Entering the era of software-defined manufacturing:

A vision for productivity

The era of software-defined manufacturing

For years, manufacturers have adopted technologies and processes to redesign and improve how things are made and how people work. Many enterprises are already on an industry modernization journey, as 92% of manufacturing executives expect smart factory solutions to be the main drivers of competitiveness in the next three years, according to a Deloitte survey.[1] Yet, modernization efforts across manufacturing sectors have been somewhat difficult to achieve, and the demands and constraints in modern manufacturing are pushing enterprises to find ways to make transformational progress and keep pace in a dynamic marketplace.

Today, product designs often have a shorter shelf life. Changing consumer tastes require flexibility in production. Manufacturing contends with hundreds, sometimes thousands, of variations as attributes are adjusted over the product life cycle. Software content is increasing in many products, with software-enabled features updated during the manufacturing process. And amid this, enterprises are struggling to manage decades of technology debt, process debt, and resistance to change—all of which hinder the agility needed in modern manufacturing.

To manage these challenges while also driving toward transformational change, a new vision is necessary—software-defined manufacturing (SDM). In this vision, **data, software, automation, products, and human workers are aligned** to close the gaps in smart operations. Manufacturing operations are controlled, managed, and optimized using software applications and services. In its fullest potential, SDM is the **seamless orchestration of people and machines** across the factory, factory network, and supply chain.

The **defining technical characteristic is abstraction,** wherein interactions with production are separated from the production's technical infrastructure using virtualization. Put another way, software and hardware are decoupled in SDM, which is a paradigm shift from current ways of working.

Consider how things often work today. Imagine a fuel pump that is part of the fuel injection system of a gas turbine. Engineering designed the pump in a 3D virtual environment, and the schematics were sent to manufacturing for production. Once there, factory managers found that due to equipment limitations, they needed to adjust a few attributes to the pump. These changes were written down on a 2D design (but not shared back with engineering). Then, to produce the pump with maximum quality, configurations on the production line needed to be changed, and there's a problem. To make the change, a human worker must physically interact with plant assets, updating software or inputting new directions. They may need to do this across numerous pieces of hardware, and meanwhile, production is at a standstill.

With SDM, this all changes. It is software that defines the production process.

Digital twins of products are maintained from design to test to manufacturing and back to engineering, for a consistent representation—or digital thread—throughout the life cycle. Production lines, designs, plant layouts, and even supply chains are rapidly adjusted, sometimes without any downtime, by leveraging a real-time communication and reference layer from factory to cloud to digital twin.

Imagine product design in a virtual environment, where coordinated systems and data feedback loops allow manufacturers to dynamically iterate without the time and waste of physical prototyping. Imagine updating hardware across a plant network with a single deployment, enabling changes to production without downtime and the ability to manufacture new product designs with the same hardware. Imagine software-embedded products, where the software serves as the communication layer between digital twins to identify discrepancies in production. Imagine bringing together software, AI, and edge sensors to reveal operational constraints and rapidly adapt workflows to overcome them—all with limited manual action required.

This is the future state to which we are collectively headed, although it is likely to look somewhat different company to company, as each manufacturer considers its own challenges and aspirations and how the SDM vision can answer them. The next task is to unpack and explore the incremental steps to enterprise-wide transformation and how technology, people, data, and processes play a role in enabling SDM for the next era of industry modernization.

Unpacking the paradigm shift and value unlocked

Industry modernization efforts often layer solutions to accelerate or improve an aspect of the manufacturing process.

Cloud compute, data collection, digital design, and other common components of modern manufacturing each yield benefits in productivity, efficiency, and quality. Yet, it is when these and other technologies are integrated into an enterprise-wide vision for SDM that their greatest potential becomes accessible. SDM's impact lies in how it enables manufacturers to take new approaches to tackling problems, accessing knowledge, and orchestrating people and machines.

First principles approach

SDM enables a first principles approach to manufacturing, bringing computational science to the shop floor and challenging orthodoxies to push the boundaries of what's possible. In the SDM vision, data, connectivity, and a shared framework for product attributes and features help overcome gaps and silos between engineering design intent on the one hand and iterating designs for manufacturability and product variations on the other. In this, SDM supports a greater level of data-driven decision-making and continuous innovation. Rather than perfunctorily relying on institutional knowledge, SDM brings tools that enable organizations to leverage preexisting assumptions as a starting hypothesis to further test, validate, and refine leading practices; this while also optimizing for future scale. Organizations can leverage data science and even quantum computing to fuel new solutions to familiar problems.

