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Smartening and Digital Transformation Plan in the Industry based on Best Practices

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Abstract
Due to smart production, Industry 4.0 has become an essential paradigm in industry. This paradigm is looking for smartening and digital transformation in industries where its goal is not only technology upgrade but also integration of advanced technology such as Artificial Intelligence, Internet of Things, Cloud computing, Digital twins and simulation software, Big Data Processing, Blockchain, etc. in production processes for increasing efficiency, flexibility, and productivity in various sections of production. Research shows that smartening and digital transformation are essential to creating a competitive advantage in global markets and leadership in the coming decades. Neglecting this change of approach can lead to losing customers and sales markets. Unfortunately, despite its advantages, implementing the smart industry faces significant challenges that can hinder its achievement of goals. So, whether at the national or corporate level, benefiting from a cohesive program for smartening and digital transformation in any industry is essential. In this paper, based on research in more than 20 leading countries in the field of smart industry, a strategic plan for smartening and digital transformation in industries has been presented. By using this strategic plan, it is possible to overcome the challenges and reach the smart industry in various fields.

Keywords: Smartening; Digital Transformation; Industry 4.0; Executive Plan.

1- Introduction

Each industrial revolution is characterized by significant technological advancements that have changed production processes. Industry 1.0 introduced mechanization through water and steam power. Following that, Industry 2.0. emphasized mass production through assembly lines. Industry 3.0 is characterized by automation facilitated through electronics and information technology. With the introduction of Industry 4.0 in the current era, the industry reached its peak at the Hannover Fair in 2011 with smart production. The concept of smart industry represents a transformative change in manufacturing processes characterized by the integration of advanced technologies such as artificial intelligence (AI), the Internet of Things (IoT), big data analytics, and robotics. This paradigm shift is not merely a technological upgrade, but it is a comprehensive reconsideration of how industries operate, leading to increasing efficiency, flexibility, and productivity across different sectors. [1-6] Overall, Industry 4.0 facilitates the advancement of smart factories capable of real-time data processing and autonomous decision-making and the monitoring, control, and optimization of production processes. This continuity not only simplifies production but also enhances sustainability by optimizing resource use and minimizing waste. [7-9] In this paper, our goal is to understand global methods to present a comprehensive plan for smartening and digital transformation in industry at a national scale. Accordingly, this paper is organized as follows.
The second section examines the key components in the field of smartening and digital transformation in industry. In this section, key technologies for smartening and digital transformation in industry are introduced. Also, the

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advantages and challenges related to smart technology and digital transformation in the industry will be introduced. In the third section, national programs for smartening and digital transformation in leading countries will be reviewed. The fourth section examines global methods for smartening and digital transformation in major industries such as pharmaceuticals, chemicals, and textiles. In the final section, a national strategic program for the implementation of the smart industry in each country will be presented based on the results obtained from the previous sections.

2- Key Components of Smartening and Digital Transformation in Industry

2-1- Key Technologies for Smartening and Digital Transformation in Industry

Although many technologies are used for smartening and digital transformation in industry, in this section, 9 of the most important technology areas in this field will be introduced. These areas are as follows:

1) Cyber-physical Systems (CPS)
This technology is the foundation of Industry 4.0. By combining physical processes and digital computing, it establishes the connection between physical manufacturing plants and digital systems, such as cloud computing and data analysis, which helps in monitoring and controlling manufacturing processes and leads to increased efficiency and safety. [10-12]

2) Internet of Things (IoT)
The Internet of Things refers to a network of connected devices that can share data. This real-time data can help improve predictive maintenance, optimization of the production processes, and assist manufacturers in responding more quickly to market demand. [13-16]

3) Cloud Computing
Cloud computing provides scalable and flexible computational resources over the internet. For producers, cloud-based solutions provide powerful tools for data storage, processing, and analysis. It can analyze the large volume of data generated by IoT devices and gain insights that can help improve production flows and product quality. [17-20]

4) Blockchain Technology
Blockchain technology, due to its potential to improve supply chain transparency, particularly in terms of compliance with various standards, is increasingly recognized. Blockchain can facilitate end-to-end tracking of raw materials, thereby increasing trust among stakeholders and ensuring compliance with various standards. [14,21-24].

5) Digital Twins and Simulation Software
The use of digital twins as virtual representations of physical assets involves simulating digital assets to predict the behavior of components or systems in the real world, enabling manufacturers to optimize production lines and test various production scenarios before actual implementation, thereby reducing the need for physical prototyping. [18,25-28].

6) Automation and Robotics
The use of robotics combined with artificial intelligence enables the creation of an assembly line that operates continuously with minimal human intervention, leading to increased speed and accuracy in production. [29]

7) 3D Printing
3D printing technology helps to reduce costs and accelerate production in the design and manufacturing of industries, especially the clothing industry. [30]

8) Augmented Reality (AR) and Virtual Reality (VR)
It allows customers to view products and make desired changes before purchasing. This technology also has widespread applications in design and prototyping. [31]

9) RFID/NFC
These technologies are used for the automatic identification and tracking of materials and products in the production process, helping companies achieve greater efficiency, accuracy, and transparency in their operations. [32-36].

10) Artificial Intelligence (AI)
Artificial Intelligence (AI) has emerged as the most transformative enabler of Industry 4.0, permeating every aspect of smart manufacturing from predictive maintenance to quality control and production planning. [37].
According to a Google Cloud survey of 517 manufacturing executives (2025), 78% of manufacturers report seeing returns from their generative AI investments, with 56% actively using AI agents and 37% having launched more than ten. [38] Over half (55%) plan to allocate 50% or more of their future AI budget to agentic AI. [37]
Industry reports identify four critical areas where AI delivers the highest impact [37]:

- **Predictive maintenance:** Reduces unplanned downtime by 30–50% and maintenance costs by 20–30%
- **Quality control:** Machine vision systems detect defects faster and more accurately than human inspection
- **Robotics & automation:** AI enables cobots to adapt to variable tasks in real-time
- **Energy management:** AI-powered optimization improves efficiency with ROI under two years.

The global smart manufacturing market, driven primarily by AI and IIoT, is projected to reach USD 1,339 billion by 2034 (CAGR 14.70%). [39]

2-2- Key Advantages of Implementing the Smart Industry

Industry 4 brings key advantages to industrial owners, allowing every industry period to be divided into pre and post-smartening and digital transformation. The most important advantages of the smart industry are mentioned below.

