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High Robotization as a Foundation for Smart Industry: The Republic of Korea and Singapore as Exemplars of Future Industrial Development

Isak Karabegović

Academy of Science and Arts of Bosnia and Herzegovina, 71000 Sarajevo, Bosnia and Herzegovina; isak1910@hotmail.com

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Abstract: Industry 4.0 marks a new phase of industrial transformation, driven by the integration of advanced technologies such as industrial robotics, the Internet of Things (IoT), artificial intelligence (AI), cloud computing, and cyber-physical systems (CPS). The Republic of Korea and Singapore are global frontrunners in this domain, ranking first and second worldwide in robot density per 10,000 manufacturing workers. This paper explores how the strategic integration of robotics with key Industry 4.0 technologies contributes to smart manufacturing and enhanced industrial performance. Using a comparative case study approach, the research analyzes national policies, investments in R&D and education, 5G infrastructure, and support for innovation ecosystems that have enabled these countries to develop flexible, automated, and intelligent production systems. Findings indicate that both Korea and Singapore have successfully combined robotics with IoT, big data analytics, and cloud platforms to create efficient and adaptive manufacturing environments. The study emphasizes that robotization alone is not sufficient; its effectiveness depends on alignment with broader digital transformation strategies. Based on longitudinal data from 2013 to 2023, sourced from the International Federation of Robotics (IFR), the OECD, and national innovation agencies, the research highlights how coordinated implementation of Industry 4.0 technologies fosters sustainable and globally competitive manufacturing.

Keywords: Industry 4.0; Robotization; Smart Factory; Republic of Korea; Singapore

1. Introduction

The emergence of Industry 4.0 signifies a transformative shift in global manufacturing, marked by the convergence of digital technologies and cyber-physical systems that enable autonomous, adaptive, and highly efficient production environments. Key components of this transformation include industrial robotics, the Internet of Things (IoT), artificial intelligence (AI), big data analytics, cloud computing, and intelligent automation systems [1–3]. The Republic of Korea and Singapore stand out as global leaders in technological implementation, ranking first and second worldwide in terms of robot density per 10,000 manufacturing workers. This study seeks to answer the following research question: *To what extent have high levels of robotization, in synergy with key Industry 4.0 technologies, contributed to positioning Republic of Korea and Singapore as prototypes of the smart industrial future?* These figures not only reflect a high degree of automation but also indicate a strategic commitment to integrating Industry 4.0 technologies within national industrial ecosystems. The Republic of Korea's Smart Factory initiative, launched in 2014, aimed to modernize manufacturing through collaborative public-private investment, resulting in over 8000 companies implementing smart systems by 2018 [4]. Singapore, in parallel, embedded smart manufacturing into its broader "Smart Nation" agenda, leveraging AI, 5G, and advanced analytics to transform industrial capabilities [5–7]. Smart factories enabled by Industry 4.0 rely on data-driven operations, where big data and cloud computing support real-time decision-making, predictive maintenance, and the customization of production [8]. This integration supports the shift from rigid, linear production models to flexible, intelligent manufacturing ecosystems. As Derigent et al. argue, such systems align with holonic architectures that enable decentralized and cooperative decision-making in complex environments [9]. Despite these advancements, the path to full digital integration is not without challenges. Issues such as cybersecurity, interoperability, workforce reskilling, and regulatory frameworks must be addressed to ensure a sustainable and inclusive industrial transformation [10]. This paper examines how high levels of robotization, in synergy with other Industry 4.0 technologies, have positioned the Republic of Korea and Singapore as prototypes of the smart industrial future. By analyzing institutional strategies, technological infrastructures, and innovation ecosystems, the study aims to highlight key lessons for emerging economies seeking to modernize their manufacturing sectors. The remainder of the paper is structured as follows: Section 2 provides a theoretical and conceptual background by reviewing relevant literature on robotics, automation, and smart industry. Section 3 presents the research methodology, including data sources and analytical techniques. Sections 3.2 and 3.3 offer a detailed comparative analysis of industrial robotization in the Republic of Korea and Singapore, respectively. Section 4 discusses the key similarities and differences between the two countries, proposes a conceptual framework, and outlines policy lessons for developing countries. Finally, Section 5 concludes the study by summarizing the main findings, implications, and recommendations for future research and practice.

Globally, Industry 4.0 represents a paradigm shift in manufacturing by enabling connectivity, automation, machine learning, and real-time data processing. Leading industrial economies, including Germany, Japan, and the United States, have restructured their industrial strategies around this concept to remain globally competitive. This paper situates the Republic of Korea and Singapore within this global movement, aiming to draw comparative insights. The block diagram below summarizes the main contributions of this study in a visual format **Figure 1**.