Knowledge access

SDM connects the factory ecosystem to manage and codify knowledge, eliminate information gaps, and facilitate access to knowledge. It allows the organization to extract information from systems data, institutional knowledge (before workers retire), and analog sources (voluminous documentation). It can do so regardless of data form or location and leverage a breadth of sources, including vendor and market data and the supply chain network. In this, knowledge access can become intuitive without specialized training or laborious work instructions. It also affects how manufacturers connect employees and machines for greater collaboration.

Orchestration

With SDM, manufacturers can access a new level of connectivity, collaboration, and human-machine orchestration to optimize processes and outcomes. The seamless data flow and coordination of human and non-human workflows unites the physical and the digital, bringing together solutions in robotics, software applications, and hardware. This integration extends from the shop floor to the C-suite, factory to factory, and across external partner networks.

By accessing capabilities in these areas, the fuller value of technology modernization can be realized. Beyond typical key performance indicators for speed and cost, SDM can improve operations at every step of the product life cycle. It expands the capacity to fill customer demands, enhance product quality, increase production efficiency, streamline the changeover process, reduce unnecessary late design changes, improve the worker experience, and ultimately drive financial impact.

This new vision for manufacturing on its own is compelling and valuable. Yet, manufacturers have pursued technology modernization for years, and transforming to SDM may appear at first to be another hardware-intensive, long-term, aspirational endeavor, even approached incrementally. However, with rising customer expectations, increasing competition, and a range of enterprise risks and constraints, manufacturers are being pushed to find new and sustainable approaches to product development, fabrication, and support.

The challenge of change

SDM can help manufacturers solve for some of the most stubborn obstacles to productivity and efficiency—and facing external and internal pressures to change, there is some urgency. Externally, manufacturers face increased cost pressures and customer demands, with rising expectations for higher product quality, increased personalization, and lower costs. Yet, disruptions in supply chains and lack of resilience can introduce significant constraints, while limited visibility into Tier-N suppliers hinders the flexibility and agility manufacturers require to adapt to emerging issues. There is also the reality that the lifespan of some products is perpetually decreasing, based on consumer demand. This is driving a need for flexibility and agility in design and production, as solving for cost, speed, and other factors is different for products unchanged over many years versus those that will be redesigned or retired in a much shorter time frame.

Internally, manufacturers are challenged by human capital requirements. More than 80% of manufacturers cite workforce constraints as a reason for turning down business opportunities.[2] Part of the challenge is that segments of the workforce are looking toward retirement, and manufacturers also face the perennial issue of attracting workers to manufacturing professions and cultivating a labor pool that elects to live and work where plants are located.

Meanwhile, legacy technologies on the factory floor have not been modernized at the pace of innovation, hindering flexibility and agility between and across engineering and manufacturing. There can be tension in technology adoption between parts of the enterprise. Engineering may design in a 3D virtual environment, but those designs may also be regressed to 2D schematics once sent for production. This loses metadata associated with the product while also challenging feedback loops that can enhance fit and feature of design, as well as product manufacturability.

Further, when systems are updated, the impact is often limited to one factory, rather than throughout the network. Capital projects are typically funded only to the extent necessary to address specific functions. As a result, broader system components may be neglected, preventing a more systematic focus. Legacy manufacturing systems deployed in a rigid fashion create technical and business debt, leading to siloed systems with poor data exchange, built-for-purpose integrations that hinder the ability to scale, and significant funding complexities. Collectively, these challenges limit the flexibility and agility industry modernization and SDM could deliver.

Facing these pressures, one challenge is determining which enterprise changes are necessary to access SDM. On the path to an answer, there are a number of factors that will require treatment.

Siloed data and technologies inhibit connectivity and orchestration. Disjointed, unconnected information hinders a scientific approach, stifles knowledge access, and complicates the ideal balance of human-machine workflows. Part of the challenge is shifting from a domain-driven architecture to one that is event-driven.

