7, resulting in a significant environmental impact, from high energy usage, chemical usage, and water consumption to the emission of greenhouse gases and hazardous pollutants.

A joint report by the global association SEMI (Semiconductor Equipment and Materials International), the Climate Consortium, and the Boston Consulting Group, mentioned that the semiconductor industry (spanning from chip design, EDA and IP, wafer fabrication, manufacturing, and package, assembly and test) is responsible for 0.3% of global carbon emissions today. Another 1% is induced by upstream and downstream suppliers and users. 65% of emissions from semiconductor manufacturing comes from using electricity to power equipment and buildings. About 30% of emissions result from using process chemicals that enter the atmosphere during manufacturing.[3]

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

Clearly, the time has come to address the environmental issues and move toward a sustainable future.

This is where legacy systems fall short and where smart manufacturing excels.
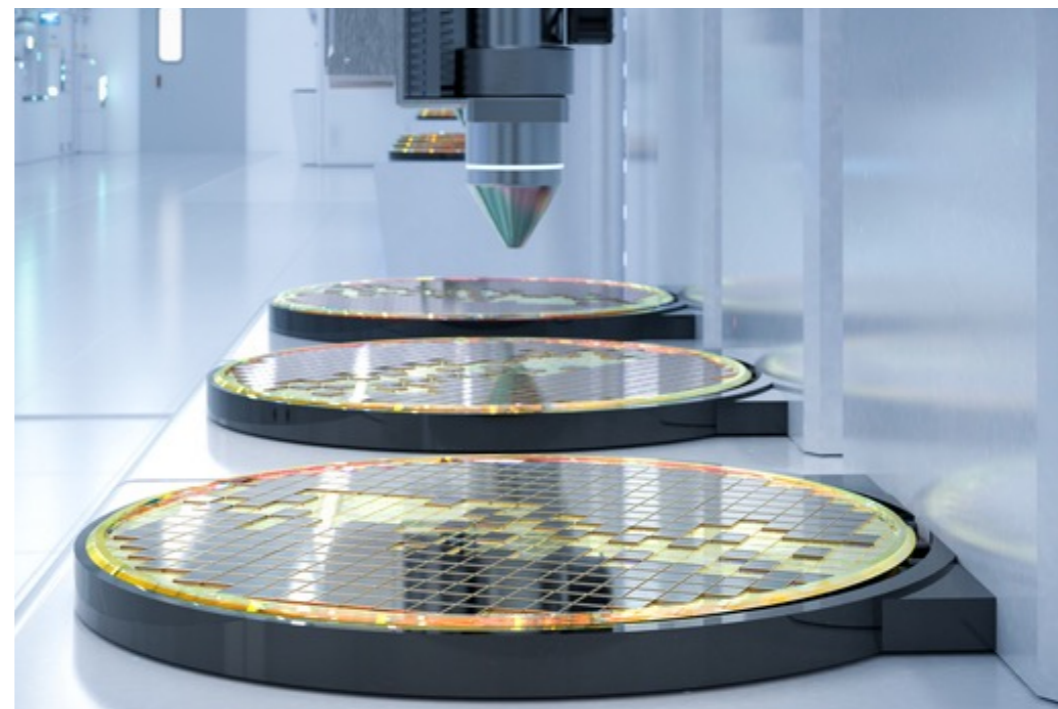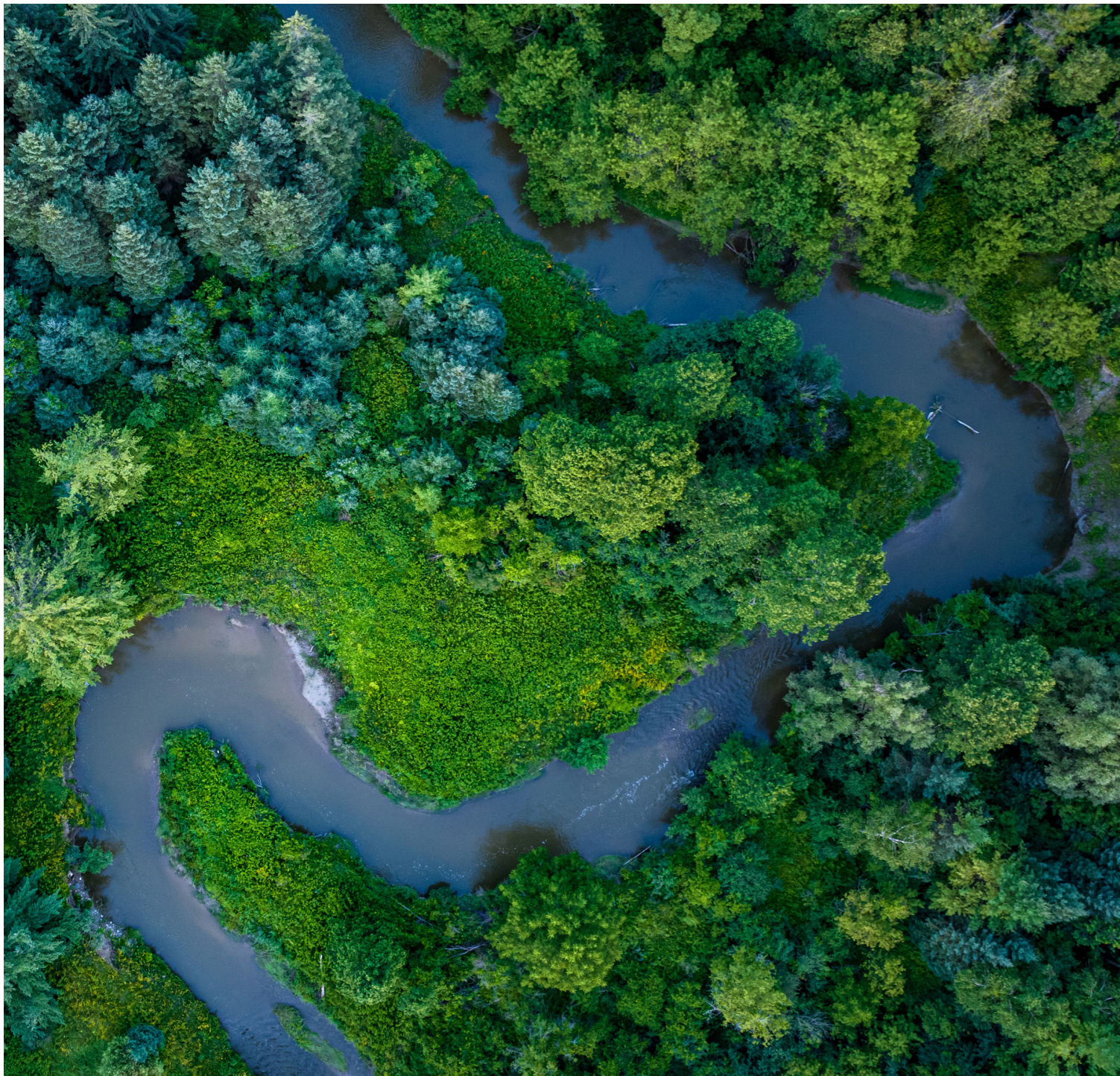
Toward a more sustainable future, and a more sustainable semiconductor industry

Meeting today's complex market and technology challenges, while pursuing the need for more sustainable design-to-production solutions, calls for a new approach.

...what if semiconductor companies could advance sustainable chip design and production processes to **scale up** with smart, secure operations throughout the product lifecycle - **while minimizing** their carbon footprint?