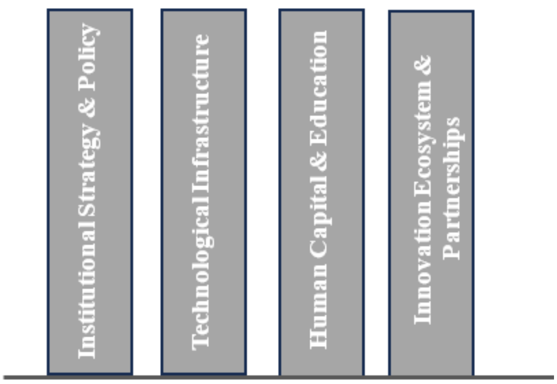


Figure 1. Key Contributions of the Study.

2. Literature Review

2.1. Concept and Characteristics of Robotics in Industry

Robotics in manufacturing has evolved to become a core component of modern production systems, particularly in the context of the Fourth Industrial Revolution (Industry 4.0), where digital technologies seamlessly integrate with physical manufacturing processes. As defined by ISO 8373:2012, an industrial robot is "an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, used for industrial applications" [11]. Robotics facilitates the automation of tasks such as material handling, assembly, and machining, with widespread use across various sectors, including automotive, electronics, and pharmaceuticals [12]. A key advantage of industrial robots is their ability to perform repetitive and hazardous tasks with precision, thereby reducing reliance on human labor and mitigating risks in dangerous environments. The high repeatability and accuracy offered by robotic systems are critical in industries where precision is paramount, such as in assembly, welding, painting, and packaging processes. Recent developments in robotics, as reported by Héraud et al., have introduced

AI and machine learning technologies, enabling robots to adapt more easily to complex production environments and perform more sophisticated tasks [13]. Unlike traditional automation systems, modern robots are equipped with sensors and adaptive algorithms that allow them to detect and respond to changes in their surroundings. This enhanced flexibility enables them to handle a wider range of tasks requiring high precision, such as object recognition and delicate assembly operations [13]. When integrated into manufacturing systems, robots lay the foundation for smart factories that leverage real-time data to optimize workflows and improve overall efficiency [14]. Furthermore, industrial robots are increasingly connected to Internet of Things (IoT) technologies, creating a network of smart devices that collaborate within the manufacturing environment. This connectivity facilitates full automation, reduces human involvement, and enhances process control and data-driven decision-making, leading to greater productivity and lower operational costs [2,15–17]. Recent advancements also include anomaly detection using knowledge-constrained deep clustering and object recognition through multimodal sensor fusion in manufacturing [18,19].

2.2. Automation, Robotics, and Smart Industry: A Comparative Analysis

The terms automation, robotics, and smart industry are often used interchangeably, but they represent distinct concepts with unique applications. Automation refers to the use of technology to perform tasks with minimal human intervention, utilizing mechanical, electrical, and computational systems to enhance efficiency and consistency. It is primarily applied to repetitive, high-volume tasks such as material handling, packaging, and basic assembly operations [20]. Robotics, by contrast, represents a more advanced form of automation, wherein industrial robots are used to perform complex physical tasks that demand greater flexibility and adaptability. Unlike traditional automated systems, robots can handle tasks such as object detection, assembly, and precise manipulation. Ghadge and Arya highlight the role of robotics in improving manufacturing flexibility, enabling industries to quickly adjust to changing customer demands and evolving production needs [21]. Robotics, therefore, serves as a critical enabler of modern, adaptable production environments. Smart industry, or Industry 4.0, transcends traditional automation and robotics by incorporating advanced digital technologies such as IoT, artificial intelligence (AI), and big data analytics. These technologies enable seamless communication between machines, humans, and systems in real time, allowing for greater operational flexibility, optimized production processes, and the development of autonomous decision-making systems. As a result, smart industry represents a paradigm shift in manufacturing, focusing on product personalization and reduced operational costs [22].

2.3. The Role of IoT, AI, and Big Data in Smart Industry

The advent of smart technologies like IoT, AI, and big data analytics has been a game-changer for modern manufacturing. These technologies allow for the creation of interconnected, intelligent systems that collect, analyze, and act on data in real time, thereby improving operational efficiency and increasing the flexibility of production processes. The IoT enables machines and devices within the manufacturing environment to communicate and share data, creating a fully integrated digital ecosystem. According to Lasi et al., IoT allows for real-time monitoring of machine performance, enabling predictive maintenance and minimizing downtime [23]. By using a range of sensors to gather data on factors like temperature, speed, and vibration, manufacturers can gain deeper insights into their operations, leading to smarter decision-making and reduced reliance on human intervention. Artificial intelligence plays a pivotal role in smart manufacturing by empowering robots and machines to make data-driven decisions. As noted by Sustersic et al., AI algorithms allow manufacturing systems to recognize patterns, adapt to changing conditions, and improve the accuracy of operations [24]. This adaptive capacity is crucial in dynamic manufacturing environments, where conditions may change rapidly and systems must adjust accordingly. Big data analytics supports the efficient functioning of smart factories by enabling the collection and analysis of vast amounts of data generated during the production process. These data are used to make informed decisions that optimize manufacturing workflows, enhance product quality, and streamline supply chains. Additionally, big data enables predictive analysis, helping manufacturers anticipate market trends and adjust production strategies in line with changing consumer demands. The integration of big data, AI, and IoT within smart factories creates highly optimized, autonomous manufacturing systems that can improve both efficiency and competitiveness on a global scale. Zeng et al. [25] highlight the synergistic potential of combining fuzzy logic controllers, digital twins, and neural networks to enhance system-level control and real-time optimization—pointing toward future directions in smart manufacturing design. Advanced AI-based energy management, such as intelligent EV charging in microgrids, exemplifies how smart control systems further integrate with industrial robotics [26].