1) Smart Production
Companies are increasingly using data analytics and machine learning to predict market trends and consumer preferences, which allows for the delivery of more tailored products. [40-46]

2) Reducing Production Costs
The adoption of automation technologies and smart inventory management systems enables manufacturers to reduce costs while producing high-quality outputs by optimizing production processes. [47]

3) Predictive Maintenance
Artificial intelligence technologies, especially machine learning and data analysis, play a key role in predictive maintenance. These systems significantly enhance the ability to identify and solve mechanical issues before operational disruptions occur and to predict failures before problems arise by analyzing large volumes of equipment data. [48]

4) Optimization and Intelligent Management of the Supply Chain
Improving logistics and supply chain management through digital tools enables producers to respond quickly to changes in demand and strengthen their export capabilities. [49]

5) Increased Productivity and Efficiency
The use of modern technologies and smartening in industry leads to a reduction in hard work in repetitive tasks and the allocation of human resources to activities with higher added value. These technologies reduce the time and costs of inventory management and quality control, leading to increased efficiency. [30,50,51].

6) Enhancing Safety
By reducing employees' exposure to hazardous tasks, workplace incidents are significantly reduced. [52]

7) Increase in Accuracy, Quality, and Customer Satisfaction
By increasing the use of smart production and robotics, it is possible to enhance precision to the nanometer level, improve processes, increase product quality, and ultimately achieve customer satisfaction. [34,36,53].

8) Circular Model and Recycling
Leading companies utilize circular economic models to reduce waste and reuse primary production resources, which leads to the preservation of natural resources and a reduction in production costs. [54]

9) Environmental Sustainability and Responsibility
Technologies such as predictive maintenance can reduce waste and energy consumption, while IoT devices help monitor environmental impacts throughout the production process. [55]

10) Global Competitiveness
Advancements in the smart industry lead to reduced response times to international demand and shorter product delivery times. [56]

2-3- Challenges of Implementing Smart Industry

The smart industry represents a significant transformation in production methods driven by the integration of advanced technologies. The successful adoption of Industry 4.0 requires a holistic approach that encompasses not only technological advancements but also strategic planning and organizational change management. However, the transition to smart production is not without obstacles. Below are some of the most important challenges in moving towards smartening and digital transformation in the industry. [3,57-59].

1) High implementation costs
One of the main challenges in the smart industry is the high costs of implementation and return on investment (ROI). [9]

2) The gap between large and small companies in implementation
The cost of implementing advanced technologies can be exorbitant for smaller producers and potentially widen the gap between large and small companies. [60-62] Small, medium, and micro enterprises (SMMEs) are essential for harnessing the benefits of smart manufacturing, as these companies constitute a significant portion of the global economy and play a critical role in driving innovation and competitiveness. [3,57-59].

3) Integration with existing systems
Many companies face challenges in integrating smart systems with their existing systems, which can limit the adoption of this technology. [22]

4) Changing organizational culture and shortage of skilled labor
The challenges associated with the transition to an intelligent industry go beyond technological obstacles. Accepting smart technologies requires fundamental changes in the way of working and organizational culture. Resistance to change, especially in companies that are accustomed to traditional production methods, is considered a major obstacle. Companies should strengthen a culture of innovation and adaptability. This cultural change is often accompanied by the need to upgrade and reskill the workforce to equip them with the necessary competencies to thrive in a smart manufacturing environment. [57-59]

5) Weakness of infrastructure

The existing infrastructure in a country may not have the necessary capabilities to implement smart industry projects and may require significant enhancements to fully support smart industry technologies. [63]

6) Digital Divide
There is a significant gap between different cities regarding access to digital infrastructure, which limits the benefits of the smart industry. [51,64]

7) Concern regarding security and privacy issues
Due to the easy access to information, there may be security challenges. This can raise concerns about privacy and data security. [65,67]

8) Dangers of Cyber Attacks
As production becomes more interconnected, the risk of cyberattacks increases, necessitating strong cybersecurity measures to protect sensitive data and systems. [68]

9) Harmonization of laws
Despite these advances in the smart industry sector, harmonizing regulations remains a challenge. As an example, the member countries of the EU have different standards for implementing EU directives in the field of the smart pharmaceutical industry, which can delay the deployment of technologies. Efforts to standardize these regulations are underway, and with initiatives such as the EU strategy, processes become simpler, and cross-border cooperation improves. [69]

10) Standardization
The absence of global standards for the production and testing of certain smart products, including smart clothing, causes problems with the compatibility of different products and creates confusion among consumers. [70]

2-4- Comparative Impact Analysis of Key Enabling Technologies

The nine technological components introduced above exhibit varying levels of industrial impact. Based on recent literature (2024–2026), Artificial Intelligence is recognized as the most transformative enabler across smart manufacturing domains. Industrial IoT serves as the foundational data infrastructure for real-time condition monitoring and asset tracking. [71,72]

Digital twins and simulation software represent the fastest-growing segment in future investment, reducing physical prototyping costs by 40–60% and improving production efficiency by 15–25%. Cloud computing demonstrates the highest current adoption rate (>57%), while automation and robotics show strong adoption, with 41% of manufacturers citing factory automation as a top investment priority. The global smart factory market is projected to reach USD 900 billion by 2034, driven primarily by automation and AI integration [202]. [73]

RFID/NFC technologies enable automated identification and real-time tracking throughout production processes. Key benefits include inventory accuracy >99%, labor cost savings (15–20%), and production throughput improvement of 5–8%. Primary implementation barriers include tag costs (USD 0.05–0.30 per unit), environmental interference (metal, liquids), and integration complexity. The global smart label market is projected to grow at 14.2% CAGR through 2034. [74-77]

Cybersecurity remains critical as manufacturing faces increasing cyber threats. Blockchain, 3D printing, and AR/VR demonstrate specialized applications with moderate growth. [78]

Table 1 synthesizes the comparative impact of each enabling technology based on adoption metrics and economic benefits.