This can only be achieved through intelligent chip design and the sustainable production practices of **smart manufacturing for semiconductors**, working in collaboration with semiconductor equipment engineering and machine builders to evolve one cohesive system that minimizes the environmental footprint while maximizing productivity.

Sustainability is a journey, but the most important step is the first one. To design for sustainability begins with the commitment to reduce the carbon footprint. Lowering energy consumption, eliminating waste generation, and reducing chemical usage are good places to start. Then comes steps such as selecting environmentally friendly materials, less regulated substances, and sourcing alternatives to PFAS (per-and polyfluoroalkyl substances) to decrease the environmental impact. Next, we must take steps to safeguard the most essential resource of all, by incorporating water-efficient technologies to minimize high-volume usage and wastewater creation. Then comes steps like leveraging Siemens FMCS (Facility Monitoring and Control System) to optimize resource and plant efficiency, while incorporating Digital Twins to plan and optimize fabs. And there are many other vital steps ahead.

That's where smart manufacturing comes in.

Your digital enterprise holds the key
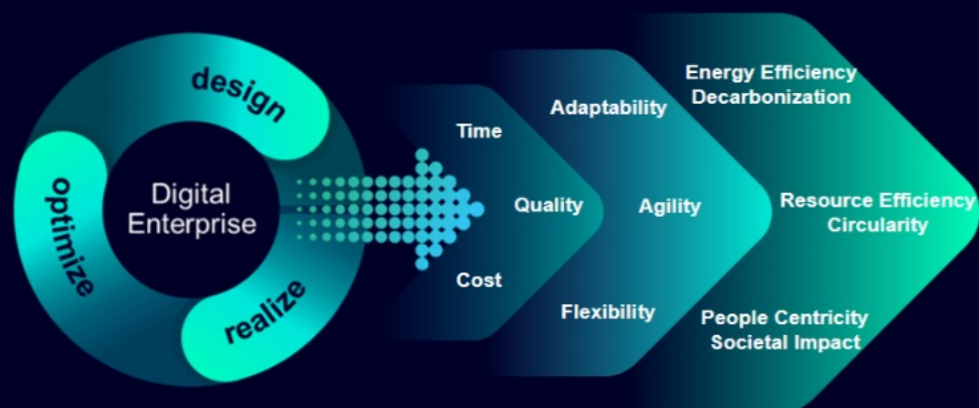
Better, faster, more profitable and more sustainable

Smart is sustainable

The path to sustainability is smart manufacturing- enabled, with a secure and sustainable design-to-production process for semiconductors that can evolve to a Digital Enterprise. The goal of becoming a Digital Enterprise serves as a comprehensive roadmap, a digital transformation pathway that guides semiconductor companies on their journey toward digital maturity and operational excellence.

As a digital enterprise, smart manufacturing capabilities, techniques and programs enable semiconductor manufacturers to achieve transformation by developing and executing one sustainable business strategy, from design to production to finished chip.

How smart manufacturing makes sustainability possible

Smart manufacturing enables sustainability. Digitalization is essential, and smart manufacturing is more comprehensively digital than the legacy systems the industry has relied on since its inception. Fragmented legacy systems, many of which are unconnected without a common data platform or common language across systems, limit the secure collaboration and traceability needed for today's ecosystem. Key design, engineering and manufacturing functions too often exist in silos where sharing information is difficult, which inhibits innovation, continuous improvement and impacts quality.

By contrast, smart manufacturing with its inherently greater digitalization creates an enterprise-wide flow of data that ties all manufacturing execution system (MES) functions together with fab, line and automation design. Smart manufacturing shares real-time data gathered throughout the fab, including data from sensors at the equipment level up through every level of product and process recording and tracking. Data is fed into analytics systems to leverage both history and predictive analytics for better future outcomes.

This comprehensive information flow of real-time and historical data enables **digital twins** of the production process and production performance to simulate various "what-if" scenarios for virtual planning. Manufacturers can test options to optimize process, product and quality improvements through analytics applied to the manufacturing process to achieve sustainability goals.

Smart manufacturing can optimize for a more sustainable design-to-production process

Siemens' end-to-end sustainability solutions reduce carbon footprints and optimize the use of water, energy, and chemicals, ensuring safer handling of hazardous materials. They support responsible sourcing and utilization of materials for a more sustainable manufacturing process.

With smart manufacturing, 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 plant operations.

Sustainable chip design and production practices reduce carbon through smart manufacturing capabilities that incorporate energy-efficient equipment, renewable energy sources, automation and AI for energy savings, enhanced efficiency, yield, and quality control.
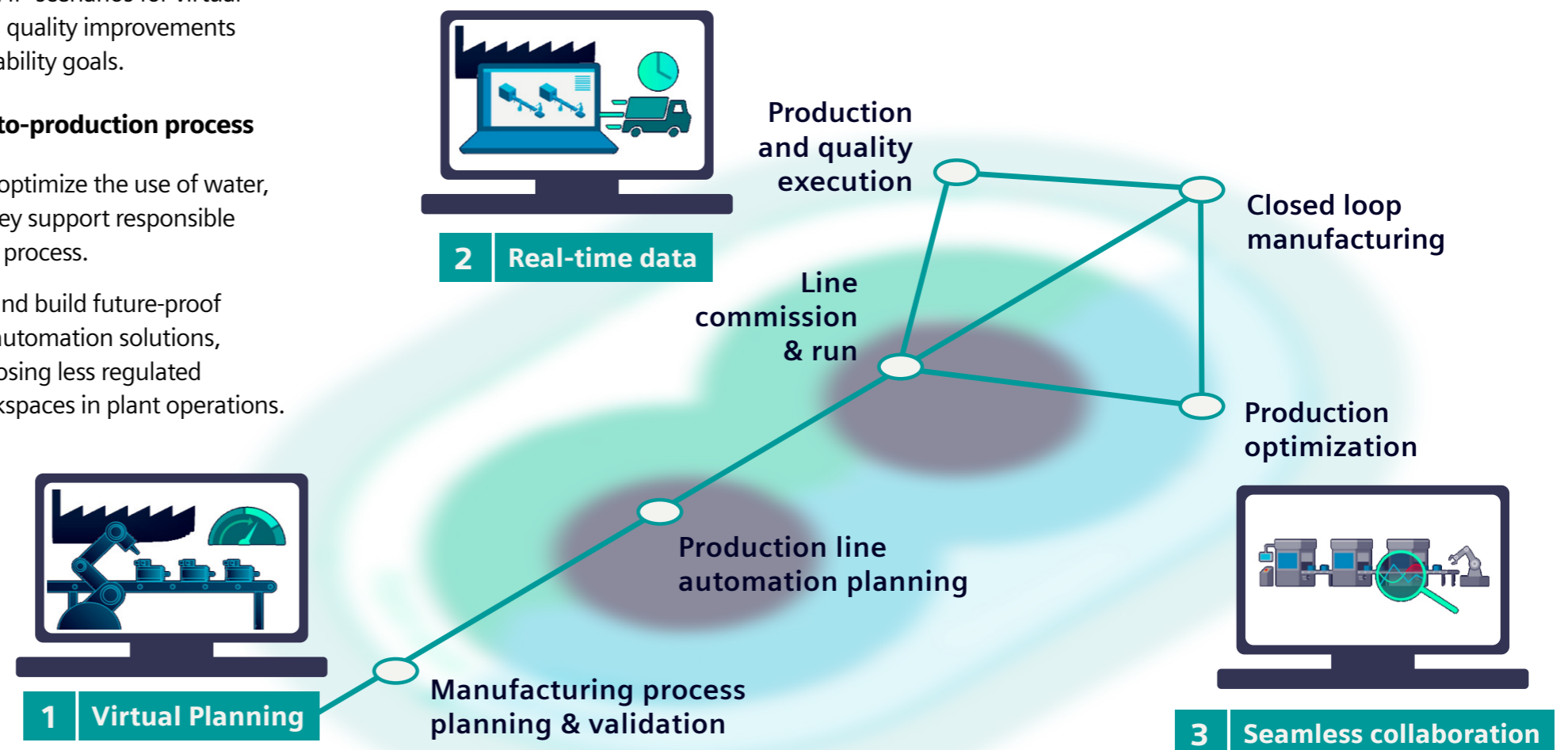
Smart manufacturing puts the power of data to work for sustainable outcomes