2.4. Theoretical Foundations Supporting Smart Industry Transformation

In addition to technological and institutional aspects, the transformation toward Industry 4.0 must be understood through relevant theoretical frameworks that explain how innovations spread and take root within national systems [24]. Two frameworks are particularly useful in supporting the arguments of this study:

- *Technology Diffusion Theory* [27]: This theory explains how, why, and at what rate new technologies spread through cultures and economies. It helps contextualize the adoption of robotics and Industry 4.0 technologies in the Republic of Korea and Singapore as part of a deliberate innovation process driven by institutional support, early adopters (e.g., large manufacturers), and enabling infrastructure.
- *National Innovation Systems (NIS)*: This framework emphasizes the importance of the interactions between institutions (government, academia, industry) in fostering technological development. The comparative analysis of the Republic of Korea and Singapore shows how cohesive NIS models—through coordinated investments, R&D strategies, and innovation policy—lead to high levels of technological integration.

These frameworks provide a theoretical grounding for the study's conceptual model (Section 4.3), offering a lens to interpret how robotization, when embedded in a supportive policy and innovation environment, leads to sustained smart industrial growth.

3. Research Methodology

3.1. Research Methodology: A Structured Approach Based on Saunders' Research Onion

This study employs a structured research methodology inspired by Saunders et al.'s "research onion" framework. The approach provides a transparent and systematic explanation of the underlying research process. The layers are elaborated as follows:

- *Research Philosophy – Pragmatism*:
  The research combines objective statistical indicators with context-sensitive interpretation, allowing the derivation of actionable lessons for emerging economies.
- *Approach – Deductive*:
  The study begins with established theoretical assumptions about the role of robotization in Industry 4.0 and tests them against the empirical realities of the Republic of Korea and Singapore.
- *Strategy – Comparative Case Study*:
  The focus is on two leading countries—The Republic of Korea and Singapore—whose industrial transformation provides rich comparative material.
- *Choice – Quantitative Monomethod*:
  The study relies on quantitative analysis of secondary data from reputable international sources, without direct surveys or interviews.
- *Time Horizon – Longitudinal*:
  The analysis covers a ten-year period (2013–2023), enabling the identification of trends and structural shifts.
- *Data Collection and Analysis Techniques*:
  Data were collected from publicly available databases of the International Federation of Robotics (IFR), the OECD, UNESCAP, and national agencies. The analysis included:
  - Descriptive statistics (e.g., robot density, annual installations),
  - Trend analysis across time series,
  - Sectoral breakdown by industry (automotive, electronics, etc.),
  - Cross-country comparison visualized through graphs and charts.

The diagrams that follow (**Figures 1–7**) illustrate the results of this analytical process, supporting the central findings of the study.

3.2. Industrial Robotization in Republic of Korea

3.2.1. Republic of Korea's Position as a Leader in Industrial Robotics

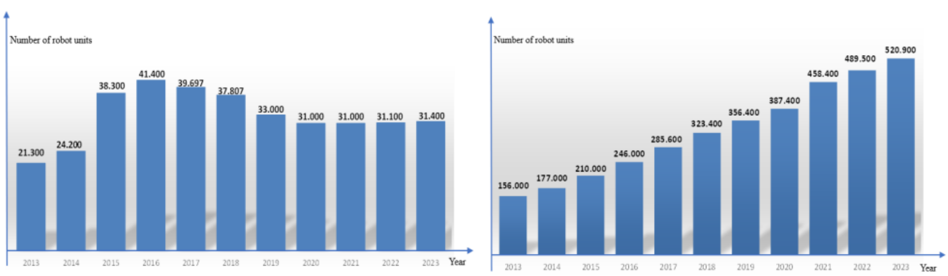
The Republic of Korea is internationally recognized as a frontrunner in industrial robotics, particularly in terms of robot density. According to data from the International Federation of Robotics (IFR), the country consistently ranks among the highest in robot density, boasting over 900 industrial robots per 10,000 workers in manufacturing. This achievement is a direct result of the Republic of Korea's robust adoption of robotic technologies across various sectors, including automotive, electronics, and semiconductors [28]. The country's success in robotics is attributed to its commitment to driving automation through both government-backed initiatives and private-sector investments. As reported by the Korea Institute for Industrial Economics and Trade (KIET), the Republic of Korea's manufacturing industry leverages robotic solutions to boost productivity, ensure quality consistency, and minimize labor costs, which, in turn, strengthens the country's competitiveness in the global market [29,30]. Furthermore, the Republic of Korea's industrial strategy emphasizes the integration of robotics with emerging technologies such as AI, IoT, and big data, fostering the creation of "smart factories" that optimize production systems [14].

