From Lean to Smart Manufacturing

Dr. James C. Chen

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Asian Productivity Organization

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PREFACE

The P-Insights, short for "Productivity Insights," is an extension of the Productivity Talk (P-Talk) series, which is a flagship program under the APO Secretariat's digital information initiative. Born out of both necessity and creativity under the prolonged COVID-19 pandemic, the interactive, livestreamed P-Talks bring practitioners, experts, policymakers, and ordinary citizens from all walks of life with a passion for productivity to share their experience, views, and practical tips on productivity improvement.

With speakers from every corner of the world, the P-Talks effectively convey productivity information to APO member countries and beyond. However, it was recognized that many of the P-Talk speakers had much more to offer beyond the 60-minute presentations and Q&A sessions that are the hallmarks of the series. To take full advantage of their broad knowledge and expertise, some were invited to elaborate on their P-Talks, resulting in this publication. It is hoped that the P-Insights will give readers a deeper understanding of the practices and applications of productivity as they are evolving during the pandemic and being adapted to meet different needs in the anticipated new normal.

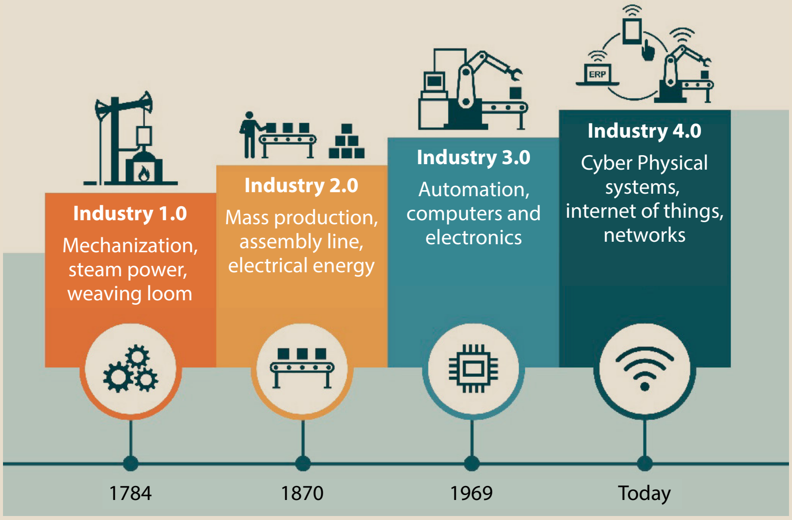
INTRODUCTION

In recent decades, the implementation of lean manufacturing concepts has yielded significant positive impacts across various industries. Lean production was initially introduced by Womack et al. [1], inspired by the Toyota Production System (TPS), aiming to effectively eliminate waste primarily through problem-specific approaches. Subsequently, Womack and Jones [2] further systematized "lean thinking," emphasizing the five critical elements of lean implementation: value; value stream; continuous flow; pull; and continuous improvement. Although lean tools and techniques have proven effective in many sectors, it appears that lean production alone may struggle to adapt to current market dynamics. Strong fluctuations in market demand challenge the concept of capacity leveling, while inflexible production lines and the need for labor-intensive adjustments in production processes, buffer stocks, and cycle times suggest that lean tools and techniques may have limited suitability for shorter product life cycles and highly customized products.

To meet the growing demand for customized products, intensifying competition, and increasing emphasis on immediate-response services, companies are increasingly turning to digital transformation and service-oriented paradigms. This shift is supported by more affordable hardware and software solutions, including cost-effective sensors and actuators, powerful networking equipment, wireless technology, and cloud computing as well as advances in big data analytics and artificial intelligence (AI). These elements collectively constitute the concept of "smart manufacturing/Industry 4.0" (Figure 1) aiming to digitize and automate production processes. However, the eagerness to adopt smart manufacturing/Industry 4.0 technologies may pose significant challenges in terms of cost–benefit analysis, implementation considerations, frameworks, and their impact on existing production practices. Therefore, integrating lean production tools with the concept of smart manufacturing/Industry 4.0, called "Lean Smart Manufacturing," to enhance productivity and reduce costs in manufacturing systems with small batches, high variety, and short product life cycles is an important theme and trend.

FIGURE 1

EVOLUTION OF SMART MANUFACTURING/INDUSTRY 4.0.



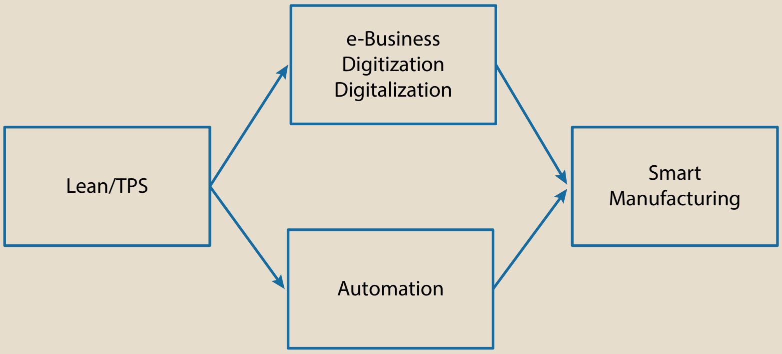
Source: https://www.aberdeen.com/blogposts/industry-4-0-industrial-iot-manufacturing-sneak-peek/.

Figure 2 shows sequential relationships among lean/TPS, digitization/ digitalization, automation, and smart manufacturing. It is suggested that enterprises first apply lean/TPS to eliminate waste and develop standardization such as standard operation procedures (SOPs). For example, it makes no sense to directly apply automated guided vehicles (AGVs) before rearranging the facility layout to decrease unnecessary material handling by applications of the "eliminate, combine, rearrange, simplify" (ECRS) model. It is impossible to adopt smart manufacturing without the successful execution of digitization/ digitalization as data richness is a prerequisite for data analytics in smart manufacturing. Strong support from top management is a must for an enterprise's journey from lean production to smart manufacturing.