Table 1: Comparative analysis of key smart industry enabling technologies

Technology	Adoption Rate	Projected Growth	Key Economic Impact	Main Barrier
Artificial Intelligence	29% at the facility level	High (CAGR 23%)	Downtime –30–50%, Maint cost –20–30%	Data quality, skills shortage
IIoT	46%	Steady	Real-time monitoring, energy –10–20%	Connectivity, security
Cloud Computing	+57%	Mature	Infrastructure cost –20–35%	Data residency, latency
Edge Computing	20–25%	High	Latency –80–90%, bandwidth –60–70%	Hardware cost
Digital Twins	6% full capability	Highest	Prototyping cost –40–60%, efficiency +15–25%	High investment
Automation & Robotics	41% top priority	High (CAGR +12%)	Productivity +15–25%, error –80–90%	CAPEX, reskilling
Cybersecurity	Growing	High	Risk mitigation, ransomware prevention	Skills shortage
Blockchain	10–15%	Moderate	Supply chain transparency	Scalability
3D Printing	15–20%	Moderate (CAGR 12–15%)	Material waste –50–70%, time-to-market –30–50%	Material limits
AR/VR	15–20%	Moderate	Training time –30–40%, errors –70–80%	Hardware cost
RFID/NFC	15–20% full integration	High (CAGR 14.2%)	Inventory accuracy +99%, labor saving 15–20%, throughput +5–8%	Tag cost ($0.05–0.30), interference
Sources: iFactory AI (2026) [73], Paszkiewicz et al. (2025) [76], RFID World (2025) [77], Fortune Business Insights (2026) [77].				

No single technology drives smart transformation alone; synergistic integration yields maximum impact. AI and IIoT form the cognitive-sensory core, while digital twins and robotics represent the next frontier. RFID/NFC bridges physical assets with digital systems, providing traceability critical for Industry 4.0. A phased approach prioritizing IIoT and AI delivers the fastest ROI (6–18 months), followed by digital twins and advanced robotics for long-term advantage. Cybersecurity and workforce upskilling remain essential enablers. [74,75,77,78]

3- National Programs for Smartening and Digital Transformation in Industry

Germany is a pioneer in smart manufacturing with its "Industrie 4.0" program, which focuses on integrating digital technologies in production, particularly in the automotive sector. With emphasis on workforce training, Singapore, through its "Smart Nation" program, leverages the IoT and automation in manufacturing and logistics. South Korea, with its "Manufacturing Innovation Strategy 3.0", focuses on IoT, AI, and robotics, and has focused on the establishment of smart factories. France's "Industry of the Future" program concentrates on attracting global talent and fostering innovation through various government programs. Via programs like the "Smart Manufacturing Leadership Coalition (SMLC)", the United States drives private-sector innovation in smart manufacturing. China, with the "Made in China 2025" program, emphasizes automation and intelligent production. India, through its "National Industrial Corridor Development Programme (NICDP)", focuses on industrial automation but faces challenges in research and development. By prioritizing sustainable production, Finland has implemented a "Smart Manufacturing" strategy, excelling in AI and IoT research and development. The Netherlands, with its "Smart Industry" program, uses intelligent technologies to enhance efficiency and test digital solutions. Italy supports digital transformation through its "Intelligent Factories" program. The United Arab Emirates, via "The UAE's Fourth Industrial Revolution (4IR) Strategy", targets robotics and AI in logistics and energy. Malaysia's "Industry4WRD" program emphasizes smart factory development and digital transformation. Finally, Indonesia, with the "Making Indonesia 4.0" program, focuses on integrating digital technologies into automotive and electronics manufacturing. [3,59,65,79-81].

Sweden uses its advanced infrastructure and skilled workforce to emphasize a sustainable, smart industry. Denmark focuses on sustainability and digital transformation, while Japan prioritizes robotics and automation, though it faces challenges in digital adaptation. The United Kingdom is committed to building a robust digital economy and enhancing advanced manufacturing capabilities. Australia has invested in IoT and automation for production, whereas Canada emphasizes the integration of AI and IoT in manufacturing. Lastly, Belgium has channeled investments into automation and digital logistics. [65,80,81].

The following section provides a detailed examination of the programs and initiatives implemented by leading countries in the smart industry and digital transformation. The selection was based on four criteria: (i) level of industrial development (advanced vs. developing), (ii) geographical distribution (Europe, Asia, North America, Middle East), (iii) diversity in governance and economic models, and (iv) variation in population scale and cultural context. This ensures that the derived strategic plan is generalizable across different national conditions.

3-1- Germany

Germany is a pioneer in the smart industry with its "Industrie 4.0" program, which began in 2011, and focuses on integrating digital technologies into manufacturing, particularly in the automotive sector. It has a clear national digital industrial strategy that emphasizes innovation and competitiveness, aiming to integrate advanced digital technologies into production processes. The National Industry 4.0 Strategy focuses on automation, data exchange, and system connectivity through cyber-physical systems (CPS), IoT, and cloud computing. Germany's approach involves extensive collaboration between the government, research institutions, and private companies. They have initiated projects such as "Autonomics for Industrie 4.0" and "Smart Service World," investing significantly in innovation and competitiveness to maintain their global leadership in automation, robotics, and advanced manufacturing. This strategy not only emphasizes technological innovation but also highlights the importance of maintaining Germany's competitive edge in global markets. This, in turn, supports its global leadership in industries such as automotive manufacturing, where precision, quality, and efficiency are crucial. The German government actively funds research and development projects to strengthen the manufacturing industry, particularly in Industry 4.0 technologies. Germany's automotive supply chain relies on small and medium-sized enterprises (SMEs), which generate 85% of the value-added in this industry. These companies, using Industry 4.0 technologies such as automation and the IoT, and with government support, can compete globally. Currently, more than 65% of German manufacturing companies are implementing Industry 4.0 technologies. [12,59,82,83].

3-2- South Korea

South Korea, through its Manufacturing Innovation Strategy 3.0, aims to establish leadership in smart manufacturing technologies, supported by government programs, corporate innovation, and global collaborations. It has adopted AI and automation as core components of its industrial transformation, utilizing smart systems for various applications, including real-time quality control, operational optimization, and predictive maintenance. Leading South Korean companies such as Samsung, LG, Hyundai, and Siemens are actively implementing Industry 4.0 principles and advancing smart manufacturing on a global scale. The South Korean government plays a pivotal role in driving smart manufacturing, allocating significant resources to Industry 4.0 programs and fostering collaboration between research institutions and innovative enterprises. One of the country's flagship projects is the "Smart Factory" program, a public-private partnership aimed at establishing 30,000 smart factories by 2030. To accelerate adoption, the government offers tax incentives and subsidies to companies that adopt sustainable practices and eco-friendly technologies. [14,27,28,84].