3.2.2. Policies and Strategic Support for Robotics

Recognizing the transformative potential of robotics, the Republic of Korea government has implemented various strategies to foster the growth of industrial robotics. Chief among these is the "Smart Manufacturing Innovation Roadmap", a government initiative that supports the widespread integration of robotics and automation technologies across industries. The roadmap outlines funding for research and development (R&D), subsidies for small and medium-sized enterprises (SMEs), and efforts to strengthen the nation's infrastructure for advanced manufacturing technologies [31]. In addition, financial incentives such as tax breaks and subsidies for companies investing in robotic systems have been integral to accelerating automation. The "Robotization Promotion Program" is a notable initiative, offering financial support to companies adopting industrial robots, implementing automation, and developing collaborative human-robot work environments [16]. These efforts align with the government's vision of enhancing industrial productivity, reducing operational costs, and positioning the Republic of Korea as a global leader in advanced manufacturing. Moreover, the government has invested in workforce development programs, providing specialized education and training in robotics, AI, and smart manufacturing. This ensures the availability of a highly skilled labor force capable of supporting the nation's growing robotics industry and adapting to the evolving demands of smart production environments [32–34].

3.2.3. The Trend of Implementation of Industrial Robots in the Republic of Korea

The analysis of industrial robot implementation trends in the Republic of Korea was conducted using statistical data provided by the International Federation of Robotics (IFR), the United Nations Economic Commission for Europe (UNECE), and the Organisation for Economic Co-operation and Development (OECD). The annual deployment trends, as well as the cumulative number of industrial robots in use, are illustrated in the following diagrams. **Figure 2** presents the yearly and total implementation of first- and second-generation industrial robots over the past decade [35–39].

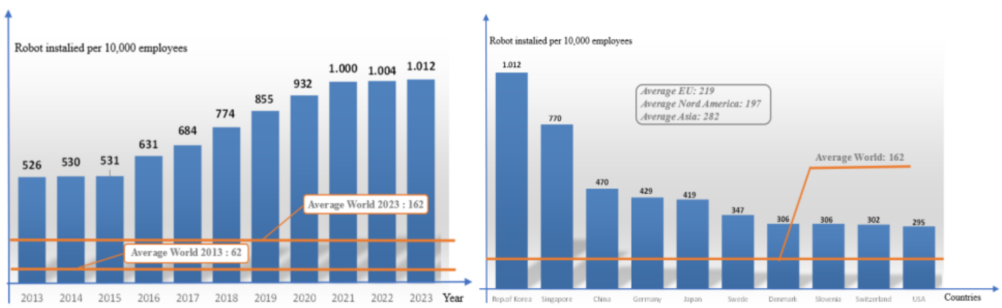


(**a**) (**b**)

Figure 2. Diagram of annual (**a**) and total (**b**) industrial robot implementation in the Republic of Korea for the period 2013–2023.

By analyzing the diagram presented in **Figure 2a**, which illustrates the annual deployment of industrial robots in the Republic of Korea, it can be concluded that the highest level of implementation occurred during the period from 2015 to 2018. The peak was recorded in 2016, with a total of 41,400 industrial robot units deployed. Over the past five years, the annual deployment has remained relatively stable, averaging approximately 31,000 units per year.

The overall trend in cumulative robot deployment in the Republic of Korea shows a continuous increase. In 2013, the total number of industrial robots in use was approximately 156,000 units. Over the following decade, this number rose to 520,900 units by 2023, representing a 3.3-fold increase. It is anticipated that this upward trend will persist in the coming years. Furthermore the Republic of Korea maintains a leading position globally in terms of robot density, measured by the number of industrial robots per 10,000 employees, as illustrated in **Figure 3** [31–34]. Based on the data presented in **Figure 3**, it is evident that the Republic of Korea has maintained its global leadership in industrial robot density—measured by the number of robots per 10,000 employees in the manufacturing sector—over the past thirteen years. This leadership began in 2012, when Korea surpassed Japan by reaching a density of 396 robots per 10,000 employees, becoming the top-ranked country worldwide. Since then, as shown in **Figure 3a**, the Republic of Korea has consistently held this leading position. Over the course of just a decade, the Republic of Korea has effectively doubled its robot density. As illustrated in **Figure 3a**, the country's robot density remains significantly above the global average. In 2023, Korea reported a density of 1012 robots per 10,000 industrial workers, compared to the global average of 162—more than six times higher. **Figure 3b** presents the top ten countries worldwide in terms of robot density in 2023. Alongside the Republic of Korea, the leading nations include: Singapore (770), China (470), Germany (429), Japan (419), Sweden (347), Denmark (306), Slovenia (306), Switzerland (302), and the United States (259). These are predominantly countries with highly developed automotive and electrical/electronics industries. We conclude that the continuation of this trend toward increased automation is likely in the coming years, paving the way for the widespread adoption of smart factories. The future leaders in this field will depend on each country's development strategy and industrial priorities.