This report first introduces the basic concepts of lean production and related tools, followed by an explanation of the definition of smart manufacturing/ Industry 4.0 and its key technologies. It will also introduce the six maturity levels that assist manufacturing industries in assessing their smart manufacturing development. Next, it explains how to integrate lean production with smart

FIGURE 2

SEQUENTIAL RELATIONSHIPS AMONG LEAN/TPS, DIGITIZATION/ DIGITALIZATION, AUTOMATION, AND SMART MANUFACTURING.



manufacturing technologies to help manufacturing systems achieve the goal of lean smart manufacturing. Finally, it illustrates applications of lean smart manufacturing through two case studies.

LEAN PRODUCTION

“Lean production” can be described as a comprehensive production approach that encompasses various industrial practices. Its primary objective is to identify value-adding processes from the customer’s perspective and facilitate the flow of these processes throughout the organization in response to customer demand [1, 3]. Originating from the conceptualization of the TPS by Taiichi Ohno at Toyota Motor Company [4], lean production aims to streamline processes to produce finished products at the required pace of customers with minimal waste. It emphasizes maximizing value while minimizing waste, optimizing efficiency, quality, and productivity. Key principles of lean production include identifying customer value, mapping value streams, creating flow, implementing pull-based systems, and continuous improvement.

Ohno [4] was instrumental in developing the method by which organizations identify waste, with his “seven wastes” model, which has become fundamental in many academic approaches. These wastes are:

1. Delay, waiting, or time spent in a queue with no value being added;
2. Producing more than what is needed;
3. Overprocessing or engaging in non-value-added activity;
4. Transportation;
5. Unnecessary movement or motion;
6. Inventory; and
7. Defects in the product.

Ohno [4] is also renowned for his “ten precepts” guiding principles for thinking and acting to achieve success:

1. You are a cost. First reduce waste.

2. First say, “I can do it.” And try before everything.
3. The workplace is a teacher. You can find answers only in the workplace.
4. Do anything immediately. Starting something right now is the only way to win.
5. Once you start something, persevere with it. Do not give up until you finish it.
6. Explain difficult things in an easy-to-understand manner. Repeat things that are easy to understand.
7. Waste is hidden. Do not hide it. Make problems visible.
8. Valueless motions are equal to shortening one’s life.
9. Re-improve what was improved for further improvement.
10. Wisdom is given equally to everybody. The point is whether one can exercise it.

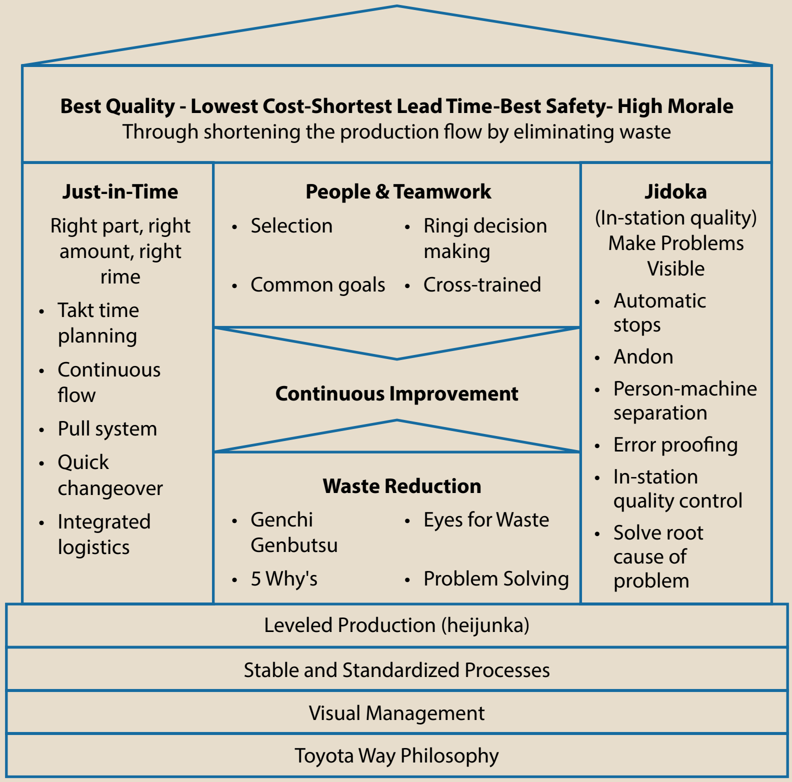
The “House of Toyota Production System” (Figure 3) is a visual representation of the key principles and elements of the TPS. It is often depicted as a two-story house, with the foundation representing the system’s philosophy and principles, and the roof representing the desired goals and outcomes. The pillars or walls of the house symbolize the essential elements of the TPS, such as just-in-time production, jidoka (automation with a human touch), standardization, continuous improvement (Kaizen), and respect for people. The House of TPS serves as a guiding framework for organizations seeking to implement lean principles and practices.

The key principles of lean production, also known as lean manufacturing, are foundational concepts that guide organizations in optimizing their operations. These principles include:

1. Value: Focus on identifying and delivering value to the customer. This involves understanding what the customer considers valuable and aligning production processes to meet those needs.

FIGURE 3

HOUSE OF TOYOTA PRODUCTION SYSTEM (TPS).



Source: Reproduced from Jeffrey [5] and Kehr and Proctor [6].

2. Mapping: Map out the entire value stream, which encompasses all the steps and activities involved in delivering a product or service, from raw materials to the end customer. By visualizing the value stream, organizations can identify waste and opportunities for improvement.

3. Flow: Ensure smooth and continuous flows of work, materials, and information through the production process. Minimize interruptions, bottlenecks, detours, backflows, waiting, and delays to enable efficient, timely delivery of products or services.

4. Pull: Implement pull-based systems where production is driven by customer demand. Work is initiated only when there is a demand for it, rather than pushing products through the process based on forecasts or arbitrary schedules. This helps reduce inventory and overproduction.