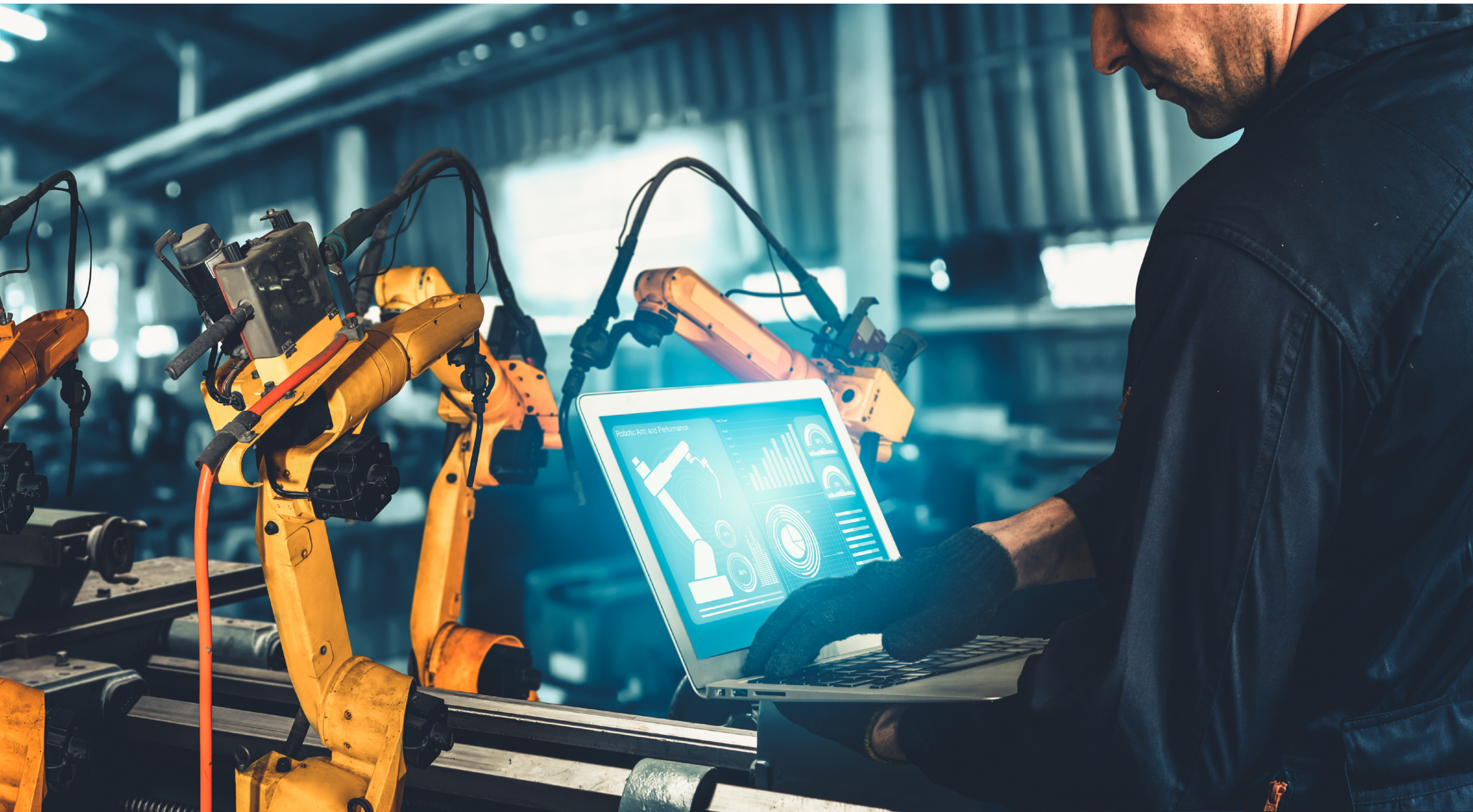
IT and OT systems may be disparate and unintegrated. This prevents data exchange and connectivity permitting communication, and it also frustrates the opportunity to connect financial and manufacturing systems to quantify impact. Organizations need to address how to holistically manage IT and OT in a converged technology environment, considering a balance of enterprise standardization with specific operational needs and concentration of ownership (centralized versus decentralized).

Cybersecurity becomes even more business critical as increasing data flows, devices, cloud services, and enabling hardware create attack vectors and vulnerabilities for bad actors. In this, mitigating tactics such as network segmentation, data access control, and continuous monitoring are table-stakes activities.

The adoption of mature and emerging technologies both complicates and enables software/hardware abstraction. In developing code that is hardware independent, engineers need assets that can accommodate the shift, and they also face the challenge of redesigning a range of traditional approaches, from system architecture to technical implementation.

A holistic approach is needed in aligning business strategy, technology investment decisions, design and governance, and talent considerations. The goal is complete ecosystem connectivity, wherein software-defined manufacturing environments, products, and interfaces permit visibility and traceability of every action and data point across the entire engineering and manufacturing life cycle.

While change is hard, a shift toward SDM can fit within ongoing plant network improvements. Greenfield investments provide an opportunity to move quickly in demonstrating value and validating investments across the network. Brownfield modernization can create the technical flexibility and agility needed to keep pace with competitors. Funding opportunities may emerge from public sector investments and grant programs. Companies in the position to build greenfield have a huge opportunity to embrace the SDM vision today, while those making brownfield investments may do so over time. In both cases, however, the North Star of SDM is the same: the seamless orchestration of people and machines to create products. The development and maturity of a suite of technologies underpins the potential.