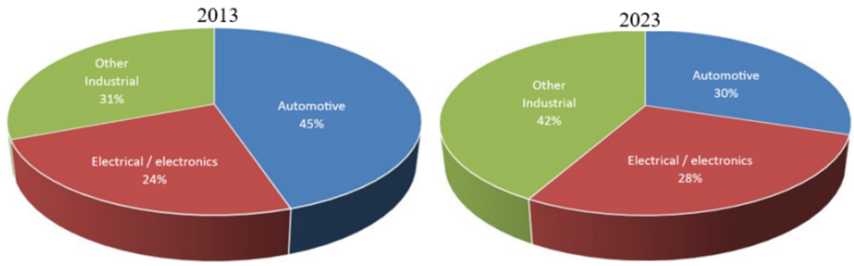


(**a**) (**b**)

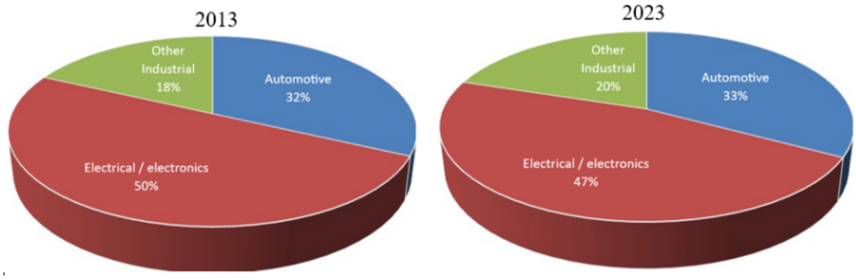
Figure 3. Implementation of industrial robots (**a**) in the Republic of Korea per 10,000 employed workers in industry in the period 2013–2023 and (**b**) in ten top countries in 2023.

3.2.4. Robotic Applications in Manufacturing and Automotive Sectors

Industrial robots have had a profound impact on Republic of Korea's manufacturing sectors, particularly in automotive production. As illustrated in **Figure 4**, the highest concentration of industrial robot deployment globally is observed in two key sectors: the automotive and the electrical/electronics industries. In 2013, 45% of all newly installed industrial robots worldwide were implemented in the automotive sector, while 24% were deployed in the electrical/electronics industry. The remaining 31% were distributed across all other industrial sectors. This distribution pattern remained relatively stable over the next decade. By 2023, the automotive industry accounted for 30% of global robot installations, the electrical/electronics sector for 28%, and all other industries combined for 42%, as shown in **Figure 4a** [35,39,40].



(**a**)



(**b**)

Figure 4. Implementation of industrial robots by industry (**a**) in the world and (**b**) the Republic of Korea in 2013 and 2023 [35,39,40].

A similar trend is evident in the Republic of Korea, where these two industries have consistently led in robot adoption. In 2013, 32% of newly installed robots were deployed in the automotive sector, and 50% in the electrical/electronics industry. A decade later, in 2023, the distribution shifted slightly to 33% in the automotive sector and 47% in the electrical/electronics sector, with the remaining 20% implemented across other industries **Figure 4b**. These figures indicate that, in the Republic of Korea, the automotive and electrical/electronics industries are significantly more dominant in terms of industrial robot adoption compared to the global average. Robot density is a key indicator reflecting the current level of automation in the world's leading automotive manufacturing economies. In 2021, the Republic of Korea recorded 2867 industrial robots in operation per 10,000 employees. Germany ranked second with 1500 units, followed by the United States with 1457 units, and Japan with 1422 units per 10,000 workers [32]. The country's automotive giants, such as Hyundai Motor Company and Kia Motors, have integrated robotics into virtually every aspect of their production lines, from assembly to welding, painting, and quality control. These robots perform repetitive tasks with high precision, reducing human error and improving overall efficiency [41]. The automation of automotive manufacturing in the Republic of Korea is driven by the need for faster production cycles, enhanced quality, and greater flexibility in meeting diverse consumer demands. In particular, robots allow manufacturers to quickly reconfigure production lines to accommodate customized vehicle specifications, maintaining high levels of productivity and reducing lead times [38]. This ability to adapt to consumer preferences is crucial as the automotive industry increasingly shifts toward personalized vehicles. In addition to the automotive sector, robotics is also widely used in the Republic of Korea's electronics sector. Companies like Samsung and LG have adopted robotic systems for tasks including assembly, testing, and packaging of consumer electronics. These systems provide precise handling of sensitive components, minimizing the risk of defects and enhancing product quality. As a result, the Republic of Korea's robotics-driven manufacturing processes have reinforced the country's dominance in the global market for high-tech products [42]. That the Republic of Korea's global leadership in the implementation of robotic technology across manufacturing processes—particularly in the automotive and electrical/electronics industries, as well as in other sectors—is further evidenced by the ongoing execution of the "Smart Manufacturing Innovation Roadmap" and the "Robot Industry Promotion Program". **Figure 5** illustrates this leadership by showing the increasing number of robotics-related companies operating in the Republic of Korea. In the automotive industry specifically, the integration of industrial robots has played a critical role in enhancing productivity, ensuring precision, and maintaining global competitiveness. Robotic systems are widely used in key production stages such as welding, painting, assembly, and quality control. The Republic of Korea automotive manufacturers have invested heavily in automation to meet high standards of efficiency, flexibility, and product customization. This widespread adoption of robotics has not only improved production throughput and reduced operational costs but has also enabled rapid adaptation to global market demands and technological advancements. As a result, the automotive sector in the Republic of Korea serves as a model for successful industrial robot integration on a national scale.