With end-to-end connectivity among systems, real-time data is collected directly from the semiconductor manufacturing execution system (MES) to inform semiconductor specific dashboards, including unique semiconductor specific Manufacturing Bill of Process/Bill of Information modules. MES for semiconductor manufacturing can leverage a digital twin of production to capture performance data in real-time, including statistical process control (SPC) and deviations from manufacturing execution, maintenance, testing, and scheduling. Continually updated with MES data, the digital twin is always ready to provide highly accurate simulation to help you identify production and sustainability improvement opportunities.

> 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."[4]

Dr. Gunter Beitinger, Head of Manufacturing, Siemens

2 Real-time data

Production and quality execution

Closed loop manufacturing

Line commission & run

Production optimization

Production line automation planning

1 Virtual Planning

Manufacturing process planning & validation

3 Seamless collaboration

Semiconductor Manufacturing Execution Systems - vital to smart manufacturing and sustainability

Semiconductor Manufacturing Execution Systems (MES) enable agile, interconnected workflows that are vital to today's semiconductor manufacturers, from front-end manufacturing and wafer fabrication to back-end manufacturing, assembly, packaging, and testing.

Smart manufacturing provides the end-to-end digitalization that takes MES to the next level, where all semiconductor systems and processes are connected to enable sharing of all design and manufacturing data via a single source of truth, continuously updated for all teams. This enables collaboration across all design, process planning, engineering, business and manufacturing disciplines, eliminating communication bottlenecks, inaccuracies and delays.

Yet smart manufacturing doesn't stop there, it also connects semiconductor enterprise resource management (ERP), and product lifecycle management (PLM) systems to MES for seamless collaboration through a continuous stream of connected data across your enterprise. Which provides the real-time visibility into production steps needed to detect issues earlier for faster business, design, engineering, and manufacturing decisions.

This superior data workflow engine powers continuous sustainability improvements

Siemens' smart manufacturing solutions empower semiconductor companies to enhance production capabilities while adhering to sustainability practices. Our end-to-end sustainability solutions reduce carbon footprints and optimize the use of water, energy, and chemicals, ensuring safer handling of hazardous materials. Additionally, they support responsible sourcing and material utilization, for a more sustainable manufacturing process. With complete traceability, compliance and verification.

Smart manufacturing also incorporates digital twins for a higher level of simulation, so you can test your production processes, including multiple MES optimization scenarios, in the digital world before building anything in the real world, which reduces optimization costs. Simulation can also model carbon reduction, material selection and many other environmental performance options to reduce environmental impact and help achieve your sustainability goals.
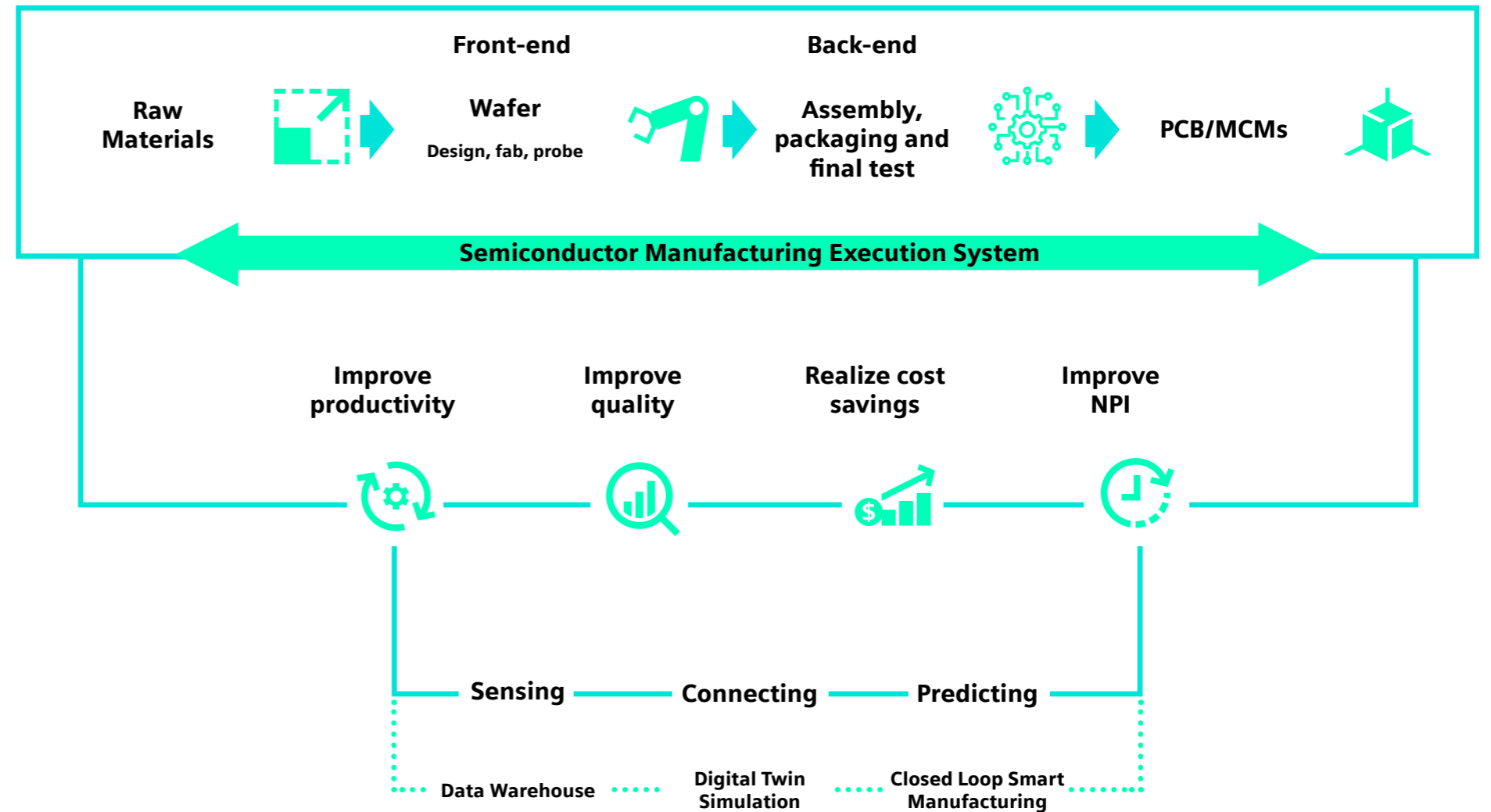
Smart manufacturing is more comprehensively digital, allowing greater and more reliable information flows."[5]

Julie Fraser, Principal, Iyno Advisors Inc.

What is the sustainability difference in smart manufacturing?