5. Continuous improvement (Kaizen): Strive for continuous improvement and perfection in all aspects of operations. Encourage a culture of Kaizen, or continuous improvement, where employees are empowered to identify and address inefficiencies and waste on an ongoing basis.

Lean tools are techniques and methodologies used within lean manufacturing or production to identify and eliminate waste, streamline processes, and improve overall efficiency. These tools are instrumental in implementing lean principles and achieving operational excellence. Some common lean tools include:

1. 5S: A workplace organization method involving five steps: sort; set in order; shine; standardize; and sustain. 5S aims to create a clean, organized, efficient work environment, reducing waste and improving safety and productivity.

2. Value Stream Mapping (VSM): A visual tool used to analyze and document the steps and flow of materials and information required to deliver a product or service to the customer. VSM helps identify waste, inefficiencies, and opportunities for improvement in the value stream.

3. Just-in-Time (JIT): A production strategy aimed at producing only what is needed, when it is needed, and in the quantity needed to fulfill customer demand. JIT minimizes inventory levels, reduces lead times, and improves efficiency by synchronizing production with customer demand.

4. Poka-yoke: Also known as mistake-proofing or error-proofing, Poka-yoke refers to designing processes or systems in a way that prevents errors or defects from occurring. This helps ensure quality and reduce the need for rework or inspection.

5. Jidoka: Often translated as "autonomation" or "automation with a human touch," this is a principle within the TPS. It refers to the practice of building quality into the production process by empowering machines and operators to automatically detect and stop when an abnormality or defect occurs. This ensures that problems are addressed at their source, preventing defective products from being passed downstream in the production line. Jidoka promotes both efficiency and quality by enabling timely intervention and continuous improvement.

6. SMED: SMED stands for "Single-Minute Exchange of Die," which is a lean manufacturing technique aimed at reducing the time it takes to complete equipment changeovers or setups. The goal of SMED is to minimize the changeover time to the point where it can be completed in single-digit minutes or less (hence the term "single-minute"). By reducing changeover times, manufacturers can increase flexibility, reduce inventory, and improve overall efficiency.

7. Kanban: A visual scheduling system used to control and manage the flow of work in a production process, kanban uses cards or signals to signal the need for more inventory or work to be done at each stage of production, enabling just-in-time production and inventory control.

8. Total Productive Maintenance (TPM): A holistic approach to equipment maintenance aimed at maximizing the efficiency and effectiveness of production equipment, TPM involves proactive maintenance, employee involvement, and continuous improvement to minimize downtime and improve overall equipment effectiveness.

9. Standard Work: Through the documentation and adherence to the best practices and procedures for performing a particular task or process, standard work ensures consistency, efficiency, and quality in operations by providing clear instructions and training guidelines on lean metrics for employees to follow.

10. Andon: Andon is a visual management tool used to indicate the status of a production process, typically on the shopfloor. It usually consists of a visual signal, such as a light or a display board, that alerts workers

and management to abnormalities or issues in the production process, such as equipment malfunctions, quality problems, or bottlenecks. The purpose of andon is to enable quick identification and response to problems, facilitating rapid problem-solving and preventing defects or delays from propagating further down the production line.

Lean Kaizen projects aim to systematically identify areas for improvement, implement changes, and continuously monitor and refine processes to achieve greater efficiency, quality, and customer satisfaction. These projects often involve cross-functional teams working together to analyze processes, identify waste, and implement solutions for improvement. Lean Kaizen projects are typically accompanied by "gemba walks," which translates to "the real place" or "where the work is done," to emphasize the importance of directly improving at the source or where work occurs by conducting onsite visits to the factory. This allows frontline employees and managers to participate in identifying and implementing small, incremental changes to improve processes, quality, and efficiency. The Asian Productivity Organization (APO) produced a video on "Gemba Walks" (https://www.apo-tokyo.org/event/gemba-walk/) which is an excellent reference. In Japan, managers are expected to perform regular gemba walks to discover Kaizen opportunities based on three criteria: quality; cost; and delivery. Table 1 lists typical topics of lean Kaizen projects.

TABLE 1

TYPICAL TOPICS OF LEAN KAIZEN PROJECTS.

• Cost Down	• Jig and Fixture Improvement
• Headcount Reduction	• Ergonomics
• Efficiency Improvement (e.g., UPPH)	• Shortening Production Line Length
• Reduction of Equipment Downtime and Idle Time	• Cell Formation
• Line Balancing	• Shortening Transportation Distance
• Yield Improvement	• Inspection Efficiency Improvement
• Rework Reduction	• 6S and Visual Management
• Improvement of On-time Delivery	• SOP Development
• Lead Time Reduction	• Training of Line Leaders

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• Warehouse Management and Inventory Control	• Energy Saving
• Space Utilization Improvement	• Pollution Prevention and Control
• Automation and Autonomation	• Efficiency Improvement of Adm. Processes
• Quick Changeover	• Efficiency Improvement of R&D Processes

Smart Manufacturing

"Smart manufacturing," also known as "Industry 4.0," refers to the use of advanced digital technologies and data analytics to improve manufacturing processes, increase efficiency, and enhance productivity. It represents the Fourth Industrial Revolution, characterized by the integration of cyberphysical systems, the Internet of Things (IoT), AI, and other technologies into manufacturing operations.

In smart manufacturing, machines, equipment, and production systems are interconnected and communicate with each other, enabling real-time monitoring, control, and optimization of processes. This connectivity allows for greater visibility and transparency across the production environment, leading to improved decision-making and operational efficiency. Key technologies and components of smart manufacturing include:

1. Cyber-Physical Systems (CPS): CPS integrate physical processes with digital technologies to monitor and control manufacturing operations in real time. These systems enable the seamless interaction between physical components and digital systems, facilitating automation, optimization, and adaptive manufacturing.

2. The IoT: The IoT involves connecting physical devices, sensors, and machines to the internet to collect and exchange data. In smart manufacturing, the IoT enables the creation of a digital thread that provides real-time insights into equipment performance, production status, and supply chain logistics.