3-3- France

France focuses on attracting global talent and strengthening innovation through various government programs such as "Industry of the Future" and "La French Fab." The French government encourages companies to adopt smarter and greener methods by providing subsidies, tax benefits, and research assistance. French companies and research organizations are at the forefront of using smart manufacturing technologies to address specific industrial challenges. Companies benefit from 20% to 30% productivity increases through smart technologies. By prioritizing innovation, sustainability, and human-centered technology, France seeks to transform its industrial landscape and establish a new global standard for the future of manufacturing. It aims to create a more agile, efficient, and sustainable industrial ecosystem in which collaborative robots (cobots), digital twins, and artificial intelligence play key roles. The strategic program "La French Fab" aims to promote resource-efficient technologies such as 3D printing, which reduces material waste, and encourages the adoption of circular economy principles where waste becomes new inputs. Another objective is facilitating energy-efficient operations using AI-based systems that optimize energy consumption. France's smart manufacturing sector is expected to experience exponential growth between 2024 and 2030, driven by technological advancements and strategic investments. [81,85-87].

3-4- The United States

Due to its strong private sector-driven economy, the United States, unlike other countries, lacks a government-led plan for smart industry development. However, the Smart Manufacturing Leadership Coalition (SMLC) program emphasizes private-sector innovations in smart manufacturing. The SMLC is a non-profit, industry-recognized consortium comprising industrial organizations, universities, research and innovation labs, and associations. By sharing successes and challenges related to adopting smart manufacturing technologies and Industry 4.0 digital technologies, the SMLC fosters trusted and beneficial collaborations with like-minded organizations of all sizes. The U.S. aims to double the manufacturing sector's contribution to the economy through smart manufacturing. It has made progress in artificial intelligence, the IoT, and robotics to modernize its industry while emphasizing cybersecurity. Digital twins, collaborative producer-consumer partnerships, remote operations, condition monitoring, and predictive maintenance are other key trends in the U.S. smart industry development. Although the U.S. is home to many leading technology companies, it ranks lower due to the lack of cohesive digital policy frameworks and government support for industrial digitalization. [88-91]

3-5- China

It has focused on smart manufacturing and increased automation with the "Made in China 2025" program. The "Made in China 2025" plan is a national strategy to modernize China's manufacturing capabilities. It emphasizes automation, the use of industrial robots, and the integration of artificial intelligence and the Internet of Things into production processes. The government offers subsidies and tax incentives to enterprises that invest in smart manufacturing technologies, and has established special zones such as smart industrial parks to promote collaboration between them. The program has helped domestic innovation, reduced dependency on imported technologies, and strengthened China's position in high-tech industries. With the improvements of these technologies, it aims to lead in semiconductors, biotechnology, and renewable energy systems. China is the largest market for industrial robots, with a focus on the automotive, electronics, and textile industries. Domestic companies such as Siasun Robotics are also strengthening their position. Using AI algorithms for predictive maintenance and reducing downtime are among the country's major plans. Companies such as Huawei and Baidu have invested in industrial AI platforms. [81]

3-6- India

India's smart industry is making rapid progress under the "National Industrial Corridor Development Programme (NICDP)", a comprehensive program comprising 32 projects across 4 phases in 11 industrial corridors. It is actively embracing Industry 4.0 principles by integrating advanced technologies such as Cyber-Physical Systems (CPS), IoT, cloud computing, and AI, leading to significant improvements in manufacturing productivity and efficiency. India's smart manufacturing perspective is characterized by diverse technological innovations. Leading institutions and companies are at the forefront of incorporating smart manufacturing technologies into their operations. These enterprises are establishing smart factories that utilize interconnected production equipment, logistics systems, and data analytics to optimize manufacturing processes. Major corporations like Tata Motors, Ford, and Honda are pioneering this transformation through their smart factories that employ connected systems, advanced data analytics, and logistics solutions. Simultaneously, small and medium enterprises (SMEs) are gradually adopting Industry 4.0 technologies to enhance their competitiveness and operational efficiency. This widespread adoption across companies of different scales demonstrates India's commitment to industrial modernization through digital transformation. The NICDP serves as the backbone of this nationwide effort, systematically developing the infrastructure and ecosystem needed to support India's growing smart manufacturing sector. The program's phased approach across multiple industrial corridors ensures balanced regional development while creating the necessary physical and digital infrastructure for smart manufacturing. As more companies - both large corporations and SMEs - continue to implement these advanced technologies, India is positioning itself as an increasingly important player in the global smart manufacturing landscape, with particular strengths in the automotive and industrial manufacturing sectors. [60-62]

3-7- Indonesia

Indonesia is currently in the early stages of smart industry development, but it demonstrates significant growth potential. The country is pursuing digitalization and innovation in its manufacturing sector through its "Making Indonesia 4.0" strategy. The smart manufacturing market is projected to grow at an impressive compound annual growth rate (CAGR) of approximately 19.51% from 2023 to 2029, indicating strong future expansion. The government has launched several key programs to drive this transformation, including the ambitious "100 Smart Cities" program and the development of the new capital city, Nusantara, as a model smart city. These projects extensively utilize cutting-edge technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and 5G networks to enhance operational efficiency and enable data-driven decision making across industrial operations. Multiple government agencies play crucial roles in this digital transformation. The Ministry of Communication and Information Technology (Kominfo) leads digital transformation strategies, while the Ministry of Industry focuses on strengthening the manufacturing sector with smart technologies. Additionally, KORIKA (the Artificial Intelligence Research and Innovation Collaboration) conducts vital AI research and development to support smart manufacturing programs. To accelerate its smart industry development, Indonesia has established strategic partnerships with global technology leaders. These include collaborations with Ericsson to advance 5G technology deployment and with the U.S. Trade and Development Agency (USTDA) for smart city projects in Nusantara. [92-97]

