SIEMENS DIGITAL INDUSTRIES SOFTWARE

The lights-sparse versus the lights-out factory

Optimizing manufacturing toward the digital and autonomous factory of the future

Executive summary

The concept of a "lights-out" factory – one in which the requirements for human activity are so minimal that the facility can operate in the dark – has been around for decades, but the digital and automation technologies needed to make it a reality at scale are just now maturing. At the same time, new market trends and perennial issues like questions about labor versus automation are making the realization of the lights-out factory that much more challenging. Widespread deployment of lights-out factories globally across industries may be years or decades away, but forward-looking manufacturers may seize opportunities today to implement lights-out processes within their conventional and smart factories – making for a "lights-sparse" facility or production line. Using quantified examples, this white paper describes both the challenges and current opportunities presented by a lights-out approach. It emphasizes feasible deployment that provides realistic value to manufacturers, such as automating repetitive or monotonous work.

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Introduction

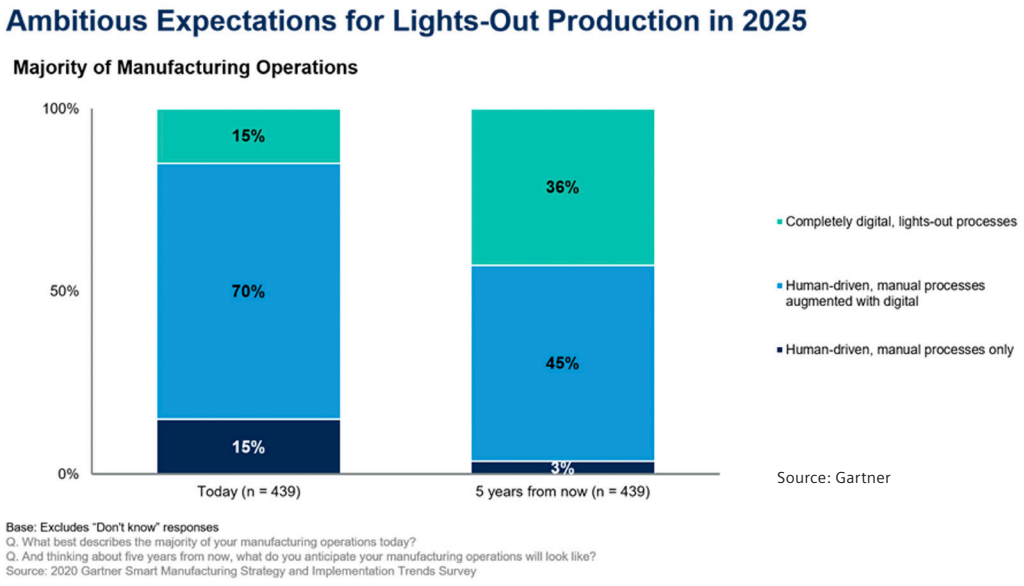
"Lights-out" concepts and real-world manufacturing