The impact of maturing and emerging technologies

SDM is enabled by a range of technologies. Many manufacturers are either in the process of adopting or have already adopted mature solutions, such as embedded systems, cloud computing, and edge computing. These technologies are typically standard in IT environments, but they tend to be rarer in OT. Meanwhile, bleeding-edge innovation marches forward, and SDM is also enabled by new technologies that are only just emerging.

Sensors and embedded systems

Sensor-enabled real-time monitoring increases visibility across environments, informs digital asset or process twins, and fuels advanced analytics and model-based simulations. The development of smart sensing integrates sensing, processing, and communication in a single device. With this, sensors can measure physical parameters (e.g., temperature, pressure) and process the data locally, permitting real-time data analysis, filtering, and decision-making at the sensor level. For process industries and hazardous environments, new developments in Ethernet-APL enable connectivity and digitization of field devices through 2-wire Ethernet. Mobile robots can also serve as monitors across multiple assets where low-frequency data is sufficient.

Cloud computing

Cloud adoption is increasing in business-critical functions, and Gartner predicts more than 70% of enterprises will use industry cloud platforms by 2027, up from less than 15% in 2023.[3] Because cloud computing is elastic with market offerings for compute on demand, enterprises can focus the workforce and capital on core engineering and manufacturing competencies, rather than investing in on-premise data centers and the talent needed to run and maintain them. Today, manufacturers are exploring cloud suitability for business-critical manufacturing applications, as well as the potential in hybrid infrastructure capabilities. Furthermore, organizations are recognizing the untapped value of industrial data stored on the cloud, in data historians, and other systems.

Edge computing

New chips and hardware capabilities enable advanced analytics and processing at the edge, and to access the value, many manufacturers are increasingly adapting established IT principles (e.g., DevSecOps) for the OT environment. The benefits of edge inference include low latency for real-time insights, as well as cost efficiency, as only critical data for model training or historical analysis is sent to the cloud. Manufacturers today can design solutions balancing cloud and edge compute to optimize system performance and cost.

AI, machine learning, Generative AI, and agentic AI

Numerous types of AI and automation are maturing. Advanced analytics capabilities inform decisions across the manufacturing value chain. There may also be opportunities to automate some decision-making, helping to streamline processes and enhance flexibility and agility. For several years, leading manufacturers have investigated how to integrate predictive AI outputs into closed-loop control systems. While this approach is being adopted cautiously, it has the potential to enhance control systems, and SDM can facilitate integration, enabling near real-time adaptability based on the advanced insights. The advent of Generative AI gives enterprises new tools to explore and summarize information across different data sources (including knowledge captured from experienced employees) and generate text, imagery, video, code, and even 3D models based on that data. Finally, the emergence of agentic AI opens the aperture of what's possible with automation in both digital and physical worlds.

Virtual PLCs

Most incumbent PLC vendors have publicly committed to bringing open and virtualized PLCs to market. Engineers can administer new functionality remotely and for a number of PLCs at once. Virtual PLCs have increased connectivity across more systems within the ISA-95 stack. Full software-enabled PLCs allow for more secure continuous integration continuous delivery (CI/CD) pipelines and DevSecOps to build applications and capabilities that are decoupled from the physical environment.

Robotics

Advancements in robotics include AI-enabled software-defined control, learning, and simulation, as well as self-optimization via closed feedback loops. Communication with robots has been simplified with the development of generalized interfaces (e.g., chatbots, low- or no-code programming), while the ability to move AI and advanced processing to the edge and in the chip enables low-latency adaptable workflows. Processes are changing to accommodate robotic production capabilities, such as roboforming, rapid liquid printing, and additive and subtractive manufacturing. Meanwhile, humanoid robotic technology is becoming commercially viable, as the cost of humanoid robots has significantly decreased and advancements in AI and hardware have expanded flexibility and adaptability for a variety of tasks.

Simulations

There are a number of areas where manufacturers can leverage simulation technology to proactively and systematically fine-tune designs and operations in a digital space, avoiding the cost, risk, and time of testing and iterating in a physical space. Scenario simulations test process and product life cycles; engineering simulations test how machines and materials will interact; and digital twins enable simulations to provide "what if" scenarios that allow for better testing in a virtual environment, including for products, processes, and plant layouts. One challenge is that while many enterprises already use digital design tools, more data is needed to enrich the model for use in simulations and MES-style instructions. The challenge is to ensure a product meets design requirements and that it can be manufactured in a reasonable time frame with commensurate effort. Generative AI can be a valuable complement to simulations, as users rely on natural language prompts and low-code environments to manipulate or adjust digital twins.