3-8- Malaysia

Malaysia is making significant strides in smart industry development as part of its economic transformation under the Fourth Industrial Revolution (Industry 4.0). The country has adopted a comprehensive approach to enhance productivity, improve quality standards, and drive innovation across key industrial sectors, with particular focus on manufacturing. Central to Malaysia's strategy is the establishment of the Smart Manufacturing Experience Center (SIRIM), which serves as a crucial platform for technology transfer, allowing local companies to test and implement Industry 4.0 solutions while providing essential training in advanced manufacturing techniques. Complementing this program is the national Industry4WRD program, specifically designed to boost productivity and quality through the adoption of cutting-edge technologies, including Internet of Things (IoT), artificial intelligence (AI), and advanced automation systems. Looking toward the future, Malaysia has set ambitious targets under its New Industrial Master Plan 2030 (NIMP), which includes attracting foreign investment to support the transformation of 3,000 conventional factories into smart manufacturing facilities by 2030. [50,51,98-101]

3-9- UAE

The smart industry in the UAE is rapidly advancing by integrating advanced technologies and the government’s strategic plans. The country is pursuing innovation, increasing productivity in various sectors, and diversifying its economy by implementing the Fourth Industrial Revolution Strategy and using technologies such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, and robotics. The government is encouraging the adoption of smart technologies in the public and private sectors by establishing institutions such as the UAE Office of Artificial Intelligence and the Smart Dubai Program. For example, the Dubai Health Authority is leveraging AI solutions to enhance healthcare services. Key institutions play an important role in the development of the smart industry in the UAE. The government has established various institutions, such as the UAE Office of Artificial Intelligence and the Smart Dubai Program, which aim to promote the adoption of smart technologies in the public and private sectors. [81,102-105]

3-10- Comparative Impact Analysis of National Smart Industry Programs

The nine national programs examined above demonstrate varying levels of industrial impact. Based on the Industry 4.0 Barometer 2026 by MHP and LMU Munich—surveying over 1,200 industrial companies across seven countries—China leads with an overall digitalization index of 72%, followed by the US (69%), India (68%), and Mexico (67%). In contrast, the DACH region (Germany, Austria, Switzerland) stagnates at 57%, and the UK has declined to 62%. [106,107]

China dominates in robot installations with 295,000 new units in 2024 (7% increase from 2023), accounting for over half of global demand. China also leads in AI adoption (71%), digital twins in logistics (84%), and software-defined manufacturing familiarity (30%). [107,108]

India emerges as a fast-growing adopter with 68% digitalization index, second-highest AI adoption (61%), and 30% SDM familiarity—tied with China. Notably, 71% of Indian companies show a willingness to invest significantly in digital technologies. [107]

South Korea maintains the world's highest robot density, with its smart factory market projected to grow at 10.3% CAGR from 2025 to 2030, targeting 30,000 smart factories by 2030. [109,110]

Germany faces challenges despite its pioneer status. Only 37% of DACH companies have adopted AI (the lowest among surveyed regions), and a mere 3% are very familiar with SDM—willingness to invest stands at only 29%. [106,107]

UAE demonstrates rapid progress with 7.7% manufacturing sector growth in Q1 2025, contributing 13.4% to non-oil GDP through its National Strategy for Industry 4.0 and Operation 300bn. [111] Table 2 synthesizes these comparative metrics.

The comparative analysis reveals three performance clusters. Leaders (China, USA) demonstrate the highest digitalization indices, with China excelling in robot density and AI adoption. Fast-growing adopters (India, South Korea, UAE) show strong momentum—India leads in investment willingness (71%) and SDM adoption, while Korea targets a $10.7B smart factory market by 2030 [c:4][c:5]. Mature but struggling pioneers (Germany, France) face legacy system inertia, with Germany showing concerningly low investment willingness (29%) and AI adoption (37%). Key success factors include government subsidies (Korea, China), strategic industrial policy (UAE's Operation 300bn), and overcoming technical debt (Germany's primary challenge). [106-108,110,111]

Table 2: Comparative analysis of national smart industry programs

Country	Program	Digitalization Index	Key Impact Metric	Investment Willingness
China	Made in China 2025	72%	295k new robots (2024), 71% AI adoption	High
USA	SMLC	69%	57% AI adoption	59%
India	NICDP	68%	30% SDM familiarity, 61% AI adoption	71%
Germany	Industrie 4.0	57% (DACH)	97% use ≥1 I4.0 tech, 45% digital twins	29%
South Korea	Manuf. Innovation 3.0	—	Smart factory market: $5.9B→$10.7B by 2030	High
UAE	4IR Strategy	—	7.7% manuf. growth (Q1 2025), 13.4% non-oil GDP	High
France	Industry of the Future	—	WEF Lighthouse site (Schneider Electric)	Moderate
Sources: MHP/LMU Industry 4.0 Barometer 2026, IFR World Robotics 2025, Grand View Research, Economy Middle East. [106-108,110,111]				

4- Global Approaches to Industrial Smartening and Digital Transformation

For a better understanding of the necessity of smartening and digital transformation in industry, this section examines the implementation of these concepts in three major industries: pharmaceuticals, chemicals, and clothing. It also analyzes the strategies and models adopted by leading countries in advancing smartening and digital transformation in these sectors. The three industries were selected due to their broad industrial coverage, high economic impact across both developed and developing countries, availability of detailed and reliable data on smartization efforts in leading nations, and the presence of significant documented achievements and lessons learned in these sectors.

4-1- Smartening and Digital Transformation in the Pharmaceutical Industry

China, the United States, the European Union, and India — as some of the world's largest pharmaceutical producers — each have specific strategies for developing this industry through smartening and digital transformation.