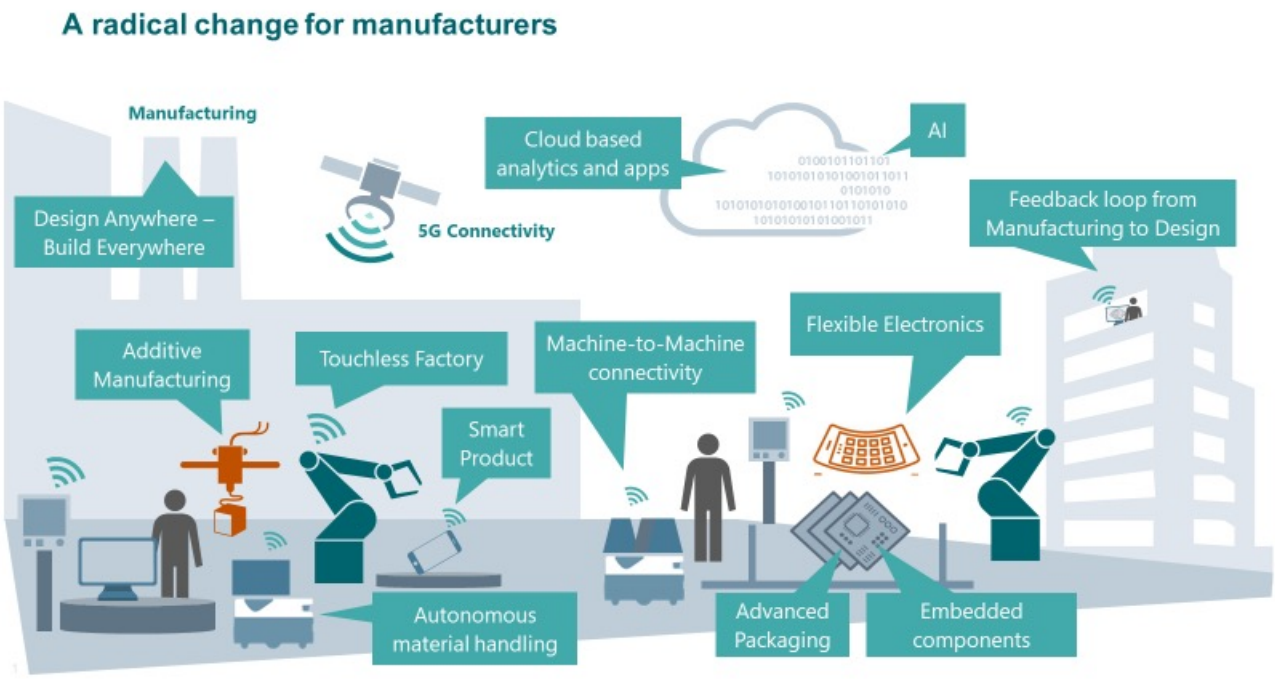
The global manufacturing community has long been intrigued by the notional concept of a completely self-sufficient factory in which the only human interactions are the placing of orders and receipt of finished products. Although this blue-sky version is unlikely to completely materialize on a large scale in the near term, it is reasonable to ask which concepts behind autonomous manufacturing might come to fruition. Importantly, any realization of these concepts must move beyond novelty and prove truly beneficial to manufacturers – improving productivity, quality, sustainability, consistency, safety, profits and certainty. According to a Gartner study, by 2025, sixty percent of manufacturers will have more than two completely lights-out processes in at least one of their facilities. It is an ambitious expectation for lights-out production.

Siemens can affirm successful implementations of what has come to be called lights-out manufacturing or lights-sparse manufacturing and is ready to help customers realize the benefits of crewless manufacturing operations where it is realistic, beneficial and sustainable.

The lights-out factory or "dark factory" made its way from the pages of science fiction (first popularized in the 1955 short story, "Autofac," by U.S. author Philip K. Dick) to the floors of actual manufacturing facilities in the latter half of the twentieth century. Called lights-out factories because they require so little human intervention that they can operate in the dark, such facilities were attempted in earnest beginning in the 1980s. These early efforts were unsuccessful, but several success stories beginning in 2001 have been widely publicized and discussed. Perhaps the most well-known is the FANUC factory in Japan that uses robots to build robots, with no human intervention reportedly for a month or more.

FANUC and other manufacturing companies have demonstrated that the lights-out factory is both possible and profitable – for their particular applications. The question remains whether it makes sense for your company to build or convert to a lights-out





factory, or more likely, convert certain processes within your facility to run lights-out. This paper is designed to help you make this determination and guide you through the digital tools and technologies already available to make lights-out workcells or production lines a reality.

At Siemens, we have found that for most of our customers, lights-out manufacturing is not an all-or-nothing proposition. Instead, we have been able to facilitate incremental lights-out implementations that benefit our customers without requiring a complete transformation of their conventional or smart-factory operations. The technological and economic feasibility of widespread lights-out manufacturing hinges on digitalization, especially on digital twin technologies. These and other related technologies that enable lights-out operation are discussed herein.

For the foreseeable future, converting or building a factory for comprehensive lights-out operation depends on several factors and could become a costly endeavor. A complete lights-out factory must be outfitted with automated guided vehicles (AGVs) and the factory floor infrastructure and floor plan that support them; self-loading and unloading production equipment and/or robots to complete each of the production steps; self-configuring machines such as CNC machine tools and robots that change out their own end effectors; modular production stations that can be automatically resequenced depending on the particular product being manufactured; vision or other nondestructive automated systems for real-time quality inspections; reconfigurable conveyor belts; pick-and-place machines; advanced networks like 5G; sensors, sensors and more sensors; and perhaps most critical of all, the digital infrastructure and control software capable of scheduling and orchestrating the entirety of the production process, from receipt of raw materials and supplier-made components (which must be quality verified) to packaging and loading finished products onto delivery vehicles.