Cyber-physical systems security

Broadly, because a cyber-physical system combines interaction or control of physical processes with computation, networking, and software, new security vulnerabilities may result from rising data volumes, the increasing breadth of users with access to data, and connected IT/OT data across layers that have historically been segregated. A shift away from the ISA-95 stack and toward event-centric system integration leverages a flexible and scalable approach where data is shared through events, making it easier to manage and secure.

Connectivity and communications protocols

Today's connectivity and protocols change how manufacturers physically connect assets, how they make sense of the data, and how that is communicated across systems and the workforce. Connecting more manufacturing assets while maintaining network performance gives manufacturers the ability to transfer, analyze, and understand data in real time. Advancements in 5G, in particular, enhance connectivity with ultra-low latency and high reliability. Whether via wireless standards or wired connectivity, assets, sensors, and edge devices communicate over a range of protocols, such as OPC UA (Open Platform Communications Unified Architecture) and MQTT (Message Queuing Telemetry Transport). These protocols support interoperability, scalability, and secure communication, which are essential for integrating Internet of Things (IoT) devices, edge computing, and cloud services.

Taking the next steps toward SDM

SDM may take different shapes depending on the manufacturing sector and the nature of its production. For high-volume, repetitive manufacturing with a low mix of products, there is a clear business case for automation, allowing faster responses to forecasts and constraints and new ways of building production lines. Conversely, for lower volume manufacturing with a greater mix of products, the SDM approach may be more focused on quality, flexibility, and creative routing strategies. And for enterprises that need to provide traceability for design, production, and performance (e.g., robotics manufacturers), SDM permits the ultimate ecosystem connectivity between the manufacturing environment, the interfaces that touch the plant and the product, and the product itself. At each point in time, manufacturers have complete visibility into operations, equipment, products, and the infrastructure around them, offering advantages for quality and compliance.

Investing in structured, integrated, and efficient frameworks accelerates digital transformation at scale to achieve strategic goals. Architecture and infrastructure, designed thoughtfully with an eye on process orchestration, empower users to build and leverage a broad set of high-value use cases, at scale, with a modern workforce. Complexity gives way to simplification through abstracted interactions between systems, removing friction and catalyzing collaboration across business, IT, OT, and engineering technology divides.

In looking ahead to an SDM future, enterprises at any stage of industry modernization can take action, be they bold steps or more incremental. In determining where to start and what comes next, manufacturers encounter key questions in the areas of data management, governance, and the workforce experience.

Data management considerations

How do we prepare data for AI and scalable solutions?
Take an early, holistic look at the data and analytics strategy to avoid challenges in scaling solutions and outcomes later down the road. Bringing together diverse data sources into a unified, contextual framework—or unified namespace—can establish a single source of truth for real-time data, making information clear and accessible across different business sectors. Making intentional design choices and deployment of connectivity and communication protocols can enable access to new knowledge sources and offer a new approach to knowledge management. Inputs can span a knowledge base informed by interviews with retiring workers; supplier and customer data connected to product and manufacturing operations data; and data from sensors and edge devices (e.g., computer vision for visual data from cameras). A well-architected manufacturing and operations data and analytics strategy is essential to simplify data integration, enhance operational efficiency, and drive real-time decision-making.[4]

Enabling predictive maintenance from the edge

A global transportation client experienced a substantial increase in shipment volume, compelling it to begin nearly 24/7 operations, which limited maintenance windows for its facility distribution assets. At the same time, the company faced hiring difficulties and rising wages in the challenging US labor market. The organization needed a predictive maintenance strategy for its facilities to reduce capacity loss, drive efficiencies, and optimize delivery service levels.

In order to enable the client to scale outcomes, connect its disparate systems at different facilities, and merge that data at the edge before sending to cloud for analytics, we recognized the importance of adopting a modern architecture strategy and recommended the client adopt a unified namespace to facilitate its operational data management needs.

This initiative aimed to establish a standardized and centralized data hub across the client's network. The strategy involved utilizing PLCs and a variety of sensors as data sources, with the intention to process and merge this data at the edge before its transmission to the cloud.

The architectural framework enabled the processing of real-time data for multiple facilities at the edge, which was subsequently consolidated at a central location, thus creating a unified namespace by linking individual facilities to a centralized hub encompassing all locations.

This setup allows any system within the network to instantly subscribe to data from different data sources for approximately 25,000 assets spread across more than 40 facilities, facilitating clean and centralized data management. It not only meets the operational, business, and IT needs for predictive maintenance but also has simplified the integration of future use cases.