Siemens is the only manufacturing partner with end-to-end solutions experience in semiconductor manufacturing and sustainable solutions. This broad experience has helped to guide the design of our smart manufacturing solutions to enable semiconductor manufacturers to achieve transformation by developing and executing one sustainable business strategy, from design to production to finished chip. With real-time data collection, advanced planning, simulation and production optimization, combined with secure, seamless collaboration across disciplines, our smart manufacturing solutions make semiconductor manufacturing smarter, more agile and more resilient to address the complex challenge of effective sustainability practices.

As a result, there are numerous benefits provided by smart manufacturing that help the semiconductor industry move toward a smarter, more sustainable future:
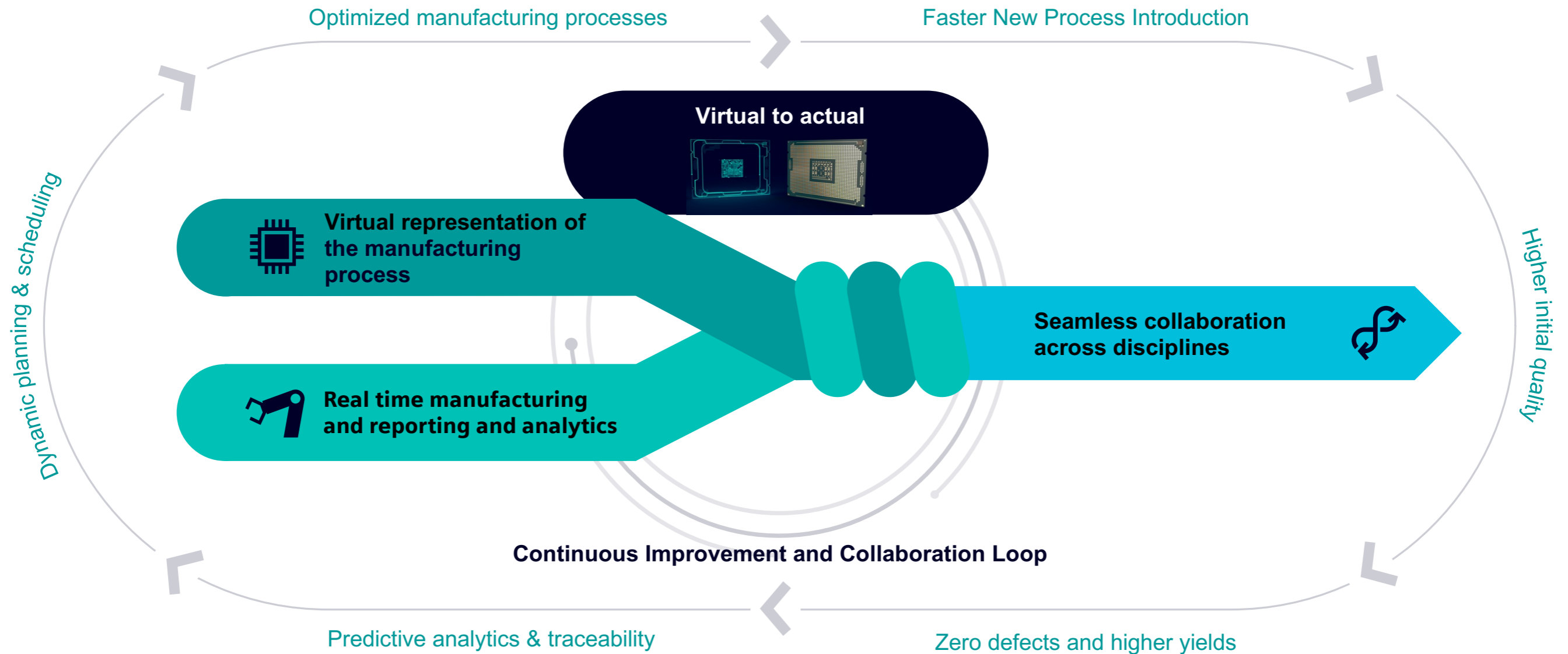
- Smart manufacturing capabilities can incorporate sustainability practices rapidly and efficiently.

- Enhanced innovation and sustainability practices are facilitated by using digital twins and data-driven insights to accelerate semiconductor development and new product introduction (NPI).

- End-to-end semiconductor process solutions embrace the 'Design-to-Production' process, spanning from the digital twin to the actual product, equipment, and production.

- Increased yield and output, along with reduced defects and optimized processes, result in higher chip quality and production efficiency.

- Reduced cost and downtime through predictive maintenance and optimized resource allocation minimize production stoppages and associated costs.

- Improved resilience and adaptability by enabling faster production cycles and flexible manufacturing processes, allowing rapid adaptation to market changes.

- Sustainable practices, including optimized energy consumption and resource utilization, contribute to a more environmentally conscious production process and infrastructure.

- Humans, machines, and digital tools evolving as one cohesive system - enhancing human capabilities through digital tools and 'human-to-machine' integration in the workspace.

What business results can you expect from an evolution to smart?

- **Achieve faster NPIs and reduce time to markets:** develop and introduce new products and services faster with the development of customized semiconductors for specific applications.

- **Eliminate re-spins:** increase yields and move toward zero defects.

- **Increased throughput:** semiconductor manufacturers can increase throughput by automating tasks, reducing setup times, and optimizing production processes.

- **Improved quality:** with predictive maintenance and closed-loop feedback, semiconductor manufacturers can improve product quality and reduce scrap rates.

- **Increased yield:** techniques such as predictive yield management and real-time yield tracking help semiconductor manufacturers increase yield and reduce waste.

- **Reduced costs:** semiconductor manufacturers can reduce costs by automating tasks, reducing waste, improving energy efficiency, and creating sustainable products and production.

- **Increased revenue:** produce products more efficiently and at a lower cost, develop and introduce new products more quickly, and meet customer demand more effectively.

The Multiplier Effect

Optimized manufacturing processes

Faster New Process Introduction

Dynamic planning & scheduling

Virtual to actual

Virtual representation of the manufacturing process

Real time manufacturing and reporting and analytics

Seamless collaboration across disciplines

Higher initial quality

Continuous Improvement and Collaboration Loop

Predictive analytics & traceability

Zero defects and higher yields

What steps are needed to evolve to smart manufacturing?

I. Virtual representation of manufacturing process.
First, you need to simulate a virtual replication of your actual manufacturing process, including process nodes and fabrication lines to gain the planning and production insights needed to eliminate defects and product re-spins for higher NPI yields.