Traditionally, the type of manufacturing that lends itself to this type of factory is mass production on a fixed schedule. The smaller the lot or batch size a factory is producing, or the more frequently it is required to make new or modified products, the perception is that it is less likely to be a good candidate for full lights-out operation. Automation and

digital manufacturing technologies can create this reality but must be incremental to reap the benefits (especially in brownfield facilities where large capital investments are already in place).

It is frequently noted that human beings are the most flexible of production resources. Human intervention remains the most efficient and economical way to implement production changes in a significant majority of manufacturing cases. Today, this human activity is supported by data-generated actionable insights and advanced technologies such as autonomous mobile robots, collaborative robots (cobots), edge computing and artificial intelligence/machine learning (AI/ML). Human-supported lights-sparse production, in which specific operations within the process are conducted at crewless locations within the factory or remotely outside the factory, is a scenario that could make the most of human, digital and automated resources.

Given the challenges of a fully automated factory for most manufacturing endeavors, then, what makes sense for a much larger segment of manufacturers is to identify specific processes or areas within a facility and/or specific blocks of time during production when crewless operation is both feasible and valuable.

Rather than targeting a complete lights-out factory, most manufacturers are better served to start with lights-sparse manufacturing within their otherwise conventional or smart factory.

At the same time, some manufacturers may want to consider the recently trending microfactory with new business models of subscriptions (instead of upfront capital investments) – a small, highly automated manufacturing space that requires a smaller labor force and uses far less energy and materials than a conventional factory. An agile microfactory is capable of high-mix, low-volume business with low cost and high ROI .

These microfactories have the advantage of embracing digital tools from the very beginning. But easy and cost-effective digital technology can be leveraged both by contract manufacturers setting up microfactories (which are small-scale by their very nature) and by corporations with centralized design and geographically dispersed manufacturing – and for that matter, by manufacturers whose operations fall somewhere in between these two models.

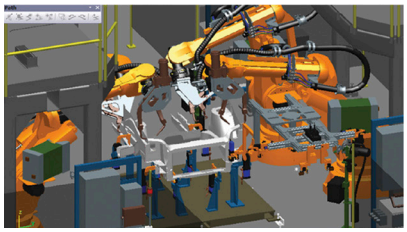
Lights-out manufacturing presents new opportunities but also new challenges

Before delving into the means of implementing lights-out manufacturing, it is important to understand the goal – the value of lights-out operations to the manufacturer. Obviously, for a cost-benefit analysis to weigh in favor of lights-out implementation, the benefits must extend well beyond savings on the utility bill and lightbulb purchases. Examples of some of the benefits enjoyed by those implementing lights-out manufacturing or processes include:

- **Reduced labor costs** – An example of a full lights-out factory, the Chinese e-commerce company JD.com operates a 40,000 square-foot lights-out warehouse with 20 robots and five technicians instead of the 500 workers a non-robotic operation would require. Implementing lights-out manufacturing in select areas of a factory would also reduce labor costs, just on a smaller scale.
- **Less reliance on a labor force** – In some parts of the world and in certain industries there are more jobs than there are workers with the requisite skills to perform them. When lights-out manufacturing takes over tedious, repetitive tasks, workers can be trained and reassigned to those tasks better handled with the flexibility and creativity human beings offer.
- **Reduced error rates** – Machines are simply better than human workers at performing repetitive tasks consistently. Machines never get fatigued or distracted, and they perform tasks with very little variation for long stretches.
- **Material management efficiencies** – The application of lights-out technologies to the movement of materials has the potential to shorten dwell time between steps as well as replenishment time. The result is reduced inventory costs and higher production rates.
- **Accelerated product lifecycles** – Lights-out operations have the potential for accelerated transitions from design to producing the finished goods. Lights-out machinery can be designed to receive digital product design and processing information, self-configure and begin production operations much more rapidly than attended machinery.

On the other side of a cost-benefit analysis is the lifecycle of automated equipment and end-of-life disposition towards sustainability. Once automated systems become obsolete or break down beyond repair, what happens to them? In a world pursuing sustainability and working toward a circular economy, manufacturers must consider whether automated equipment enables reduce, re-use, recycle benefits while in use, and whether retired equipment can be re-used or recycled itself. Greenfield factories and microfactories can be designed from the very beginning with sustainability taken into consideration.