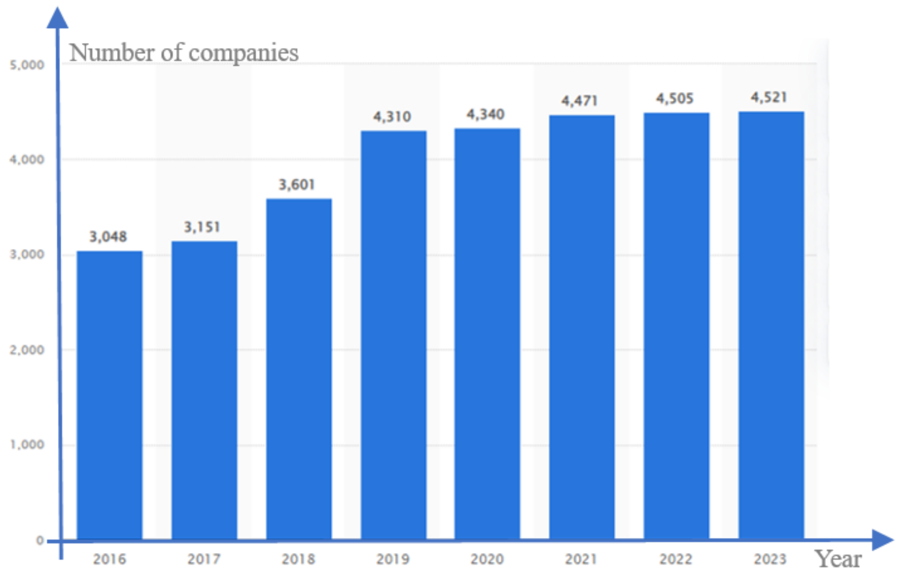


Figure 5. Trend in the number of robotics technology companies in the Republic of Korea from 2016 to 2023 [39].

The sheer growth in the number of these companies reflects the strategic direction of the Republic of Korea's government toward the development of smart factories. This trend highlights not only the increasing demand for advanced automation solutions but also the emergence of a robust industrial ecosystem that supports innovation, integration, and the application of robotics across various manufacturing sectors. Robotics companies in the Republic of Korea play a crucial role in providing core technologies, system integration services, and customized automation solutions, which collectively contribute to the transition toward intelligent and highly flexible production environments. Their expansion signals a maturing market aligned with national priorities in digital transformation and industrial competitiveness. Furthermore, the Republic of Korea is making significant strides in the development of collaborative robots (cobots). Designed to work alongside human operators, these robots have seen growing adoption in environments that require flexibility and close human interaction. Small and medium-sized enterprises (SMEs) in the Republic of Korea, in particular, have found cobots to be a cost-effective solution for integrating automation into their production lines, enhancing efficiency without requiring large-scale capital investment [43].

3.3. Industrial Robotization in Singapore

3.3.1. Singapore as an Example of Smart Industry

Singapore has established itself as a global leader in industrial robotization, ranking second worldwide in robot density in manufacturing, with 770 robots per 10,000 workers [44]. This success is the result of a long-term government strategy based on digitalization, automation, and workforce education. One of the key instruments that has supported this transformation is the Smart Industry Readiness Index (SIRI), developed by the Economic Development Board (EDB) and TÜV SÜD, which allows companies to assess and optimize their level of digital readiness [45]. The application of this tool has helped small and medium-sized enterprises (SMEs) implement industrial automation in a systematic manner [46]. A significant contribution is also made by the Jurong Innovation District (JID), an advanced industrial complex that hosts research centers and manufacturing units of companies such as

Siemens, Hyundai, and Bosch Rexroth. JID serves as an example of how industrial robotics, academic institutions, and startups can be integrated into an innovation ecosystem [47].