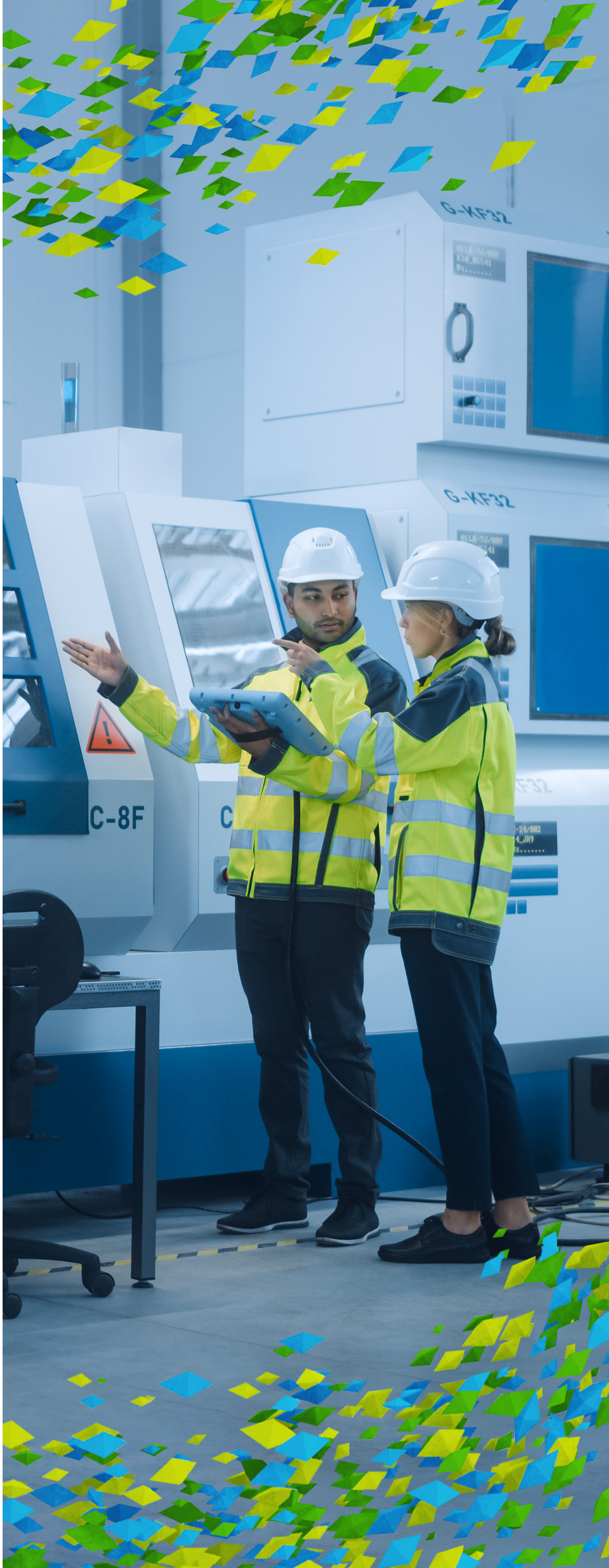
How do we analyze the data?

Investing in IT/OT enablement can grant new visibility and insight. To prepare for the more advanced components of SDM workflows, enterprises need to invest in foundational data elements, including capturing how work is currently performed and how it affects operability and the bottom line. With emerging technologies such as edge, Generative AI, and model-based simulations, manufacturers have new tools at their fingertips to process, analyze, and interact with data and insights. Integrating robust AI and data operations necessitates a business lens for decision-making on underlying data and supporting infrastructure. Factors that affect decisions on where data is processed—whether on the edge or in the cloud—include latency, processing power, bandwidth, the cost of computation, and how the resulting insights will be used (e.g., real-time decision-making versus retroactive analysis). Additionally, AI-powered applications can be used to interrogate data and interact with insights in new ways; in some cases, without specialized skill sets. Furthermore, simulations powered by a digital thread can be used to analyze and visualize optimization opportunities for the product, factory, or broader supply chain.

How do we deliver insights to people—or systems—at the right time?

A connected environment gives diverse stakeholders the ability to access data relevant to their role, all drawn from the same source of data truth. With SDM, knowledge and insights are seamlessly embedded into daily workflows. For example, factory floor workers may need real-time insights through augmented work instructions or dashboards to facilitate production shift handovers. Executive stakeholders may instead need a control-tower view across multiple factory locations.