Enabling a lights-sparse facility to be considered today, a number of technologies have gained capabilities essential to lights-out manufacturing. Not the least of these are industrial software innovations, discussed below. Here are some others:



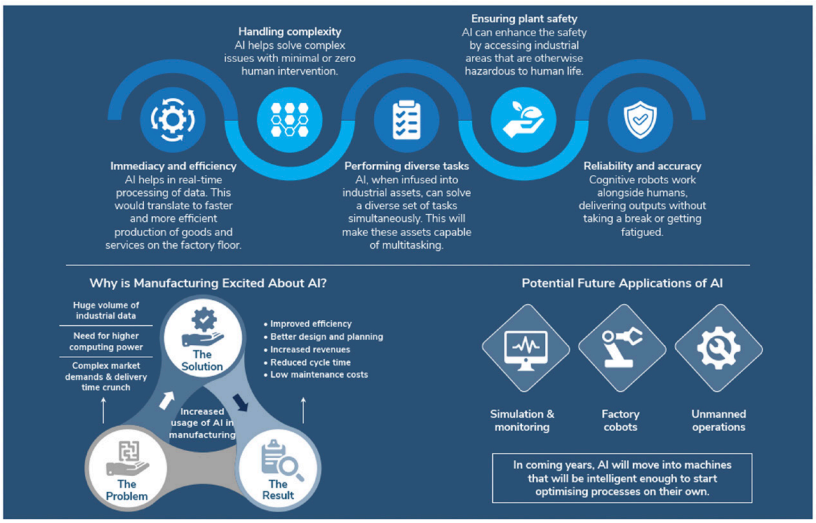
Robotics have advanced on numerous fronts, including synchronization with machines and work-in-progress components, increased range of motion, new gripping technology and much more. Chinese automotive equipment supplier Guangzhou MINO Auto Equipment Co., Ltd. (MINO), for example, recently completed a welding project in which 63 KUKA robots with an 80 percent level of automation are expected to achieve an annual throughput of up to 180,000 units. (Read the full story here.) The project was enabled in part by swift digital verification of the production system using Siemens Tecnomatix® software for virtual simulation and testing. In addition to autonomous robots, advancements in cobots do not eliminate human labor, but they make workers more efficient and productive, potentially reducing the number of workers needed on the production floor.

Process innovations such as 3D printing and other additive manufacturing (AM) techniques, plus hybrid manufacturing technologies that combine additive techniques with fully automated computer numerical control (CNC) equipment, make net-shape or near-net-shape production of components and products possible, with process steps guided through a direct interface with the digital factory. A recent AM success story is the startup Sintavia, which is using AM processes to make precision metal components for aerospace applications. Sintavia employs the Siemens end-to-end digital AM solution to orchestrate its production. (Read more about Sintavia here.) Additive manufacturing often begins with a high degree of automation and a reduced number of production steps or production stations – making it more amenable to lights-out operation than some conventional manufacturing operations.

Operational technology (OT) such as programmable logic controllers (PLCs), edge devices, drivers, sensors, 5G and the industrial internet of things (IIoT) offer accelerated processing speeds that enable automation equipment to rapidly respond to manufacturing conditions. Unattended machines can therefore initiate, proceed, adjust and stop operations that previously required human intervention. Critical enabling technology is the 5G mobile wireless communication standard, which is able to support a wireless data infrastructure within the factory with devices such as the Siemens Scalance MUM856-1 industrial 5G internet router (learn more here).

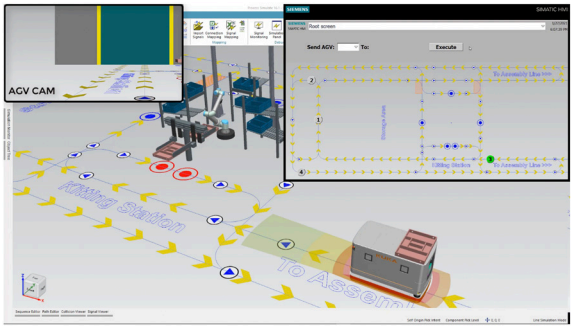
Enhanced data-driven operational orchestration technology opens the door to reduced human intervention at the production line. A centralized orchestration control room with a multi-experience user interface, for example, may empower a single operator to oversee multiple machine operations, possibly from a remote location. Conversely, distributed user access to a centralized digital platform, such as that offered by Siemens Opcenter™ software for manufacturing operations management (MOM) with vertical and horizontal integration of data and processes, means that any authorized stakeholder can remotely access in a secure way the operational insights for decisive actions about any dark process in the manufacturer's facility.