3. AI and Machine Learning: AI and Machine Learning technologies analyze large volumes of data to identify patterns, predict outcomes,

and optimize processes. In smart manufacturing, AI algorithms can be used for predictive maintenance, quality control, demand forecasting, and production optimization. Figure 4 lists the potential applications of machine learning in manufacturing systems.

4. Additive Manufacturing (3D printing): Additive manufacturing enables the production of complex parts and components by building them layer by layer from digital design files. This technology offers greater flexibility, customization, and cost-effectiveness compared with traditional manufacturing methods.

5. Advanced robotics and automation: Robotics and automation technologies automate repetitive tasks, increase productivity, and improve safety in manufacturing operations. Collaborative robots (cobots), autonomous vehicles, and AGVs are examples of advanced robotics used in smart manufacturing.

6. Cloud computing and big data analytics: Cloud computing provides scalable and flexible computing resources for storing, processing, and analyzing manufacturing data. Big data analytic techniques extract actionable insights from large datasets, enabling data-driven decision-making and continuous improvement.

7. Augmented reality (AR) and Virtual reality (VR): AR and VR technologies enhance training, maintenance, and troubleshooting processes by providing immersive, interactive experiences. In smart manufacturing, AR and VR applications are used for employee training, remote assistance, and digital prototyping.

Infosys [7] has proposed the six maturity levels on the path to Industry 4.0 (Figure 5) to assist enterprises in assessing the readiness of an organization for smart manufacturing from the four perspectives of resources, information systems, organization structure, and organization culture.

1. Computerization: In the initial stage, known as "computerization," information and communication technologies (ICT) are utilized to automate manual production and support activities in the factory, paving the way for automation or computer-integrated manufacturing (CIM).

FIGURE 4

POTENTIAL APPLICATIONS OF MACHINE LEARNING IN MANUFACTURING SYSTEMS.

Machine learning opportunities in manufacturing

Highest-ranked use cases, based on survey responses	Use case type	Impact	Data richness
Predict failure and recommend proactive maintenance for production and moving equipment	Predictive maintenance	1.3	1.0
Optimize complex manufacturing process in real time (determine where to dedicate resources to reduce bottlenecks and cycle time)	Operations/ logistics optimization (real time)	1.1	1.0
Predict future demand trends and potential constraints in supply chain	Forecasting	0.8	0.7
Identify design problems in pre-production to reduce ramp-up time to maximum output (i.e., yield ramp)	Predictive analytics	0.6	0.3
Identify root causes for low product yield (e.g., tool-/die-specific issues) in manufacturing	Discover new trends/ anomalies	0.5	0.7
Detect defects and quality issues during production using visual and other data	Process unstructured data	0.4	0.7
Optimize resource allocation in R&D and manufacturing, leveraging diverse data (e.g., communications, documentation) to track progress	Resource allocation	0.4	0.3
Optimize R&D experimental efficiency through process/operations	Operations/ logistics optimization (real time)	0.4	0.3
Determine root causes for quality issues developed outside of manufacturing (e.g., during delivery, in supply chain)	Discover new trends/ anomalies	0.3	0.7
Identify critical factors to reduce number of required experiments for R&D and testing (e.g., component testing)	Predictive analytics	0.2	0.7

Source: https://theosz.medium.com/120-machine-learning-business-ideas-from-the-new-mckinsey-report-b81b239f336.

2. Connectivity: On the second level, "connectivity" is implemented in a structured, hierarchical manner with defined functionalities. However, this is limited to enterprise integration of "within-company" supply chains, connectivity, and automation.

3. Visibility: An organization equipped with real-time data collection capability gains visibility into its production systems. At this stage, a "digital shadow" is established, containing all relevant information of sufficient quality and in real time for decision-making purposes. This visibility empowers production managers to base their decisions on information rather than experience.

4. Transparency: Once an organization has acquired all relevant information, it can progress to the next stage of Industry 4.0: transparency. Companies that achieve transparency understand the reasons behind past and current events within their complex systems. Decision-making moves beyond reliance on past impacts and historical data. At this level, the focus shifts from measuring specific KPIs to comprehensively understanding all aspects, thereby creating complete transparency of manufacturing processes in real time across production facilities.

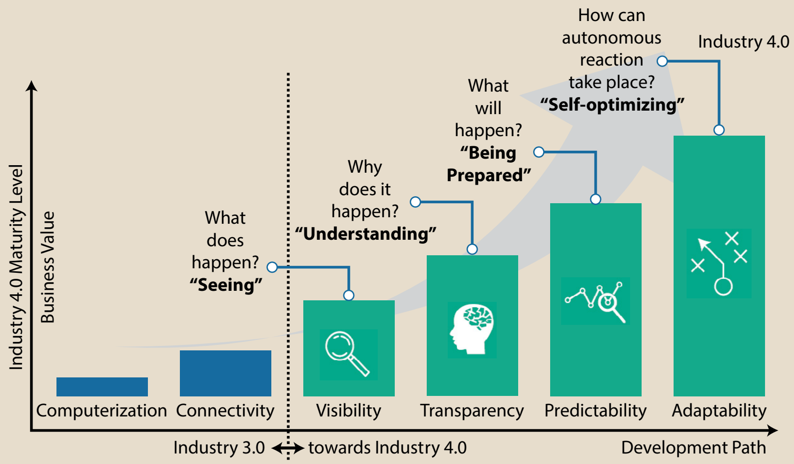
5. Predictability: In the "predictability" stage, manufacturers shift the focus to analyzing information and interpreting results. Data analytic methods like complex event processing are crucial for real-time analysis of event patterns in big data streams. These patterns are systematically stored and categorized for future analysis, forming "smart data" rather than raw big data. Smart data, enriched and context-sensitive, aids in predicting future events based on a comprehensive understanding of system dynamics. Requirements include case-based reasoning, machine learning or deep learning algorithms, and the ability to design and assess trigger-event scenarios and their probabilities.