SDM is about not just delivering data to people but also closing feedback loops in systems for continuous improvement and optimization. For example, data around product engineering and materials data can be fed back into inventory management systems, which, in turn, informs procurement and even customer relationship management systems for real-time delivery order updates. In the most mature vision for SDM, closed feedback loops give assets and robots the ability to self-optimize or self-train. SDM provides the avenue through which manufacturers can define how best to orchestrate robotics and the human workforce.



Building the plant of the future

A large industrials company with a network spanning continents and dozens of facilities and plants faced growing demand to create more capacity across its network while also enhancing safety. The company focused on eight areas and 25 improvement targets, including expanding capacity, improving safety, and increasing product quality. To address these priorities, the organization adopted key technologies to fuel three value-driving solutions:

1. Enhancing workplace safety

Leveraging an AI model to identify safety risks via video, data is integrated via a safety control tower and paired with real-time collision avoidance technology. As a result, forklift drivers and pedestrians potentially at risk are alerted by proximity-sensing armbands, and the solution is expected to reduce the reportable incident rate by 15% to 20%.

2. Improving cycle time

Vibration on assets creates issues with product quality and productivity. To accurately predict and prevent disruption, an AI model computes in real time whether a vibration will occur. That data is sent to the control system to automatically adjust the speed of the asset component. The solution limits quality issues while also providing insight into root causes of mechanical issues and is expected to boost throughput by 3%.

3. Reducing unplanned downtime

Sensors monitoring asset conditions (e.g., vibration, temperature, and torque) feed data to machine learning models to detect potential failures before they occur. The system then automatically creates work orders for the maintenance team. The target is reducing breakdowns by half and, ultimately, to eliminate them completely in critical assets.

Technology governance considerations

How do we do this securely?

As more assets and advanced cyber-physical systems are brought online to capture data and power SDM, it can introduce potential cybersecurity risks that must be mitigated. Fortunately, even as SDM is a new and transformative vision for manufacturers, many of the leading practices for enterprise cybersecurity still apply.

Cybersecurity grows out of aligning the business, OT, and IT under a defined cyber strategy and control framework, where roles and responsibilities are assigned, understood, and documented. Technology asset data flows in cyber-physical systems permit greater asset visibility and understanding, informing more focused risk assessments. Meanwhile, network segmentation can be enhanced by limiting connectivity and taking an event-centric approach. Event-centric architecture includes an MQTT broker to simplify communication; a data hub to collect data from devices and formats; an Industrial IoT platform to enable data analysis and automation; and a cyber-physical systems protection platform, which discovers and protects connected devices. In moving to an event-centric model, ISA levels may need to be reevaluated, which has implications for the enterprise cybersecurity framework that accounts for data access and control, agile incident response, continuous monitoring of sensor and network data, and greater system resilience.

Access management is essential, and a secure remote access solution can enable consistent processes across locations and more tightly controlled administrator access. This aligns with centralizing OT cybersecurity monitoring in a security operations center that is focused on identifying vulnerabilities and potential system compromise. In this, the process is just as important as the data, and while automation could be used to improve security by accelerating the delivery of some solutions, human oversight remains important, given that cybersecurity is at the core of the business.

Even with the best preparation, cyber events may still occur, and manufacturers can enhance their response and recovery capabilities via consistent backups at the site level and playbooks that establish roles and incident response plans that can be rehearsed and improved.

How do we apply this at different levels of scale across operations?

With the foundations of a data strategy, optimized analytics, and connected operations, manufacturers can begin to think about how SDM is applied beyond the four walls of a factory to collaborate with product engineering, sales, and suppliers and distributors. Manufacturers can detect and respond to events, constraints, or optimization opportunities as they emerge and in real time. Value can be unlocked across the manufacturing function and broader supply chain network operations.

How do we transform the software development life cycle?

A shift to SDM will significantly affect employees and processes for managing system software. Adopting an agile and iterative software development life cycle (SDLC) supports continuous integration and deployment, minimizing downtime and enabling rapid updates and improvements that span the entire stack. Real-time monitoring and feedback enable data-driven decisions, and a more flexible and responsive SDLC fosters innovation, reduces time-to-market for new products, and helps maintain a competitive edge. Importantly, as SDM brings systems together, the SDLC spans not just virtual PLCs but cloud and edge platforms as well.

Workforce considerations

How does SDM enhance the workforce experience?

Half of manufacturers report that a high level of digital proficiency is important or very important for their workforce, according to a recent survey.[5] Taking an SDM approach may increase this need for skilled talent. As democratization of Generative AI can reduce the need for specialized data science skill sets, increased competencies around technology fluency and software engineering may be needed to support SDM. There will also be a rising need for soft skills, such as adaptability, problem-solving, critical and cross-functional thinking, initiative, and leadership.