Benefits of Artificial Intelligence in Manufacturing



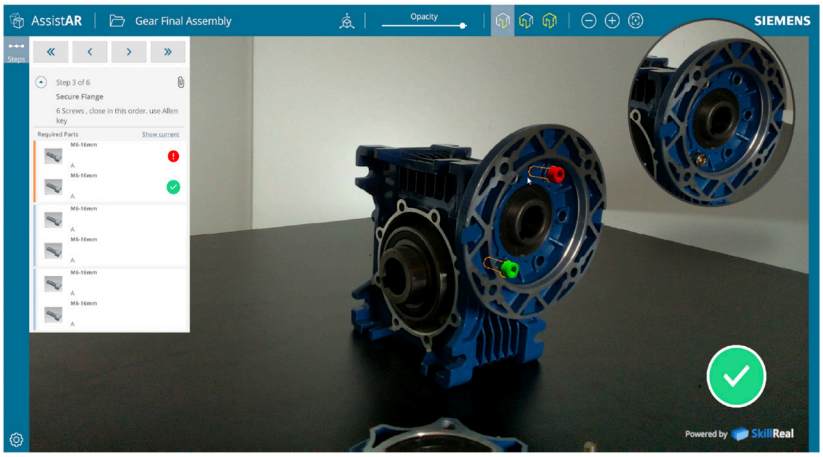
Source:
Frost & Sullivan

Virtual commissioning enables debugging of automation control logic and PLC code in a virtual environment before download to real equipment, offered by Siemens Tecnomatix virtual commissioning capabilities. The associated simulation and virtual validation help confirm that automation equipment will work as expected in autonomous mode.



Artificial intelligence/machine learning enables machines not only to learn process steps but also to improve performance, so that productivity and quality both are enhanced without human intervention. Siemens continuously enriches integrated AI capabilities across its solutions – Artificial Intelligence on the shop floor.

Extended reality (XR) technologies, including virtual reality (VR) and augmented reality (AR), enable manufacturers to reduce the tasks an operator must accomplish, and the time spent doing them at the production line. Among the features of Siemens AssistAR augmented reality solution, for example, is automatic validation, which compares the physical assembly to its virtual counterpart at the end of each assembly step without the intervention of an operator or inspector. Voice and text-to-speech technology



enhances remote human-machine interaction, making crewless operations more feasible in the data-driven manufacturing world.

While these developments may accelerate the implementation of lights-out manufacturing, other recent trends and perennial market conditions make lights-out implementation more challenging today. This is especially true for brownfield factories, where design and implementation of lights-out operations are complicated by the necessary transition from existing manufacturing approaches. Greenfield factories, on the other hand, can leverage technologies right away to prepare the facility for the challenges listed below, building the facility with factory floor modularization, automation, 5G, AI/ML, other enabling digital technologies, and a data-driven mindset.

Design anywhere, build everywhere is the latest mantra associated with the trend toward manufacturing globalization. By making deliberate choices about where and when to run production, manufacturers expect to reduce manufacturing costs and accelerate time-to-market. They want to make production decisions based on location, on-site material inventory, machine capacity, skilled labor availability, shipping requirements – any parameter that impacts timely, efficient and cost-effective production. For these global manufacturing enterprises, lights-out manufacturing adds a dimension of complexity to any design anywhere, build everywhere decision matrix.

If a lights-out or lights-sparse factory is one of the build everywhere options, for example, considerations regarding skilled labor may be replaced with those regarding the manufacturing equipment's capabilities for autonomous operations, as well as the equipment's or workcell's ability to self-configure/reconfigure based on the product variant to be produced. Additionally, even if a dark factory or lights-out operation within a conventional factory is capable of carrying out a particular production run at a lower operational cost than a fully conventional factory, does that location have access to needed resources? Digital tools are essential not only for the planning and scheduling decisions to be made in such circumstances, but also for communication of design, supply, production engineering, quality requirements and inspection/test mechanisms and feedback of production information.