6. Adaptability: Adaptability is the extreme level of connectivity and automation of the system (e.g., the production system) to react automatically to changing exogenous conditions. Those exogenous conditions need not be the ones that occurred in the past, but the

system is trained to self-adapt and adjust to completely new circumstances. Therefore, a deep understanding of all interdependencies within the system and all of its influences is critical.

FIGURE 5

SMART MANUFACTURING/INDUSTRY 4.0 MATURITY INDEX.



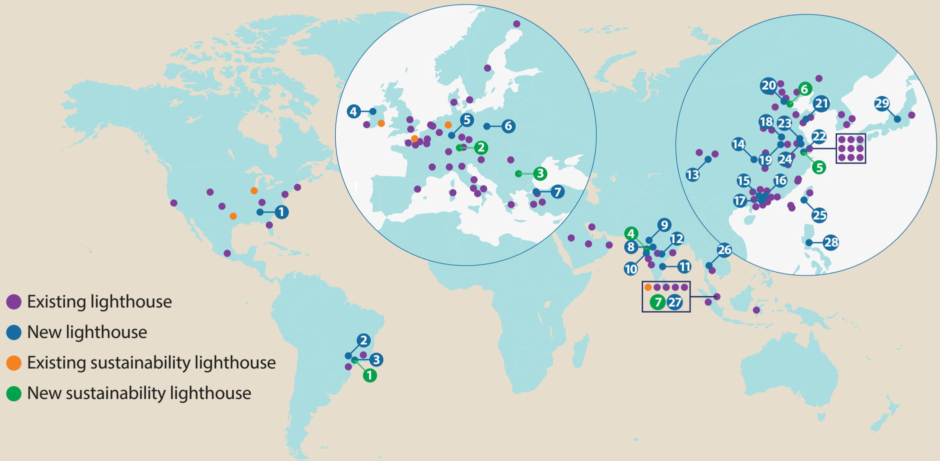
Source: Reproduced from Infosys [7].

"Lighthouse factories" are exemplary manufacturing facilities recognized by the World Economic Forum (WEF), working in collaboration with McKinsey & Company, for their leadership in adopting advanced technologies and implementing Industry 4.0 principles. These factories serve as models of excellence, demonstrating how innovative technologies such as automation, AI, the IoT, and data analytics can transform manufacturing operations and drive competitiveness.

The "Global Lighthouse Network" refers to a collaborative initiative led by the WEF that connects lighthouse factories around the world. The network aims to facilitate knowledge sharing, best practice dissemination, and collaboration among leading manufacturing facilities. By fostering collaboration and exchanges of ideas, the Global Lighthouse Network seeks to accelerate the adoption of Industry 4.0 technologies across the manufacturing sector, driving broader transformation and economic growth. Figure 6 shows that the Global Lighthouse Network comprised 132 lighthouses as of January 2023 and 29 new lighthouses in 2022 are included in this network.

FIGURE 6

THE GLOBAL LIGHTHOUSE NETWORK COMPRISED 132 LIGHTHOUSES AS OF JANUARY 2023.



New lighthouses in 2022

1. **LG Electronics** Clarksville, US
2. **Unilever** Indaiatuba, BR
3. **Flex** Sorocaba, BR
4. **The Coca-Cola Company** Ballina, IE
5. **MantaMESH** Fröttstädt, DE
6. **Danone** Opole, PL
7. **Bosch** Bursa, TR
8. **Cipla** Indore, IN
9. **CEAT** Halol, IN
10. **Johnson & Johnson Consumer Health** Mulund, IN
11. **Mondelez** Sri City, IN
12. **Dr. Reddy's Laboratories** Hyderabad, IN
13. **Contemporary Amperex Technology** Yibin, CN
14. **Sany Heavy Industry** Changsha, CN
15. **Wistron** Zhongshan, CN
16. **Foxconn Industrial Internet** Shenzhen, CN
17. **Midea** Foshan, CN
18. **Lenovo** Hefei, CN
19. **Haier** Hefei, CN
20. **Unilever** Tianjin, CN
21. **Haier** Qingdao, CN
22. **Western Digital** Shanghai, CN
23. **Mondelez** Suzhou, CN
24. **Huayi New Material** Shanghai, CN
25. **Advanced Semiconductor Engineering** Kaohsiung, TW, CN
26. **Western Digital** Bang Pa-in, TH
27. **Agilent Technologies** Singapore, SG
28. **Western Digital** Laguna, PH
29. **Procter & Gamble** Takasaki, JP

New sustainability lighthouses:

1. **Flex** Sorocaba, BR
2. **Siemens** Amberg, DE
3. **Arçelik** Ulmi, RO
4. **Unilever** Dapada, IN
5. **Western Digital** Shanghai, CN
6. **Haier** Tianjin, CN
7. **Micron** Singapore, SG

Source: Reproduced from World Economic Forum [8].

From Lean to Smart Manufacturing: Lean Smart Manufacturing

For decades, manufacturers have utilized lean principles and tools to streamline operations and enhance productivity. The lean methodology forms the basis for achieving operational excellence by standardizing processes, fostering a culture of continuous improvement, and empowering shopfloor workers. However, as operational complexity continues to rise, many companies have found that lean production alone is insufficient to tackle their operational challenges. In recent years, a suite of advanced digital technologies, collectively referred to as Industry 4.0, has emerged to provide novel solutions for addressing complexity and enhancing productivity. By deploying a tailored mix of these technologies, manufacturers can enhance speed, efficiency, and coordination, and even enable self-managing factory operations.

Table 2 shows the significant differences between lean/Kaizen projects and smart manufacturing projects. It is easier to execute lean/Kaizen projects and to learn and use lean tools. Furthermore, enterprises can expect a shorter time to obtain the benefits from lean/Kaizen projects as their KPIs are directly linked with the "hard" savings and "short" savings. The KPIs of smart manufacturing projects, in many cases, are related to the confusion matrix with true-positives, false-negatives, false-positives, and true-negatives that are difficult to directly link with savings. AI model application needs to pass a threshold to achieve solid improvement. Furthermore, it is difficult for the management to grasp machine learning and deep learning in AI applications, compared with ECRS widely used in lean/Kaizen projects.