II. Real time manufacturing and reporting and analytics.
Secondly, you need to close the loop with real-time manufacturing data from your MES to update your simulation models for a new level of data intelligence to improve production performance for a make-it-right-the-first-time, traceable, secure, sustainable, and high yield semiconductor manufacturing operation.
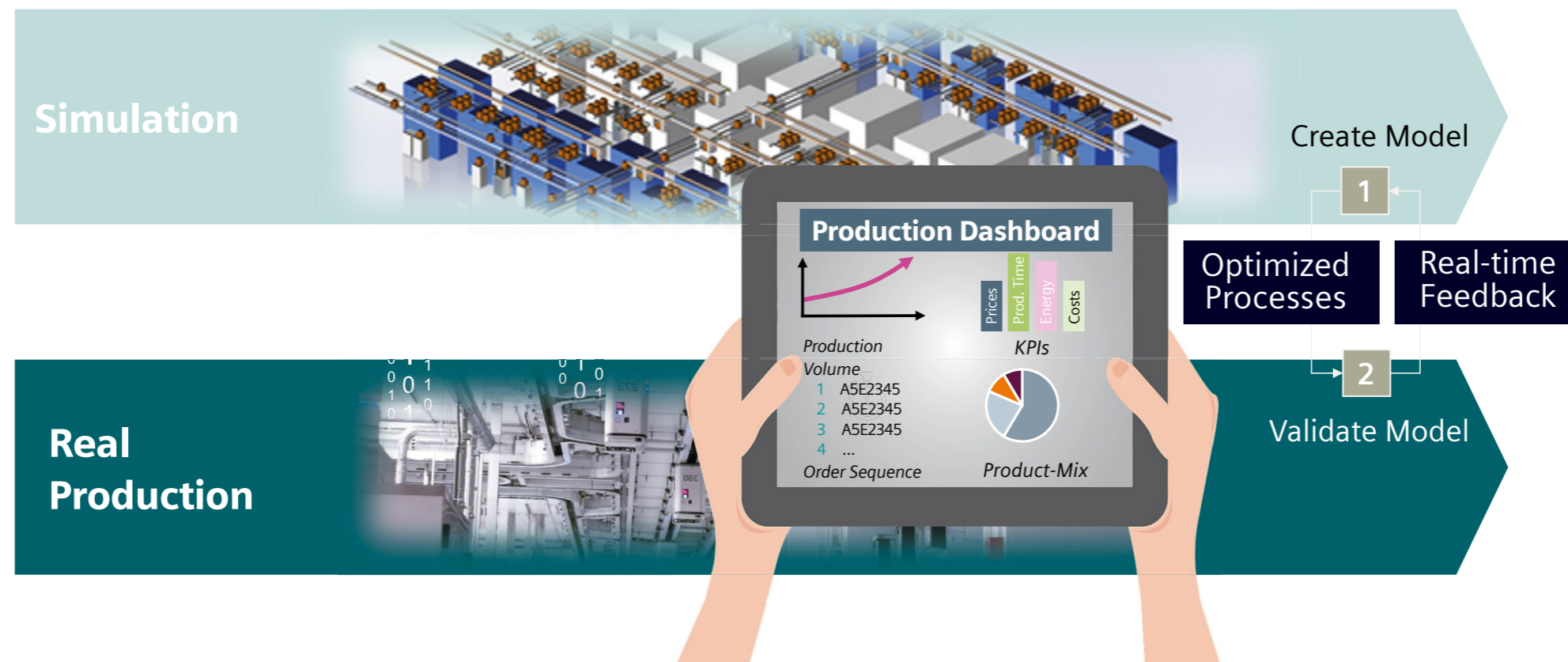
III. Seamless collaboration across disciplines.
Thirdly, you need "The Multiplier Effect" – the rich data connection linking smart manufacturing and every design and production discipline that delivers the right information at the right place at the right time in the right context to power seamless collaboration across all domains for a fully integrated manufacturing system. With closed loop feedback for continuous learning and improvement, you can make MES adjustments, adopt AI, and become fully preventive to mitigate risk, increase NPI yields and compete at the speed of business today.

Step I: The virtual replication of your manufacturing process

First, you need to simulate a virtual representation of your current semiconductor manufacturing process, including your process nodes, fabrication lines and real-time production data to gain the insights needed to improve your process, increase sustainability, and eliminate defects and re-spins to achieve higher NPI yields.

You need plant simulation and process simulation powered by digital twins to make a virtual model of your actual manufacturing process, continuously updated with real-time data and the virtual qualification of new process nodes. Simulation enables you to continuously perform "what-if" analysis from current model updates.

Simulation

Real Production

Create Model

1

Optimized Processes

Real-time Feedback

2

Validate Model

Production Dashboard

Prices
Prod. Time
Energy
Costs

Production Volume
1 A5E2345
2 A5E2345
3 A5E2345
4 ...
Order Sequence

KPIs

Product-Mix

Simulation empowers production optimization

By leveraging digital twins, you can predict production issues early to become prescriptive with performance insights about how and where to make operational adjustments to your MES, adopt AI, and become fully preventive to mitigate risk, and build first-time right products.

The digital twin is a highly accurate virtual model of either the product (the product digital twin) or its manufacturing process (the production digital twin). These models simulate real-world conditions in a virtual model prior to building a semiconductor product or designing actual manufacturing operations. Simulation can be used to simulate multiple what-if scenarios that can be evaluated virtually at reduced cost to optimize products and processes.
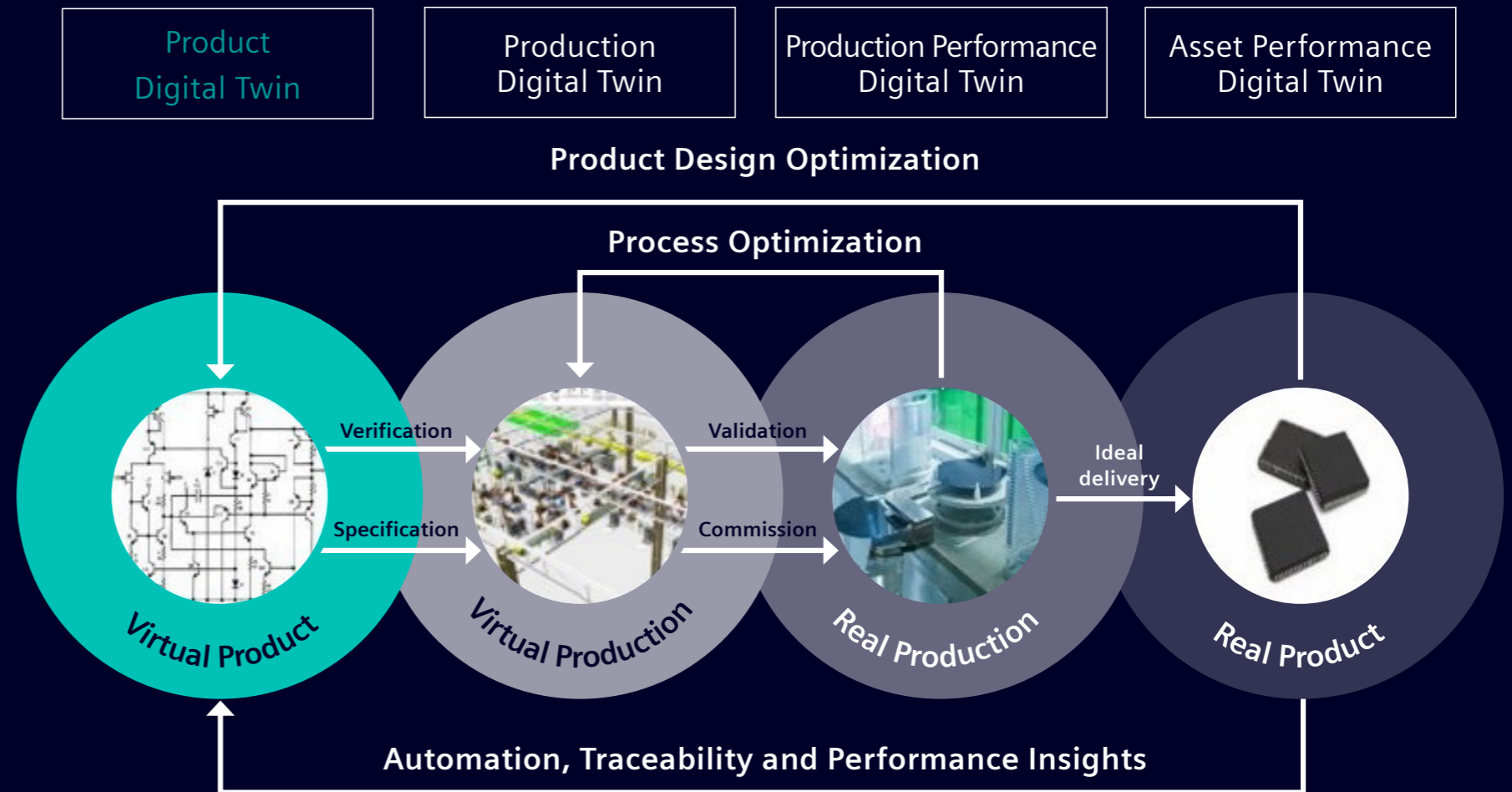
Digital twins are constantly updated from your semiconductor MES for exacting accuracy. By continuously collecting data from real-life manufacturing processes, manufacturing simulations can be continuously improved, resulting in more efficient manufacturing processes. The virtual model will dynamically inform and optimize the production environment for both detective (monitoring), and predictive (AI) functions.
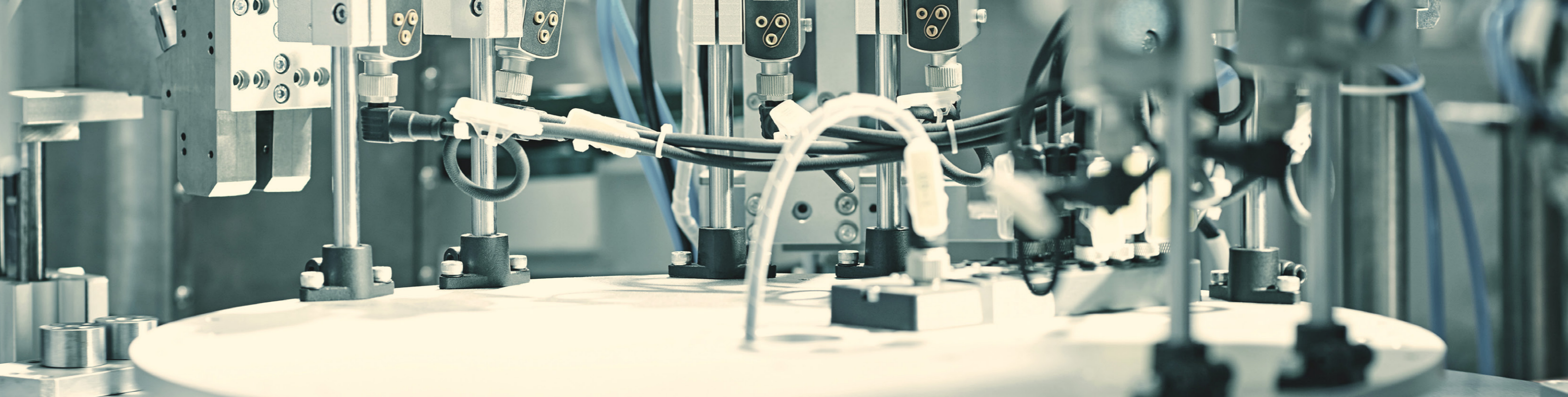
Digital twins also can be highly effective models for carbon reduction, material selection, energy and resource usage, chemical usage, water conservation, and many other environmental performance considerations to reduce environmental impact and help achieve your sustainability goals.