4-1-1- China's Model for Smartening and Digital Transformation in the Pharmaceutical Industry

China has a specific plan for smartening and digital transformation in the pharmaceutical sector, which is based on government incentives and infrastructure development. Through initiatives such as *Made in China 2025*, the Chinese government supports innovation in biopharmaceuticals. These efforts have reduced Legal obstacles and turned China into an attractive hub for AI-based drug research and development. AI-related academic programs at universities are also helping to address the shortage of specialized interdisciplinary talent in this field. Investment in AI-driven drug discovery has surged, and companies like **XtalPi** and **Hengrui Pharmaceuticals** have secured significant funding to strengthen their capabilities. Below are examples of how China has benefited from smartening and digital transformation in the pharmaceutical industry:

1. Use of Artificial Intelligence in Drug Discovery
Insilico Medicine, a leading company in AI-based drug discovery, has significantly reduced the drug development timeline using AI tools such as *PandaOmics* and *Chemistry42* to identify drug targets and generate new molecules. By analyzing vast genetic and clinical datasets, AI models predict drug efficacy and safety more effectively than traditional methods. These tools have also identified new targets and optimized drug candidates, leading to faster and more cost-effective research and development. [112]

2. Use of Artificial Intelligence in Clinical Trials:
AI is used to quickly identify eligible patients and diversify clinical trial populations. Real-time monitoring improves data accuracy and regulatory compliance, addressing common challenges of traditional methods. Collaborations between AI startups and pharmaceutical giants—such as the partnership between Insilico Medicine and Fosun Pharma—highlight the growing role of AI in developing innovative treatments, such as cancer immunotherapies. [113]

4-1-2- The European Union's Model for Smartening and Digital Transformation in the Pharmaceutical Industry

The Horizon Europe program plays a key role in accelerating pharmaceutical research and development, prioritizing projects focused on personalized medicine and innovative drug delivery systems. This program, through substantial public funding and innovation initiatives, facilitates collaboration between universities, technology firms, and the pharmaceutical industry. These efforts aim to tailor treatments more precisely to patient needs while minimizing environmental impacts. Another key initiative is the Digital Product Passport of the European Union, designed to integrate digital traceability capabilities in industries. It provides consumers and regulators with complete information on a product's life cycle, including its environmental footprint. The following are large-scale examples of how the EU has utilized smartening and digital transformation in the pharmaceutical sector:

1. Blockchain for Tracking in the Drug Production and Distribution Chain:
The European Union has mandated the use of blockchain technology to enhance traceability in the production and distribution of pharmaceuticals. This technology ensures that every stage of the supply chain is recorded in an immutable ledger, thereby reducing the risk of counterfeit drugs entering the market. Blockchain not only guarantees the authenticity of pharmaceutical products but also facilitates compliance with strict EU regulations, such as the *Falsified Medicines Directive*. Pharmaceutical companies utilize blockchain to improve patient safety, increase transparency, and streamline product recall processes. For example, blockchain is increasingly being integrated with Internet of Things (IoT) devices for real-time monitoring, ensuring that temperature-sensitive products, such as vaccines, maintain their efficacy during transportation. [114]

2. Sustainable Manufacturing Practices
The European Union is a global leader in adopting sustainable manufacturing technologies in the pharmaceutical sector. These green initiatives include transitioning to energy-efficient processes, using renewable energy sources, and designing eco-friendly packaging. For instance, companies in Germany and the UK have invested in technologies that reduce carbon emissions and implement waste recycling. European pharmaceutical firms have also aligned with the *European Green Deal* and adopted *Extended Producer Responsibility (EPR)* policies. These initiatives require manufacturers to consider the full life cycle of their products—from design to disposal—and promote circular economy principles. Additionally, some companies are employing advanced bioprocessing methods that replace costly chemical processes with sustainable biological alternatives. [115]

4-1-3- India's Model for Smartening and Digital Transformation in the Pharmaceutical Industry

India's pharmaceutical sector, traditionally reliant on manual processes, is rapidly adopting advanced automation technologies to enhance productivity and regulatory compliance. This transformation includes the implementation of robotic systems, industrial IoT, and automation software such as Manufacturing Execution Systems (MES). Through continued integration of automation and data analytics, India is strengthening its position as a global pharmaceutical hub. Enhanced collaboration between the IT and pharmaceutical sectors, supported by policy reforms, is expected to accelerate these developments. Furthermore, India is leveraging its IT capabilities to introduce predictive analytics and big data tools into pharmaceutical workflows. To address challenges, the Indian government has launched initiatives such as *Pharma Vision 2020*, which focuses on enhancing global competitiveness, fostering innovation in drug discovery and manufacturing, and encouraging public-private partnerships to bridge technological gaps. Below are examples of how India is utilizing smart tools and digital transformation in the pharmaceutical industry:

1) Cold Chain Management:
For temperature-sensitive biologics, automation with IoT sensors enables seamless logistics management by monitoring storage and transportation conditions in real time, minimizing the risk of product spoilage. [116]

2) Industrial Implementation:
Leading pharmaceutical companies in India are integrating smart sensors and AI-based robotics to streamline operations and align with global compliance standards such as FDA and EMA regulations. [117]

3) Supply Chain Optimization:
By integrating analytics, pharmaceutical companies are reducing delivery times and responding dynamically to market demand. Tools like Enterprise Resource Planning (ERP) systems help unify resource management and improve operational efficiency. [118]

4) Innovation in R&D and Drug Discovery:
Analytical platforms facilitate faster identification of potential treatments and improved clinical trial outcomes by predicting success rates. Data analytics also aids drug discovery by analyzing genetic, clinical, and molecular data to identify new drug candidates. [119]

4-1-4- Smartening and Digital Transformation in the U.S. Pharmaceutical Industry

The U.S. pharmaceutical industry is a global leader in smartening and digital transformation. The following are some notable applications of these technologies in American pharmaceutical companies:

1) Decentralized Clinical Trials:
The U.S. pharmaceutical industry is at the forefront of adopting decentralized clinical trials, utilizing technologies such as artificial intelligence, blockchain, and telehealth to modernize trial methodologies. Wearable devices and remote monitoring tools enable real-time data collection, significantly improving patient access and their interaction with tests. These innovations have been particularly effective in expanding trial participation among underrepresented populations and generating diverse datasets. Recent studies show that decentralized trials can reduce costs by 30–40% and accelerate timelines. Companies like Medable use AI-powered tools to enhance recruitment and monitoring, optimizing the overall process. [120]

2) Supply Chain Automation
Automation in the U.S. pharmaceutical supply chain is critical, especially for biologics and vaccines requiring cold chain logistics. IoT devices are widely used for temperature and environmental monitoring, minimizing spoilage risks during distribution. RFID technology combined with AI enables real-time inventory tracking, increases transparency, and reduces waste. Advanced analytics also support supply chain management by forecasting demand and optimizing production schedules, thereby improving overall efficiency. These technologies proved essential during COVID-19 vaccine distribution, where companies like Pfizer used them to scale up production and enable rapid delivery. [121]