TABLE 2

LEAN/KAIZEN PROJECTS VS. SMART MANUFACTURING PROJECTS.

Lean/Kaizen
Easier to execute
Easier to learn and use tools
Less expensive investment
Shorter time to get the benefit
KPI directly links to savings
Can achieve gradual and partial improvement
Data collection and analysis
QC tool application

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Lean/Kaizen
A consultant coaches factory Kaizen teams to execute
Factory teams are the execution forces
Smart Manufacturing
More difficult to execute
More difficult to learn and use tools
More expensive in investment
Longer time to get the benefit
KPI indirectly links to savings
Need to pass a threshold to get the improvement
Big data collection and analysis
AI model application
A smart manufacturing team helps a factory to execute
More cooperation with external partners

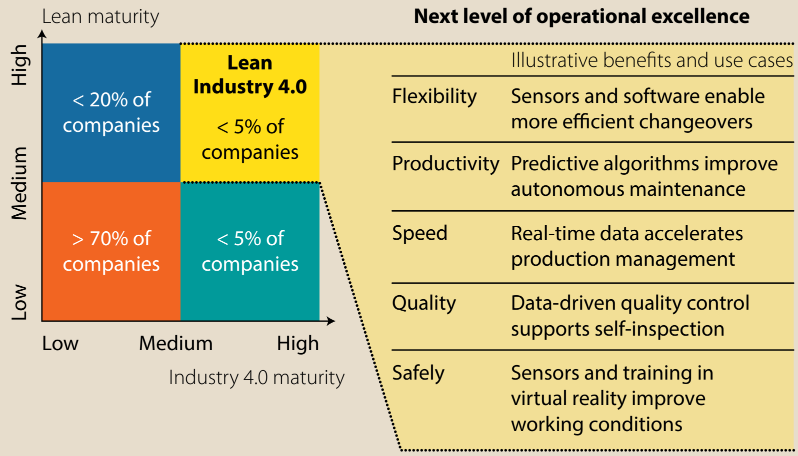
Manufacturers aiming to optimize operations must grasp the interaction between traditional lean production and smart manufacturing/Industry 4.0. Having supported numerous operational excellence programs in recent years, we have observed companies achieving significant synergies by adopting lean production and smart manufacturing/Industry 4.0 in a holistic manner, rather than separately or sequentially. The integrated approach, known as "Lean Smart Manufacturing," is often the most effective path to attain the next level of operational excellence.

Manufacturers that have successfully implemented lean smart manufacturing can achieve up to a 40% reduction in conversion costs over five to 10 years, significantly surpassing the reductions seen with the best-in-class independent implementation of lean or Industry 4.0. These higher cost reductions often result from the adoption of technologies that enhance plant processes and structures, such as optimizing layouts. However, less than 5% of the manufacturing companies we have observed have reached a high level of maturity in lean smart manufacturing (Figure 7).

The integration of lean production and smart manufacturing/Industry 4.0 represents a crucial research area deserving thorough exploration. With the emergence of CIM, there was speculation that future factories could operate

FIGURE 7

LEAN SMART MANUFACTURING EXPANDS OPPORTUNITIES FOR OPERATIONAL EXCELLENCE AND REVENUE GROWTH.



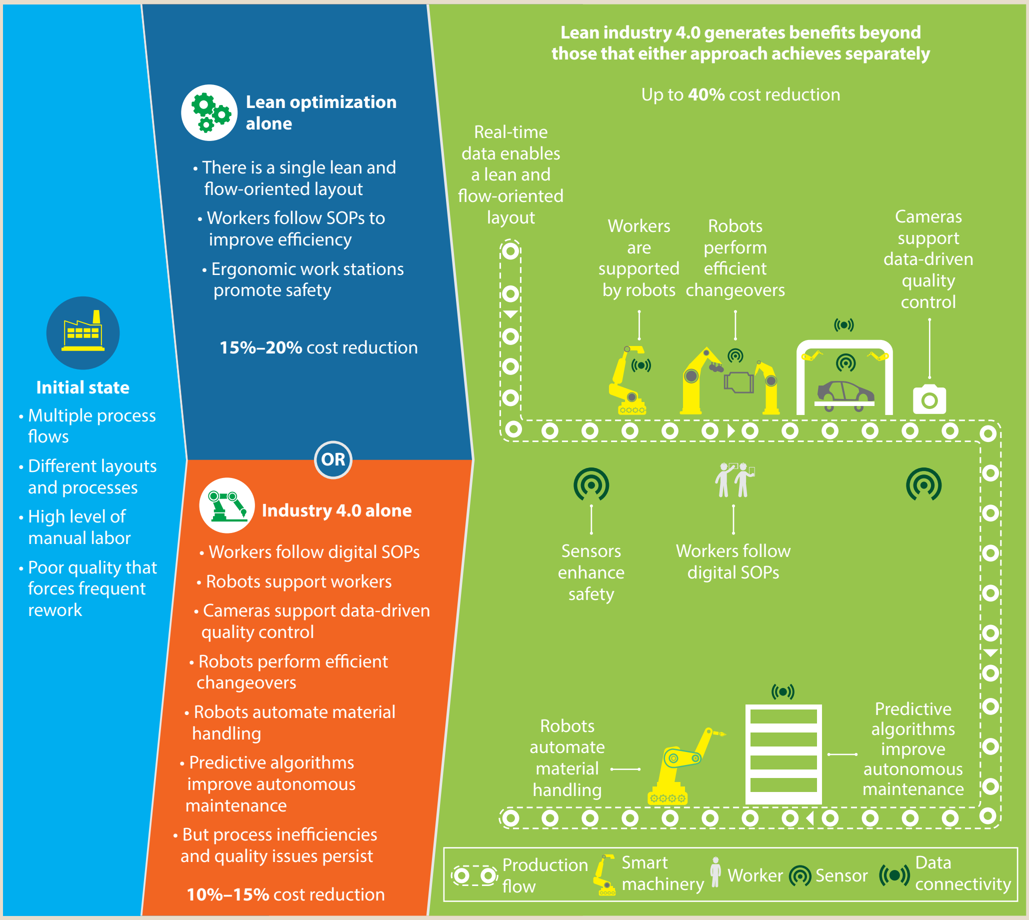
Source: https://www.bcg.com/publications/2017/lean-meets-industry-4.0.