The financial considerations around sourcing, onboarding, and retaining talent (particularly for frontline or hazardous roles) are top of mind for manufacturers, and the capabilities SDM affords could support talent acquisition and retention by improving the workforce experience. As such, adoption and change management will be important across the SDM journey, requiring a support model to bring the workforce along and empower them with the knowledge and skills needed in SDM. Manufacturers need to consider the impact and receptiveness of the human workforce. This means communicating and evidencing how technology solutions are advantageous to the worker, including improving productivity and decision-making, helping to upskill workers, creating a safer work environment, and nurturing leadership that drives human-machine collaboration. It also means building and promoting human trust in AI outputs and the reliability of automations and systems. As workflows are transformed and the enterprise becomes more reliant on data and technology, human stakeholders need confidence in the tools they use. With that trust comes value to the workforce and the enterprise, but without it, value may be elusive.

How do we roll out and sustain new ways of working?

Change is a team effort, and in light of technology convergence, IT and operations hold shared priorities affecting how the organization modernizes and maintains an integrated environment. A Smart Manufacturing Center of Excellence brings together executive stakeholders from IT, operations, procurement, and other lines of business to make strategic decisions at the operational level, enhance and optimize capacity and service delivery, and reach for the transformative use cases and applications that unlock competitive differentiation.

Manufacturers also need to define and establish an integrated IT/OT operating model. It should take into account the skill sets and capabilities the organization will need for an SDM enterprise.

Moving to configurable production lines and dynamic manufacturing processes may require a shift in the type and makeup of the workforce, with greater demand for workers who have the skills to maintain control systems, connected assets, robots, and all the technologies enabling SDM. Consider third-party specialists to help lead the transformation, upskill the workforce, and drive change management. Ultimately, the leading practices for sustainable change and technology adoption are the same with SDM as with any digital transformation: start small with value-driving use cases, shift to scale when ready, and pivot to focus on continuous improvement.

Taking the next steps on the path to SDM

SDM is a bold aspiration that requires change across engineering design, the transfer to production, and manufacturing itself. In thinking about the path forward, there are two overarching aspects to SDM transformation. First is a continued focus on engineering principles from the standpoint of how to create the most flexible product that can adapt over time in response to customer demands or the introduction of new technology. SDM helps overcome challenges that hinder the ability to be more responsive to customer demands, design flexible products, and more quickly adapt product designs and manufacturing in a flexible way.

Second is a recognition that automation and factory tooling lead to high up-front costs for hardware, but as the productivity and efficiency advantages of SDM are realized, initial costs give way to savings and revenue. Investments across factory assets, enabling technologies, and processes needed for SDM will enable more flexible, efficient, and optimized manufacturing.

As manufacturers weigh how best to move ahead with SDM at the forefront, there are some clear considerations for how to get started.

SDM demands **executive sponsorship and change leaders** across functional areas. Aligning decisions and investments with enterprise strategy, executives are positioned to prioritize change and rally the participation of stakeholders across the organization. Clear goals and internal collaboration help manufacturing, engineering, technology, and talent leaders meet shared objectives and coordinate on risk mitigation.

Technology innovation is progressing rapidly. **Modernize opportunistically with increased investments** in foundational capabilities and process transformation, and take a holistic view of the set of technologies that will enable use cases and capabilities that are incremental, high frequency, and with dramatically reduced cost and effort. With this, design for connected data and integrated systems not only within the factory walls but across the network and supply chain, and adopt a holistic technology framework that balances data acceleration with enterprise standardization. Be open to adjusting this strategy and approach as technologies continue to evolve and mature.

Finally, leaders should **approach SDM with the human workforce in mind.** Organizations have the potential to reshape the future of manufacturing operations, how work is executed, and what skill sets are needed with SDM. New technologies and processes require new skills but without abandoning previous knowledge. How technology functions and is deployed has a direct impact on the employee experience, and by extension, employee satisfaction and retention. Develop an integrated workforce and technology strategy that can guide decisions about how to design, deploy, and encourage change. In conceiving of a unified human-machine workforce, focus on nurturing human trust and confidence in machine outputs. As the enterprise changes to embrace the SDM vision, consider the implications for the personas needed in an environment where manual product changes are a thing of the past and data and technology management are the priorities.

The SDM vision, while aspirational, is within reach and represents the next step in manufacturing modernization. It is an opportunity to think differently about data, production, and architecture, with the potential for fuller ROI on technology investments over the long term. Indeed, with SDM, manufacturing can be dynamically adjusted to meet the diverse and ever-changing world of inputs, outputs, and demand.

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