3.3.2. National Initiatives and Investments in Robotization

National programs such as the National Robotics Programme (NRP) form the foundation of public investment in the development of robotics in Singapore [43,44]. Between 2016 and 2019, over SGD 450 million was invested, and in 2024, an additional SGD 60 million was allocated to support industrial applications of robotics in manufacturing, healthcare, and logistics [44]. As part of the national digitalization strategy, Singapore launched the National AI Strategy 2.0, with planned investments of over SGD 1 billion over the next five years. The goal of this strategy is to position the country as a global leader in the application of artificial intelligence and automation [48,49]. The government also actively subsidizes the adoption of robotics in small and medium-sized enterprises through public-private partnerships and tax incentives [50]. These measures shape the innovation ecosystem and enable the rapid adoption of new technologies [51].

3.3.3. Trends in the Implementation of Industrial Robots in Singapore

The trend of industrial robot implementation in Singapore has been analyzed based on statistical data from the International Federation of Robotics (IFR), the United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), and the Organisation for Economic Co-operation and Development (OECD). Annual trends in the deployment of industrial robots, as well as the total number of units implemented, are illustrated in the following diagrams. Diagram **Figure 6** presents the annual implementation of first- and second-generation industrial robots, along with the cumulative implementation over the past ten years [35–39].

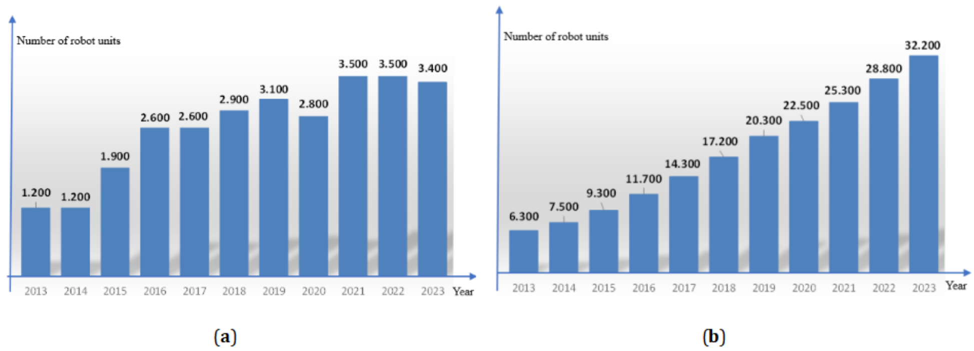


Figure 6. Diagram of (**a**) Annual and (**b**) Cumulative Implementation of Industrial Robots in Singapore (2013–2023).

Diagram **Figure 6a** illustrates the annual trend in the implementation of industrial robots in Singapore from 2013 to 2023. This chart shows fluctuations in the number of robots installed each year, with a notable increase in recent years, indicating growing interest in industrial automation. Diagram **Figure 6b** on the other hand, presents the cumulative implementation of industrial robots over the same period, showing the total number of robots deployed in Singapore by 2023. The cumulative number has grown significantly, reaffirming Singapore's position as one of the leading countries in industrial robot adoption. Together, these diagrams highlight Singapore's substantial progress in industrial automation, with an increasing share of robots integrated into the manufacturing sectors.

The diagram **Figure 7** illustrates the number of industrial robots installed in Singapore per 10,000 employees in the manufacturing sector from 2013 to 2023. The number of installed robots increased steadily, with a sharp rise in 2019, when the figure peaked at 918 robots per 10,000 employees. Following this peak, the number remained stable and continued to grow, reaching 770 robots per 10,000 employees by 2023. This trend reflects the increasing adoption of automation in Singapore's industrial sector. In comparison, the global average number of robots per 10,000 employees was 62 in 2013 and rose to 162 by 2023, indicating that Singapore significantly exceeds the global average in the implementation of industrial robotics.

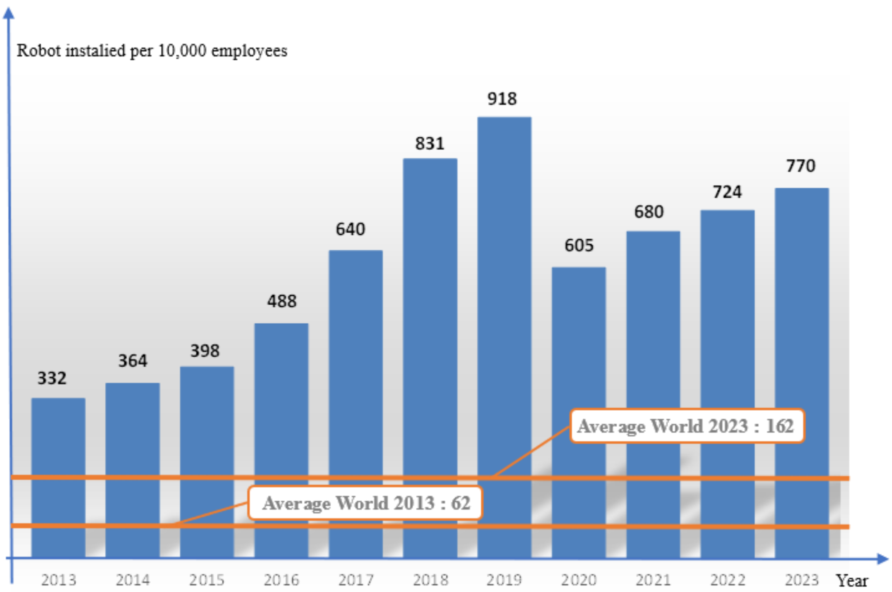


Figure 7. Implementation of Industrial Robots in Singapore per 10,000 Employees in the Manufacturing Sector (2013–2023) [35–39].