autonomously, eliminating the need for human operators. While this notion proved impractical in reality, it spurred the development of lean automation, leveraging robotics and automation technologies to achieve lean production principles. Ohno's TPS is founded on two pillars: just in time and autonomation [4]. Autonomation involves automating manual processes, including inspection; in other words, equipment should halt automatically upon detecting issues, preventing defective products from advancing down the production line. For example, manual inspection or testing operations may result in misjudgments due to insufficient past experience or work fatigue, leading to the misclassification of good products as defective (i.e., type I error, alpha error, or producer's risk), causing revenue waste, or the misclassification of defective products as good (i.e., type II error, beta error, or consumer's risk), resulting in quality cost losses. Automated equipment can solve this problem to reduce waste and cost losses. Human intervention is only required when defects are detected. Thus, automation has been pivotal in lean production from its inception, with smart manufacturing/ Industry 4.0 representing a significant advance in this domain.

According to the BCG experience (https://www.bcg.com/publications/2017/lean-meets-industry-4.0), companies adopting the integrated lean smart manufacturing approach have achieved up to a 40% reduction in conversion costs (Figure 8). Additionally, companies have leveraged this integrated approach to reduce costs related to poor quality by 20% and work-in-process inventory by 30%. Table 3 also lists specific lean practices and smart manufacturing/Industry 4.0 technologies that can be implemented to address the current production challenges at both the shopfloor and managerial levels.

FIGURE 8

WITH AN INTEGRATED APPROACH, LEAN AND SMART MANUFACTURING/INDUSTRY 4.0 ARE MUTUALLY ENABLING.



Source: https://www.bcg.com/publications/2017/lean-meets-industry-4.0.

TABLE 3

PRODUCTION CHALLENGES AND SPECIFIC HELPFUL SMART MANUFACTURING/INDUSTRY 4.0 AND LEAN TOOLS.

Production challenge/ problem	Lean tool/technique that can help	Smart manufacturing/ Industry 4.0 technology that can help
Lot tracking	Kanban	Web/cloud Kanban, RFID tags, intelligent bins
Inventory control		RFID tags, NFC, QR codes, VR/AR
Machine failure	Poka-yoke, Andon	Sensor/actuator, real-time data, cloud
Material handling		AGV, robot gripper
Resource sharing/ collaborative design		Cloud, VR/AR
Overproduction	Kanban	
Quality control	Poka-yoke, Jidoka	Big data, sensor/actuator
Leveled utilization	Heijunka	
Long-term planning	Hoshin Kanri	Big data
Low utilization ratio of equipment	SMED, 5S	Robot gripper
Deficient product	Jidoka	Sensor/actuator
Seeking perfection	VSM, Continuous Improvement	Big data, real-time data
Worker training	Kaizen	VR/AR

Source: Reproduced from Shahin et al. [9].

Case Study 1: Cloud Kanban

To illustrate the integration of Industry 4.0 technologies and lean tools to achieve "Lean Smart Manufacturing," an EAT (estimated-actual-total) kanban framework was designed for dashboard-type process monitoring, applicable across various industries [9]. While traditional kanban systems are effective for controlling work-in-progress inventory in manufacturing or managing software requirements in software engineering, they often lack enterprise-wide resource management capabilities. To address this gap, an enhanced platform was developed leveraging cloud technology as a key component of Industry 4.0. This cloud-based decision support system (DSS), coupled with a robust continuous improvement methodology, empowers operations managers to make informed decisions. Developed and implemented for a generic service operations management (SOM) organization, our framework utilizes the innovative Microsoft Azure cloud platform.

In a typical service scenario, a job order consists of multiple activities. The first step involves estimating the total amount of the job and individual activities. For each activity within the job, an estimated amount per shift is determined based on the “standard rate per hour” (SRPH) for the activity. The second step entails creating a rough-cut schedule, typically through a “capacity vs. requirement” analysis based on existing resources, including machines, employees, and raw materials. The third step involves simulation using a decision support system. For priority jobs, an ant-colony algorithm-based simulation is conducted to assess the optimization feasibility of the rough-cut schedules. If necessary, fine-tuning of rough-cut schedules is performed based on the simulation results. The fourth step involves gathering actual production quantities, including labor hours used, the number of defective products, and production hours lost due to downtime. Over time, production data help refine and establish the SRPH. Finally, the job and activity progress are displayed using the estimated actual and total kanban system. Figure 9 illustrates the main menu of the cloud-based kanban system, which includes modules for entering production data and conducting ant colony-based simulations to validate rough-cut capacity planning. The system comprises seven modules: production; scheduling; performance indicators; decision support; system setup; quality; and customer service.

Case Study 2: Smart Lean-based Manufacturing System

The objective of this case study is to present a structured integration between digital value stream mapping (DVSM) and specific lean tools, aiming to advance lean-oriented Industry 4.0 or smart factories [10]. DVSM serves as the IT facilitator for lean methodologies, prioritizing time-based product flow, a cornerstone of lean success. As indicated by Ramadan [11], DVSM can be defined as: “a computerized event-driven lean-based IT system that runs in real-time according to lean practices and tools to monitor and control all manufacturing aspects to effectively reduce wastes and maximize value.”

FIGURE 9

CLOUD KANBAN.