The human factor

For a truly holistic solution, your digital twin approach should also simulate human interaction with processes and technologies to optimize talent, worker allocations, ergonomic environments, productivity, and sustainability to ensure continuous business growth.

Manufacturing Intelligence

| Product Digital Twin | Production Digital Twin | Production Performance Digital Twin | Asset Performance Digital Twin |

Product Design Optimization

Process Optimization

Verification — Validation — Ideal delivery

Specification — Commission

Virtual Product — Virtual Production — Real Production — Real Product

Automation, Traceability and Performance Insights

With a digital twin, you can start capturing real-time manufacturing data and feed that data back into virtual models for simulation to:

- assess forecasting scenarios to ensure capacity for near and long-term orders
- accurately simulate human interaction with processes and technologies
- evaluate necessary changes within manufacturing processes
- optimize sustainable design and manufacturing processes
- capture and replicate your best practices to set a higher quality level than before
- optimize talent, worker allocations, ergonomic environments, productivity, and sustainability
- make better capital expenditure decisions using historical and forecasted data

By supporting the planning, design and implementation of smart, agile production and automation solutions with our digitalization service experts, Siemens can help to execute your digital transformation, boosting your competitiveness and increasing speed to market supported by secure, robust resources on the cloud.

Virtual representation of manufacturing process

Design and simulate manufacturing processes before they are realized, minimizing risk and ensure the processes are efficient and effective with minimal respins.	**Identify areas of waste and inefficiency, such as bottlenecks, unnecessary steps, and excessive inventory. Once waste has been identified, manufacturers can take steps to eliminate it.**
Create and optimize production plans and schedules. This helps to reduce setup times, minimize WIP inventory, and maximize machine utilization.	**Simulate the impact of different process parameters on product quality. This helps manufacturers identify the optimal settings for each process, leading to improved product quality and reduced scrap rates.**

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Defining your KPIs and incorporating them into the digital twin from the very beginning while measuring a product's sustainability impact across the design process provides the insight to succeed."[6]

Eryn Devola, VP Sustainability, Siemens Digital Industries Software

Step II. Close the loop with real-time manufacturing and reporting and analytics

Secondly, by using real-time manufacturing reporting and analytics you gain the advantage of continuous learning and quality improvement to execute advanced semiconductor fabrication runs with next-gen efficiency.

With a smart manufacturing environment that provides a higher level of data intelligence and automation, you can improve collaboration from design to production for a make-it-right-the-first-time, traceable, secure, and high yield semiconductor manufacturing operation.

With smart manufacturing, you gain the capability to update simulation models in real time using current MES operating data. You can leverage semiconductor specific Manufacturing Bill of Process and Bill of Information solutions that streamline and automate manufacturing recipe and work instructions. And you gain the advantage of data-driven Fab Insights provided by Fab Metrology Machine learning analytics and insights.

By leveraging a closed loop approach, you also gain the advantage of greater process flexibility and efficiency, with complete integration of regulatory and quality requirements along with synchronized production processes for optimal supply chain management. In addition, you can take advantage of cloud and edge analytics to support predictive maintenance.

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Smart manufacturing utilizes a mix of simulation, execution control and analytics to drive continuous improvement for a make-it-right-the-first-time with a high yield manufacturing process."[7]