3) Personalized Medicine
Predictive analytics and machine learning have revolutionized personalized medicine in the United States. By analyzing genomic data and patient health records, pharmaceutical companies can develop treatments tailored to individual patients. This approach has been particularly effective in advancing oncology treatments, such as targeted cancer therapies, and in accelerating vaccine development. For instance, the rapid development of Moderna's mRNA COVID-19 vaccine was largely enabled by computational models that predicted protein structures and immune responses. These technologies are now being applied more broadly to rare genetic disorders and immunotherapies. [122]

4) Regulatory Compliance
Automation plays a vital role in ensuring compliance with the FDA's stringent standards. Robotic Process Automation (RPA) and AI-based quality control systems ensure adherence to Good Manufacturing Practices (GMP) and detect anomalies in production processes. Natural Language Processing (NLP) tools are used to monitor drug side effects and ensure post-market surveillance compliance. [123]

4-2- Smartening and Digital Transformation in the Chemical Industry

The United States, Germany, and China are leading in smartening and digital transformation within the chemical industry. Germany leverages modular production and digital technologies to maintain its competitive edge and global market leadership. The smart chemical industry in the United States is defined by the integration of advanced technologies and innovative practices aimed at improving efficiency, sustainability, and safety in chemical production and application. Meanwhile, China is making substantial investments in digital transformation to enhance its global competitiveness in the chemical sector. Below are some of the most significant applications of emerging technologies in smartening the chemical industry:

1) Automation and Artificial Intelligence
Automation and AI technologies are revolutionizing chemical manufacturing by optimizing processes, predicting maintenance needs, improving product quality through analysis of vast datasets, reducing human error, increasing productivity, and enabling more efficient operations. [124]

2) Digitalization and Data Analytics
Industrial Internet of Things (IIoT) is used to create smart and connected facilities that allow for real-time monitoring and data-driven decision-making, enhancing supply chain flexibility and operational agility. [125]

3) Sustainable Practices
There is a strong emphasis on green and sustainable chemistry, aimed at minimizing environmental impact through processes that reduce or eliminate hazardous materials. This includes innovations such as bioremediation and the development of Safe and Sustainable by Design (SSbD) chemicals. [126]

4) Advanced Materials and Nanotechnology
Nanotechnology and advanced materials are being used to create products with enhanced functional properties for a wide range of applications, from coatings to drug delivery systems and sustainable packaging solutions. [127]

5) Carbon Capture and Circular Economy:
Carbon Capture and Utilization (CCU) technologies convert CO_2 emissions into valuable products. This aligns with the broader trend toward circularity in the chemical industry, where waste is minimized and resources are reused. [128]

6) Modular Production
Modular automation technologies simplify engineering processes, provide flexibility in production, allow for rapid adaptation to market demands, and reduce time-to-market for new products. [129]

4-2-1- Germany's Model for Digital and Smart Transformation in the Chemical Industry

By utilizing modular production and digital technologies to maintain its competitive edge and leadership in the global market, Germany's smart chemical industry stands at the forefront of technological innovation. Key institutions driving development, innovation, and smart transformation in Germany's chemical industry include:

1) Fraunhofer-Gesellschaft
A leading applied research organization comprising 76 institutes, focusing on various technological advancements within the chemical sector. [130]

2) Technical University of Berlin
Home to the Chemical Invention Factory, which fosters the transformation of research outcomes into innovative chemical startups. [131]

3) German Electrical and Electronic Manufacturers' Association (ZVEI)
Plays a crucial role in promoting the concepts of modular production and automation technologies. [80]

4-2-2- The United States Model for Digital and Smart Transformation in the Chemical Industry

The smart chemical industry in the United States is defined by the integration of advanced technologies and innovative practices aimed at improving efficiency, sustainability and safety in the production and application of chemicals. This sector is increasingly adopting digitalization and automation to optimize processes, reduce environmental impacts, and enhance product quality. Leading companies such as Smart Chemical Solutions and SMART CHEM offer advanced chemical formulations and comprehensive services to boost operational efficiency and monitor environmental compliance. Key institutions that play a crucial role in the development, innovation, and smart capabilities of the chemical industries in the United States include:

1) Research Institutions
Universities and research organizations such as ETH Zurich and the Lawrence Berkeley National Laboratory are conducting advanced studies in chemical engineering and materials science that contribute to technological advancements in the industry. [132]

2) Industry Associations
Organizations like the American Chemical Society and the American Chemistry Council provide resources, advocacy, and networking opportunities for companies in the sector. [133]

3) Government Agencies
The Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA) regulate chemical production practices and ensure environmental safety and compliance, which are critical for the industry's sustainable growth. [134]

4-2-3- China's Model for Digital and Smart Transformation in the Chemical Industry

China's smart chemical industry is at a pivotal point, characterized by the integration of advanced technologies and a focus on sustainability. This country is poised to enhance its global competitiveness in the chemical sector through significant investments in research and development and collaboration among various institutions. The development of smart chemical industrial parks is a notable trend in China. These parks are designed to integrate various smart technologies to create sustainable and efficient chemical production environments. They focus on reducing waste and energy consumption while enhancing productivity. It is predicted that China's chemical industry will account for more than half of global chemical market growth over the next decade, highlighting its increasing importance in the global supply chain.
Key institutions involved in the development, innovation, and smart transformation of China's chemical industry include; [135,136]

1) Shanghai Research Institute of Chemical Industry
This institute focuses on research and development in chemical processes and materials, collaborating with industry players to enhance innovation. [137]

2) China National Chemical Corporation (ChemChina)

As one of the largest chemical companies in China, ChemChina is deeply engaged in integrating smart technologies into its operations and has been a leader in adopting AI and IoT solutions. [136]

3) Universities and Research Institutions
Many universities collaborate with chemical companies to advance innovation. For example, partnerships with institutions such as Tsinghua University and Zhejiang University focus on the development of new materials and sustainable chemical processes. [137]

4-3- Digital and Smart Transformation in the Clothing Industry

The United States, Germany, China, Japan, and South Korea are the leading countries in adopting smart clothing technologies. The United States represents the largest market for smart garments. Due to its technological advancements and the growing market for health-related smart textiles, Germany stands out. China is rapidly expanding its market through increasing investments in technology and a large consumer base interested in health monitoring. For their technological innovation and early adoption of wearable technologies, Japan and South Korea are well known. Some of the most significant applications of emerging technologies in the smart transformation of the clothing industry are as follows:. [40-46,138-140] [124]