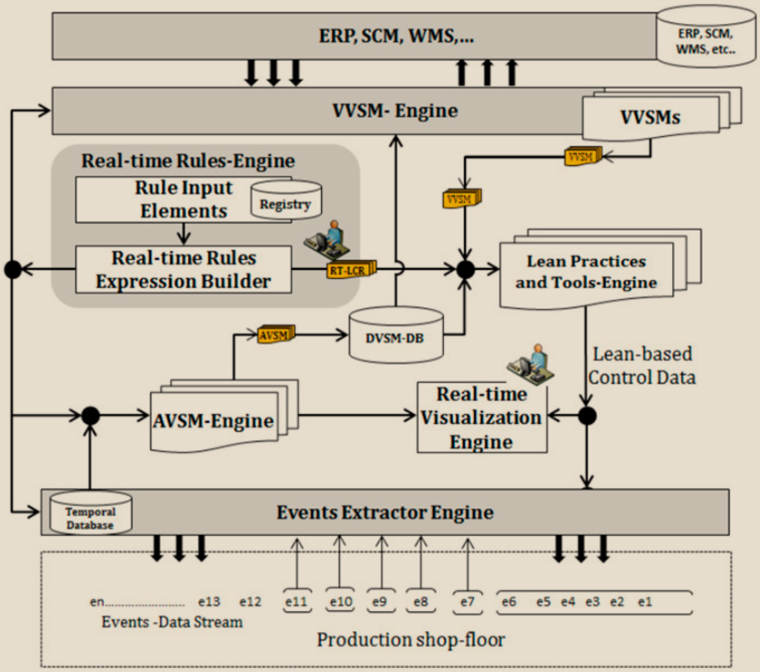
Source: Reproduced from Shahin et al. [9].

Figure 10 depicts an overview of DVSM components. In order to fully leverage the capabilities of DVSM in manufacturing environments, a systematic deployment of RFID systems is essential to achieve maximum real-time data capture accuracy. This entails installing RFID across all production areas to establish a smart or intelligent manufacturing environment. However, certain manufacturing settings may pose challenges to achieving high levels of real-time visibility solely through RFID. In such cases, complementary technologies like Wireless Sensor Networks (WSNs), digital cameras, 2D barcodes, automation devices, Programmable Logic Controllers (PLCs), or other technological solutions can be employed to enhance data collection alongside RFID. In instances where real-time events cannot be automatically captured, lean practitioners may resort to manual data entry by workers using a touch user interface (TUI).

Once manufacturing environments are equipped with smart capabilities, DVSM becomes primed to enhance any lean tool. The smart evolution of lean tools and practices begins by constructing suitable real-time lean control rules (RT-LCRs) using a real-time rules engine (RT-RE). Within this engine, lean specialists utilize the real-time rules expression builder (RT-REB) module, assisted by the "rule input elements" (RIE) module, to create various RT-LCRs. These constructed RT-LCRs are then uploaded onto the lean practices and tools engine (LPTE) to run in real time. Throughout production, the RT-LCRs of targeted tools such as 5S, standardized work, and Poka-yoke leverage real-time production data from actual value stream mapping (AVSM) to monitor and control these lean tools intelligently. This monitoring and control system aligns with the standard lean-based environment represented by virtual value stream mapping (VVSM).

FIGURE 10

OVERVIEW OF COMPONENTS OF DYNAMIC VALUE STREAM MAPPING (DVSM) FOR LEAN 4.0.



Source: Reproduced from Ramadan and Salah [10].

CONCLUSION

Lean production has been the dominant paradigm in manufacturing environments over the past 40 years, helping to reduce waste and lower costs to enhance industry profitability. However, in recent years, with the evolution of Industry 4.0 and the emergence of related digitalization and AI technologies, the manufacturing industry is increasingly adopting smart manufacturing/ Industry 4.0 technologies to facilitate the digital transformation of production systems. Therefore, how to integrate lean production and smart manufacturing/ Industry 4.0 to help the manufacturing industry move toward the "lean smart manufacturing" model is an important topic. Hence, this report first introduces the basic concepts and related tools of lean production, then explains the definition of smart manufacturing/Industry 4.0 and related key technologies. It also introduces the six maturity levels to assist the manufacturing industry in evaluating its development in smart manufacturing, followed by an explanation of how to integrate lean production with smart manufacturing technologies to achieve the goal of lean smart manufacturing. Finally, two case studies are presented to illustrate the applications of lean smart manufacturing.

REFERENCES

[1] Womack J.P., Jones D.T., Roos D. The Machine that Changed the World: The Triumph of Lean Production. New York: Rawson Macmillan; 1990.

[2] Womack J.P., Jones D.T. Lean thinking—banish waste and create wealth in your corporation. Journal of the Operational Research Society 1997; 48(11): 1148.

[3] Shah R., Ward P.T. Defining and developing measures of lean production. Journal of Operation Management 2007; 25(4): 785–805.

[4] Ohno T. Toyota Production System: Beyond Large-scale Production. New York: CRC Press; 1988.

[5] Jeffrey K.L. The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer. New York: McGraw-Hill; 2004.

[6] Kehr T.W., Proctor M.D. People pillars: Re-structuring the Toyota Production System (TPS) House based on inadequacies revealed during the automotive recall crisis. Quality and Reliability Engineering International 2017; 33(4): 921–930.

[7] Infosys. Making Industry 4.0 Real—Using the Acatech I4.0 Maturity Index. White paper; 2018.

[8] World Economic Forum. Global Lighthouse Network: Shaping the Next Chapter of the Fourth Industrial Revolution. White Paper; 2023.

[9] Shahin M., Chen F.F., Bouzary H., Krishnaiyer K. Integration of lean practices and Industry 4.0 technologies: smart manufacturing for next-generation enterprises. International Journal of Advanced Manufacturing Technology 2020; 107: 2927–2936.

[10] Ramadan M., Salah B. Smart lean manufacturing in the context of Industry 4.0: A case study. International Journal of Industrial and Manufacturing Engineering 2019; 13(3): 174–181.

[11] Ramadan M. RFID-enabled dynamic value stream mapping for smart real-time lean-based manufacturing system. 2016; PhD dissertation, University Duisburg-Essen.

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