Mass customization and individualized production are growing requirements across nearly every manufacturing sector, from specialty food and beverage items to new automobiles. Consumers want individualized products, but at the prices they would pay for mass-produced goods. To keep up with these demands, manufacturers must accommodate short innovation cycles with more complex products, and as a consequence, they need to more closely integrate modeling, engineering and simulation with manufacturing production. This means that the manufacturing floor must be more flexible than ever before – but lights-out manufacturing operations are more suited to long, steady production runs of the same product. Ultimately, lights-out manufacturing and flexible manufacturing are not mutually exclusive; in fact, digital manufacturing tools available today are capable of addressing the need for flexibility and realizing lights-out where it is feasible. Until a

manufacturer has outfitted a factory with modular production equipment able to reconfigure itself, however, these digital tools will have to treat mass customization and lights-out manufacturing as competing interests.

Tradeoffs between labor and automation directly confront manufacturers considering lights-out manufacturing. Generally, humans are flexible but more error-prone and slower, while automation is less flexible but faster and less error-prone. With the design anywhere, build everywhere and mass customization trends described above, flexibility may be the factor for manufacturers deciding between lights-out and conventional operations. Again, digital systems for manufacturing engineering can facilitate such decision making today with tools such as plant and process simulations.

Entrenched mindsets and human inertia may keep some manufacturers from initiating moves towards lights-out manufacturing. According to the Gartner study, advancements in technology will make lights-out production processes a reality in 2025. But the lights-out smart factories must balance between augmented and automated processes, organizational and technical challenges. For manufacturers with the foresight to explore and prepare for lights-out manufacturing, there is an opportunity for a powerful competitive advantage.

The path to lights-out manufacturing traverses every point of product life

How does a forward-thinking manufacturer prepare for lights-out manufacturing? What are the prerequisites? Once a decision to invest in lights-out or lights-sparse operations has been made, the key to implementation is how a company will leverage digital manufacturing tools to support crewless areas of the shop floor. Implementation of lights-out manufacturing, as we have discussed, can be undertaken incrementally, with certain operations and/or certain time periods of a production run targeted, one at a time, for crewless operation.

For example, in many complex manufacturing operations, inspection of work-in-progress is often performed manually by human inspectors. This may be true even when manufacturing value-added operations are highly automated, and this makes manual inspection a bottleneck against productivity gains. Automated inspection is a type of lights-out or lights-sparse undertaking. The inspection system captures data and/or images of as-built features (or anomalies) and analyzes it, referring to design data as the standard. When nonconformances occur, a lights-sparse operation might send an alert to a human operator for corrective action; a lights-out inspection system would include automated resolution of nonconformances. Beyond this detection/correction activity, automatic inspection data may be analyzed to generate manufacturing intelligence that feeds continuous improvement efforts. When embedded with AI/ML-based algorithms, an unsupervised and supervised learning mechanism can be built to create possibilities for needed self-resolution/prescriptions.

To accelerate the programming of unattended coordinate measuring machine (CMM) inspection, Ford powertrain manufacturing engineering uses Siemens NX™ software for CMM inspection programming. This software employs machine-readable product and manufacturing information (PMI) to accelerate the launch of automated CNC machining and inspection of new powertrain components.

Preparation for each lights-out manufacturing operation within a production facility must include the closing of gaps between virtual and real production, between the digital and physical factory. After all, without human intervention, production machines will take only those actions they are programmed or

digitally directed to take. To realize lights-out manufacturing, then, manufacturers must consider how the virtual and real worlds will interact throughout a product lifecycle.

The automotive equipment supplier MINO illustrates this close tie between virtual and real production. Using a digital manufacturing solution, the company exchanges data and collaborates with automakers throughout the planning, simulation and commissioning stages. The digital manufacturing system has helped MINO meet customer requirements while reducing project cycles by up to 30 percent. Virtual commissioning before mechanical installation has reduced on-site debugging time by 35 percent, resulting in significant cost savings and faster production startup, while mitigating risk on the shop floor.

When actual operations are no longer attended by human operators, digital tools must provide manufacturing overseers with full, interactive visibility into each lights-out function. Visibility is achieved by orchestrating operations and collecting critical data to implement needed integration for lights-out operations. Simple products made on one or two machines require relatively uncomplicated communication from design to manufacture; but complex products involving multiple operations and machines require integration from orders to scheduling to production and delivery. Additionally, digital tools must enable dynamic responses either to changes in the supply chain or to upstream change management, along with seamless virtual validation for flawless lights-out production.