1) Smart Manufacturing and Digitalization
Companies such as Nike and Levi's utilize artificial intelligence (AI) and the Internet of Things (IoT) to monitor production, predict demand, reduce waste, and ultimately achieve more accurate and efficient clothing manufacturing. [141]

2) 3D Printing
Firms like Nike, Adidas, and Hugo Boss employ AI and 3D printing technology for custom clothing design and production, optimizing manufacturing processes, reducing costs, and accelerating production. [142]

3) Circular Models and Recycling
German companies such as Adidas adopt circular economy models in clothing production to reduce waste and use recycled materials. Nike employs its Flyknit digital knitting technology to produce footwear while reducing raw material usage by up to 60%. [143]

4) Robotics and Automation
Robots are increasingly used in the clothing industry to enhance the speed and accuracy of manufacturing processes, enabling both mass production and customized output. [144]

5) Enhancing Customer Experience with Augmented Reality (AR)
By using AR technology, German stores provide virtual fitting rooms for customers to try on clothing virtually. [145]

6) Laser Technology
Companies such as Levi's have replaced traditional chemical processes with laser technology to shorten production times and reduce water and chemical usage. [146]

7) Smart Clothing
Garments embedded with sensors for health monitoring, fitness tracking, and energy generation through user movement are being increasingly developed. [147]

8) Smart Supply Chain Management
Levi's employs digital systems to manage its entire supply chain in real-time, enabling reduced delays in raw material sourcing and faster production. [34–40, 106–108] [148]

4-3-1- China's Model for Digital and Smart Transformation in the Clothing Industry

The deeper integration of digital and smart technologies into production lines is helping China maintain its position as a global leader in the clothing industry. China's advancements in smart clothing are rapidly evolving through the collaboration of key institutions and companies:

1) China Textile Information Center (CTIC)
Plays a pivotal role in advancing the digital transformation of the textile industry. CTIC supports factories in adopting modern technologies such as artificial intelligence (AI) and production automation by offering expert guidance and insights [149].

2) China National Textile and Clothing Council (CNTAC)
Leads extensive collaborations to promote the adoption of smart technologies and the implementation of sustainable practices throughout the industry. It also works with manufacturers and government bodies to align industry standards with international benchmarks [150].

3) Leading Textile Companies
Factories under groups like Dasheng Jiangsu exemplify the use of smart technologies to optimize production, enhance quality control, and reduce waste. Shandong Ruyi Technology Group has also improved its production efficiency and responsiveness to diverse customer needs through the use of predictive maintenance and smart logistics systems [151].

4) Research Institutes and Universities
Institutions such as Donghua University are active in textile engineering and smart materials research, contributing to the advancement of sustainable and intelligent technologies in the clothing industry [152].

5- Strategic Plan for Implementing Smart Industry

The vision of this strategic plan is to enable countries to build smart industries based on Industry 4.0 principles, enhancing both the quality and quantity of production while creating competitive advantages in domestic and international markets. Naturally, achieving such a goal requires a national roadmap for digital transformation and industrial digital and smart transformation. In this regard, the following strategies are essential: [153]

1) Special support for tripartite collaboration among government, private sector, and academic/research institutions to foster shared understanding and synergy in knowledge and capabilities for implementing smart industry:

- Establishing specialized associations in the smart industry to connect government entities, private companies, and academic institutions
- Providing financial support for research institutions through examination of the industry challenges and offering smart solutions
- Organizing necessary events and training programs for industries by scientific and research institutions.
[154,155]

2) Promoting a culture of digital transformation and smartening in industry:

- Hosting public events and forums
- Facilitating connections between industry leaders and research institutions
- Preparing educational content and documentation
- Sending industry leaders, managers, and researchers on international visits to learn from advanced smart industries and transfer the experience domestically.
[154,156]

3) Providing a national government strategy to support a circular and sustainable economy aimed at waste reduction and environmental protection:

- Developing and issuing relevant circulars and guidelines
- Offering specific incentives for the implementation of government environmental policies
- Delivering training for industries on circular economy principles.
[156]

4) Developing the necessary IT infrastructure through industrial smart transformation projects:

- Coordinating with key stakeholders such as the Ministry of Communications, the Budget and Planning Organization, the Ministry of Science, etc., to create the required infrastructure
- Reducing and eliminating the digital divide between cities, urban areas, and different industries across the supply chain.
[154]

5) Government financial support for industries—especially small and medium-sized enterprises (SMEs)—to implement smart technologies.

- Offering financial facilities
- Providing financial incentives for infrastructure development
- Tax exemptions and other supportive policies
- Facilitate and regulatory reform.
[154]

6) Establishing dedicated smart industry zones and corridors.

- Creating special industrial parks for the smart industry
- Designating zones or corridors focused on the smart industry within the country.
[157]

5-1- Scope and Limitations of the Proposed Plan

The strategic plan presented in this section is derived from a systematic comparative study of successful national smart industry programs (Section 3) and smartization efforts in three industries – chemicals, pharmaceuticals, and apparel (Section 4). Quantitative evidence supporting the effectiveness of these programs, including digitalization indices, AI adoption rates, robot installations, and investment willingness, has been provided in Section 3-10 and Table 2.

The proposed plan provides a structured strategic roadmap rather than a detailed implementation manual. Specific implementation indicators and numerical thresholds depend heavily on the adopter's maturity level, industrial sector, and national context. While reference indicators (based on ISO 22400 and SIRI standards) and a cost-benefit analysis have been provided as guidance, adopters are encouraged to calibrate these thresholds during a pilot implementation phase before full-scale rollout.

Future research should focus on empirical validation of the proposed framework through case studies in diverse industrial and national contexts.

6- Conclusions

Smartening and digital transformation in industry are key components and competitive advantages for optimal and effective production and leadership in global markets. To achieve this, a detailed and coherent plan is necessary that can address the challenges along the way and support the industry in reaching its goals. Examining the experiences of leading countries and industries in this field can be highly effective in creating such a plan. This article presents an operational plan for smartening and digital transformation in developing countries, drawing from these valuable experiences. Implementing this plan can greatly accelerate the achievement of desired goals while overcoming challenges in the development of the digital industry.

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