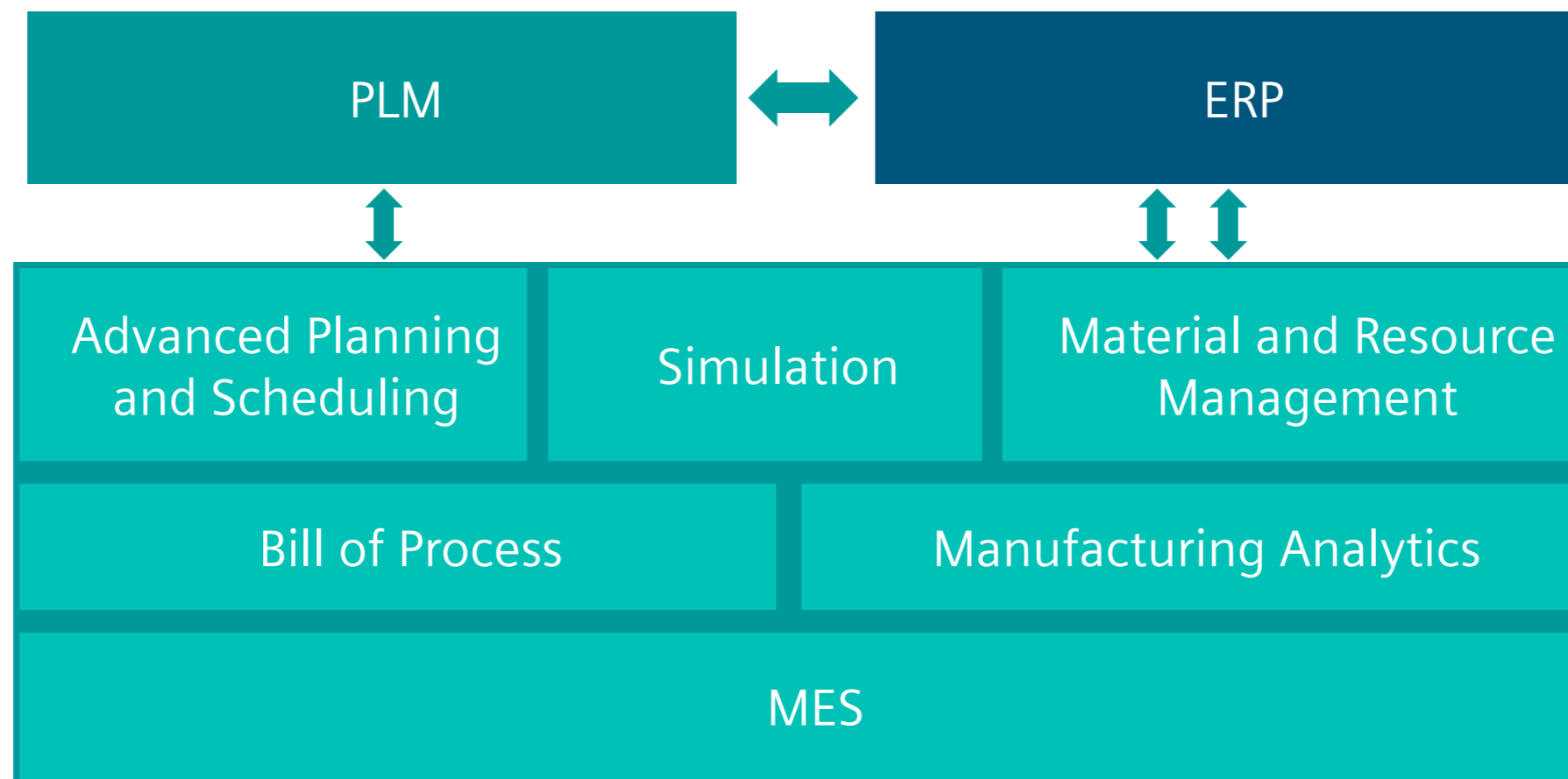*Julie Fraser, Principal Iyno Advisors Inc.*

Operate agile production lines and collect real-time data at optimal efficiency

Use data to maintain and leverage engineering simulation models from PLAN to evaluate changes driven by technology or product updates.

Direct process data to run a self-contained digital twin model on the industrial IoT platform for modeling continuous improvement.

Eliminate disruption from changes in product runs - delivering a batch of one with the same efficiency and quality as a batch of 1000.

Rapidly identify and predict production and quality issues, even before they occur. Use advanced analytics to turn high volumes of data into actionable insight.

PLM	⟷	ERP

Advanced Planning and Scheduling	Simulation	Material and Resource Management

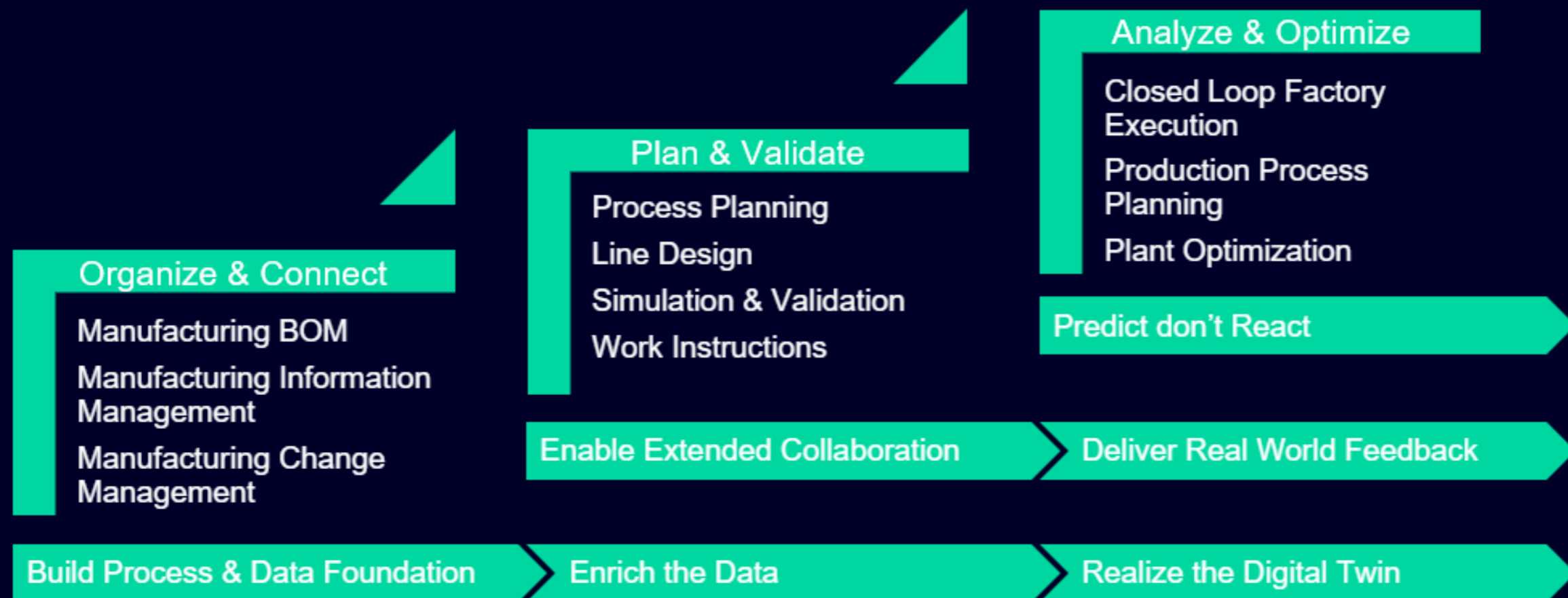| Bill of Process	Manufacturing Analytics

MES

Step III: Get connected across all disciplines

The third thing you need is to make a seamless connection between the virtual world and the actual manufacturing world.

As manufacturing conditions and processes change, you can continuously feed updated data from the real world back into the virtual world in a closed loop, which lets you continuously evaluate improvements.

With a continuous stream of connected data across all your enterprise, disciplines and domains, you gain the current insights needed to make business, engineering, and manufacturing decisions that work in real time.

When ready, you can implement your data-driven decisions through your MES to deliver the highest levels of initial quality with designs built right the first time, without disrupting your lean manufacturing processes.

Analyze & Optimize

Closed Loop Factory Execution

Production Process Planning

Plant Optimization

Plan & Validate

Process Planning

Line Design

Simulation & Validation

Work Instructions

Organize & Connect

Manufacturing BOM

Manufacturing Information Management

Manufacturing Change Management

Predict don't React

Enable Extended Collaboration → Deliver Real World Feedback

Build Process & Data Foundation → Enrich the Data → Realize the Digital Twin

What does smart manufacturing mean for your business?