The ideal is for each machine to remain busy. To achieve this level of efficiency when one or several production steps will take place without human intervention, the digital manufacturing processes account for different time requirements of different operations, the need to minimize process changeovers, complex coordination of material movement, and many other factors that are closely tied to the automation layer. By anticipating and addressing these issues digitally, lights-out operations replace human flexibility and spontaneous responsiveness with data-driven manufacturing. That is, digital systems provide real-time data insights that are fully correlated across processes, enabling automated predictive and prescriptive responses.

The comprehensive digital twin is the workhorse of lights-out manufacturing

Central to the digital tools that facilitate lights-out and lights-sparse operations is the digital twin, which is the virtual representation of a physical product and associated processes, from conception through lifetime product performance in the hands of the end user. This comprehensive digital twin empowers manufacturers not only to simulate, predict and optimize products and production systems without physical prototypes, but also to close the manufacturing loop by incorporating into an evolving digital twin real-time performance, operating conditions and changes over time.

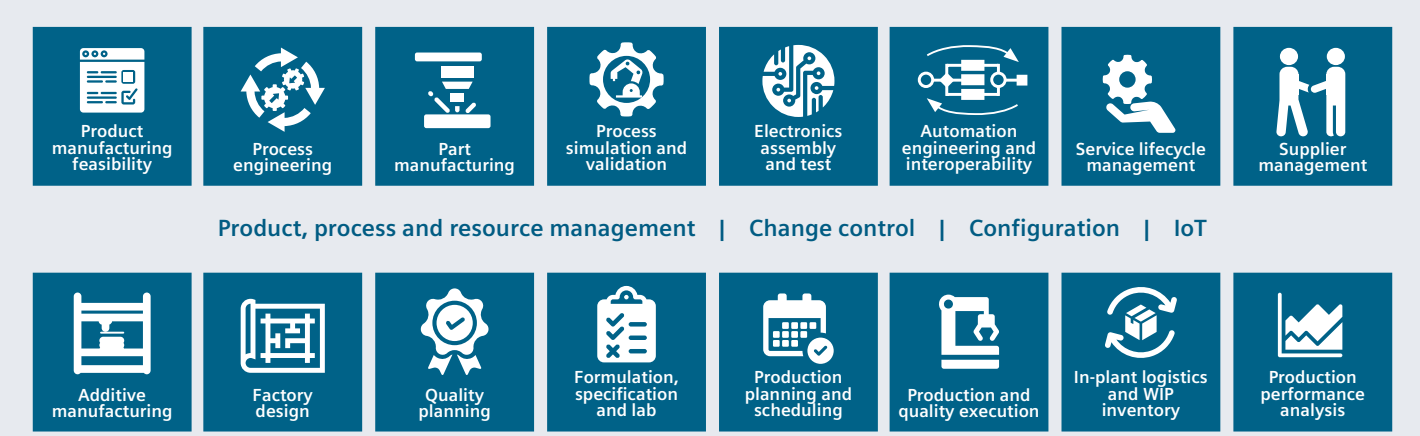
Visibility of the digital twin is provided by a data infrastructure known as the digital thread and its continuity along the value chain. The digital twin provides the format into which design, engineering, manufacturing and field data are organized in coherent, accessible and useful models; and the digital thread (once fully built out) creates a collaborative, connected information conduit across product design, production engineering, manufacturing execution, automation and data-driven intelligence. The digital thread and digital continuity is critical as manufacturers bring innovations to life and at scale today, because the domains across mechanical, electronics and software have blurred and continue to do so across disciplines. (Learn more about the role of the digital twin and digital thread in manufacturing digital transformation here.)

A comprehensive digital twin captures the full product life and is needed for fully automated production in a dark factory, but more specific types of digital twins are key to the incremental implementation of lights-out manufacturing operations. Siemens has identified four key digital twins for manufacturing operations: the digital twins of product, production facility, production, and performance. As a precise digital model, each digital twin displays development through the entire lifecycle and allows manufacturers to predict behavior, optimize performance and implement insights from design and production experiences.

- **The digital twin for product** provides the virtual-physical connection that helps manufacturers analyze how a product performs under various conditions and make adjustments in the virtual world to ensure that the physical product will perform as planned
- **The digital twin for production facility** helps manufacturing engineers and planners navigate through the facility in digital representations and visualizations
- **The digital twin for production** helps manufacturers address the process engineering changes needed to accomplish lights-out operations
- **The digital twin for performance** helps provide timely insights from lights-out processes that can be used in advanced analytics for data-driven orchestration of ongoing lights-out activities

With the comprehensive digital twin, manufacturers gain foresight by simulating product, people, processes and resources in the virtual realm before implementing production on the manufacturing floor – a key first step in their journey towards lights-sparse processes. They gain additional insights by matching real-world to predicted performance, and they can use those insights to drive continuous improvements. Manufacturers are using the comprehensive digital twin, with embedded IoT data and analytics, to realize lights-out manufacturing by way of actionable manufacturing insights that bring about continuous improvement, reducing production costs and improving quality. While the digital twin is advantageous in any manufacturing environment, it is essential to lights-out manufacturing.

Digital tools are essential to lights-out operations



Digital enterprise software solutions are the means by which the digital twin and the digital thread are created, accessed and utilized to implement manufacturing operations of all kinds, including lights-out operations. With its digital enterprise platform, Siemens seeks to partner with manufacturers on their digitalization journeys. Siemens can leverage the digital enterprise to discover behaviors and provide more exact evaluations on product and processes – instead of simple prediction of expected results. The Siemens approach to the implementation of lights-out manufacturing involves collecting all data from design and the shop floor into real-time manufacturing intelligence to predict and deliver a reliable process.

Within the digital enterprise, the central support of lights-out and lights-sparse manufacturing endeavors is provided by a digital manufacturing solution, including manufacturing engineering (with simulations), virtual commissioning and manufacturing operations management (MOM) software. Digital manufacturing software serves as the bridge from the virtual world of product ideas, computer-aided design (CAD) and planning to the real world of production. It is the basis for digital continuity between innovative product designs and best-in-class product and production performance. These digital tools ensure that quality and efficiency are built into the manufacturing process and are proactively and systematically enforced. As part of Siemens' holistic, end-to-end approach to the digital factory, digital manufacturing software integrates easily with equipment, controllers and enterprise business applications. The result is complete visibility, control and manufacturing optimization of production and processes across the enterprise – exactly the outcome on which successful lights-out manufacturing depends.

Digital technologies that provide effective, efficient, standardized solutions for manufacturing engineering and manufacturing operations are poised to address the challenges of lights-out manufacturing implementation.

Just as manufacturers may approach lights-out manufacturing on an incremental basis, the same is true of their implementation of digital manufacturing. Manufacturers can employ digital manufacturing subsystems to implement the digital twin and the digital thread in a modular, stepwise fashion, with ongoing returns on investment that support the next module or step. From their current level of digitalization, manufacturers can incrementally integrate legacy and custom functionality systems. Eventually, a manufacturer will transition from each legacy system to a next-generation software solution. This approach protects earlier investments while it starts building towards a flexible and efficient unified digital enterprise.

Digital solutions will usher in new capabilities in lights-out and other future factories

Today's digital technology is capable of orchestrating lights-out manufacturing processes, workcells and production shifts. The move to greater lights-out implementation and, ultimately, the widespread growth of full lights-out factories, seems likely to take place through a slow evolution of manufacturing approaches – but the technologies enabling this move are already on the horizon. A marriage of digital and physical manufacturing technologies will enable increasing flexibility, to a point in the future that lights-out factories are able to accommodate mass customization and design anywhere, build everywhere manufacturing approaches.

Two key developments will open the door to this growth: modular automation and the ability to self-configure at a plant-wide level. Modular automation has been the subject of joint pioneering work between Siemens and the pharmaceutical and chemical group Merck, which has designed a filter plant comprised of manufacturing modules that can be connected in serial, parallel or both, depending on the process requirements of each product. Modules can be docked with a production backbone in the appropriate physical configuration and interconnected digitally through their module type packages (MTPs), which contain information on what each module can do. The manufacturing control system orchestrates the modules for each production run. (Read the full story here.)

Conclusion

As digitalization follows automation into the fourth industrial revolution, concepts like lights-out manufacturing will be realized. These developments are not a mere fulfillment of some sci-fi vision of the future from the past century. Instead, they are the outcome of collaborative efforts among manufacturers, automation specialists and digitalization software suppliers seeking to achieve the perennial goal of manufacturing: an increase of productivity, efficiency, speed and quality, resulting in higher competitiveness for companies on their way to the future of industry.

Lights-out factory or dark factory – a manufacturing facility that can operate for long periods of time with no human intervention

Lights-out manufacturing or lights-sparse manufacturing – areas and/or time periods within a conventional or smart factory that operate with no human intervention

Lights-sparse factory – a manufacturing facility with numerous crewless operations, which may be incrementally evolving toward a full lights-out factory

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