Bottom line, a fully connected smart factory, utilizing data-driven insights from operational performance can deliver significant opportunities for continuous improvement and improved sustainability.

With the ability to collaborate seamlessly on a secure, open platform that connects all manufacturing solutions within your enterprise and across your supply chain, you can deliver the highest levels of initial quality to deliver designs that are right when built the first time. With robust, out-of-the-box solutions that seamlessly manage data from all domains, your teams can improve NPIs, reduce costs and drive innovation for a competitive advantage. For example, with a product lifecycle management (PLM) solution that can send the BOP (bill of process) directly to SAP, it allows you to support multiple sites that may use different MES, which provides the efficiency of a single point of access.

Embracing smart manufacturing is key. With smart manufacturing, you won't be just reacting, but you will proactively accelerate your foundry evolution to optimize manufacturing and put your company in prime position to win the race to build the semiconductors of the future.

Evolve from the inefficiency of being reactive to the efficiency of being predictive

Many traditional IC foundries are reactive, relying on post-incident analysis and corrective steps that often lead to production delays. But the adoption of smart manufacturing, with the digital twin collecting comprehensive real-time data, simulating next-generation processes, and informing smarter and more timely decisions, is the key to digital transformation. The evolution is on from the slow pace of reactive problem-solving to the rapid evolution of continuous learning, proactive quality management and predictive methodologies that prevent defects to deliver a higher level of semiconductor quality and higher yields.

The evolution from lean to smart manufacturing is key to your company's success and sustainability.

Seamlessly collaborate across all disciplines through a hub of enterprise systems

Connect your machines, lines, factories and supply chain with an open, comprehensive IoT solution.

Eliminate silos of data to achieve end-to-end visibility of your entire production process and increase process efficiency.

Model and analyze the operational efficiency of high-value assets using virtual sensors. Optimize manufacturing processes using predictive insights from AI and analytics.

Adopt the latest advances in the process automation to improve overall equipment efficiency (OEE) and lower your total cost-of-ownership.

Go Digital. Become
a smart, sustainable
digital enterprise.

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Often the ability of a smart factory is described as collecting data, analyzing and understanding them, aggregating them to meaningful information and predicting future events and finally even deriving decisions from them to influence and stabilize the future state-of-the-art process."[8]

Dr. Gunter Beitinger, Head of Manufacturing, Siemens AG

Take the next step. Accelerate your future.

When your smart manufacturing is ready for full production, you are equipped and ready to predict production issues early to become prescriptive with real-time performance insights about how and where to make operational adjustments to your MES, adopt AI, and become fully preventive to mitigate risk, achieve first-time right products, increase NPI yields, improve sustainability, and grow your business.

Siemens is the only manufacturing partner with end-to-end solutions experience in semiconductor manufacturing and sustainable solutions, making us the ideal choice to support your sustainability goals.

It all begins with a progressive evolution to smart manufacturing.

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

Learn more
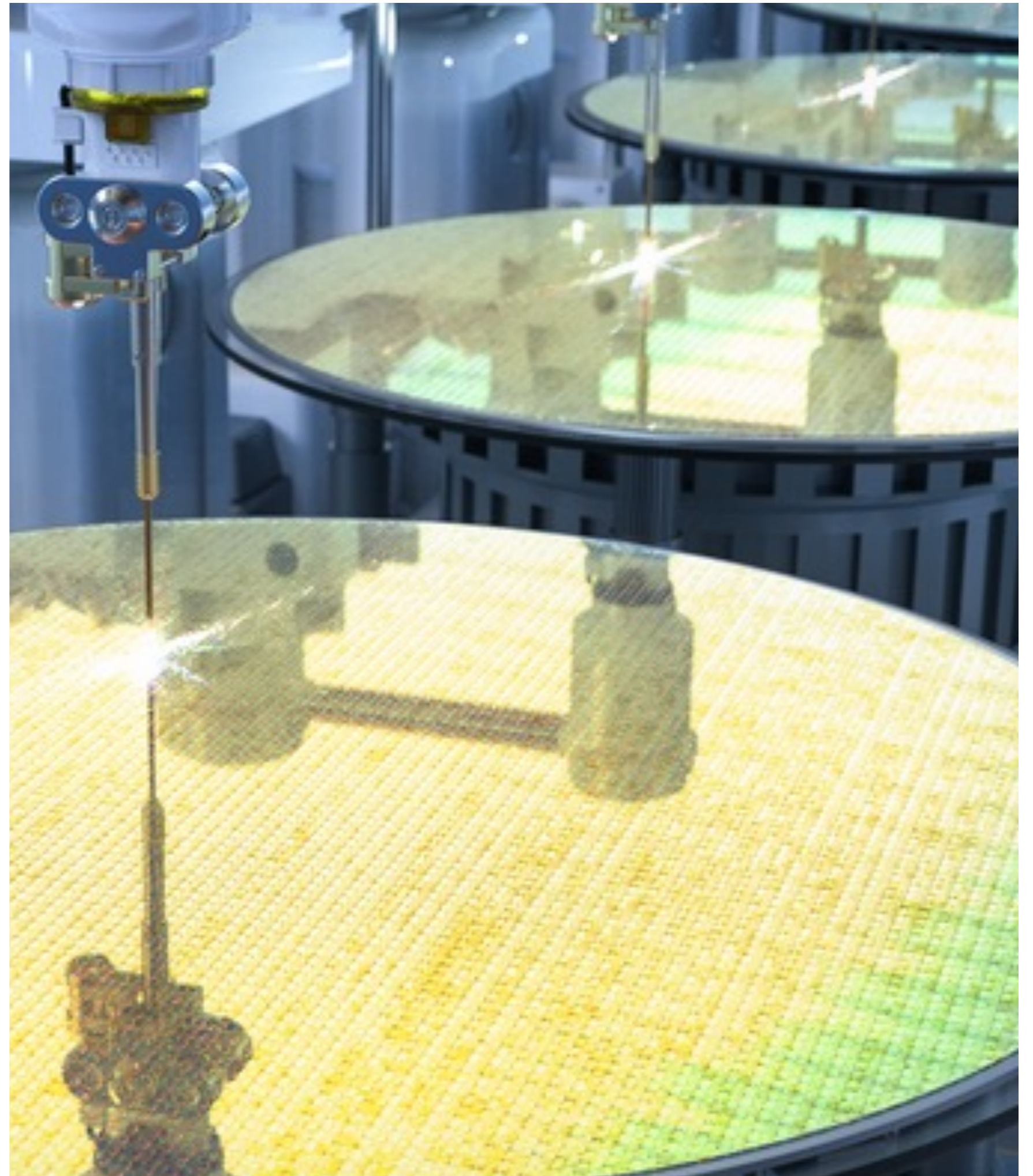
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8. Siemens blog: Dr. Gunter Beitinger, Head of Manufacturing, Siemens AG, 25 July 2019 https://blog.siemens.com/2019/07/the-journey-from-a-factory-to-a-lean-factory-to-a-lean-digital-factory/

Siemens Digital Industries (DI) is an innovation leader in automation and digitalization. In close collaboration with partners and customers, DI drives the digital transformation in the process and manufacturing industry. With its Digital Enterprise portfolio, Siemens offers companies of all sizes end-to-end products, solutions and services for the integration and digitization of the entire value chain. Optimized for the specific requirements of each industry, the unique portfolio enables customers to increase their productivity and flexibility. DI is continuously expanding its portfolio through innovations and the integration of future technologies. Siemens Digital Industries is headquartered in Nuremberg and employs around 72,000 people worldwide.

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