An analysis of **Figure 8**, which illustrates the implementation of industrial robots across various industries in Singapore in 2013 and 2023, reveals that the electrical/electronics industry is the most dominant sector in terms of robot deployment. In 2013, 81% of all industrial robots were implemented in the electrical/electronics industry, and by 2023, this share had increased to 90%, as shown in **Figure 8**. The electrical/electronics industry is one of the key pillars of Singapore's economy, contributing significantly to the country's exports. It focuses on the production of microprocessors, semiconductors, electronic components, and high-precision equipment. This sector is highly automated, with extensive use of robots, artificial intelligence systems, and advanced manufacturing technologies in line with Industry 4.0 principles. The Singaporean government actively supports digitalization and automation through investments and partnerships with global companies such as Infineon, Micron, and STMicroelectronics. Automation enables greater efficiency, cost reduction, and high-quality control. Furthermore, the industry is closely integrated with research and development centers, which fosters continuous innovation.

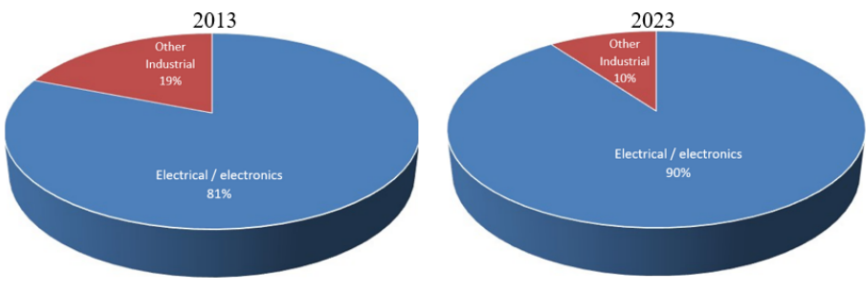


Figure 8. Implementation of Industrial Robots by Industry in Singapore in 2013 and 2023 [35,39].

4. Discussion

4.1. Shared Characteristics in the Approach to Robotization

The Republic of Korea and Singapore are global leaders in industrial robot density, with 1012 and 770 robots per 10,000 manufacturing employees, respectively [52]. Both countries demonstrate strong governmental support for digitization and automation through national strategies such as the Republic of Korea's *Manufacturing In-*

novation 3.0 and Singapore's *Smart Nation* initiative. Significant emphasis is placed on education and workforce reskilling to align with the demands of highly automated industrial environments. Strategic partnerships with global technology companies—including Infineon, Micron, and STMicroelectronics in Singapore, and Samsung and Hyundai Robotics in the Republic of Korea—illustrate a common model of public-private collaboration aimed at accelerating robotization. Empirical evidence also shows a statistically significant correlation between industrial robot deployment and labor productivity growth, as demonstrated by Zhao et al. [53] using panel data across manufacturing industries. Germany's decentralized approach to Industry 4.0, exemplified by initiatives like Plattform Industrie 4.0, and Japan's focus on robotics in healthcare and services, offer complementary perspectives to the cases of the Republic of Korea and Singapore.

4.2. Differences in the Application of Robotics

Despite sharing similar objectives, the Republic of Korea and Singapore differ in the scope and focus of industrial robot implementation. The Republic of Korea applies robotics across a broader range of industries, including automotive, electronics, and metal processing. In 2022, approximately 32,000 industrial robots were installed in the Republic of Korea, over 9600 of which were deployed in the electronics industry [54]. The country's industrial robotics market continues to grow, driven by large-scale manufacturing and the widespread adoption of advanced automation technologies. In contrast, Singapore's focus is concentrated in the electronics sector, which accounted for 90% of all industrial robot installations in 2023 [55]. This specialization is attributed to its compact manufacturing base and export-oriented economic structure. Singapore excels particularly in the integration of robotics into high-precision manufacturing and semiconductor fabrication, while the Republic of Korea emphasizes mass production and heavy industry.

4.3. Proposed Conceptual Framework for the Implementation of Robotization in Line with Industry 4.0

Based on the analysis of the cases of Republic of Korea and Singapore, a conceptual framework can be derived that comprises four key pillars essential for a successful transition to smart industry [56]:

1. *Institutional Strategy and Public Policy*:
    - National digital and industrial strategies (e.g., Smart Nation, Manufacturing Innovation 3.0).
    - Support through subsidies, tax incentives, and regulatory mechanisms.
    - Long-term development vision and political stability.
2. *Technological Infrastructure and Digital Transformation*:
    - Deployment and expansion of industrial robotics.
    - Development and integration of 5G, artificial intelligence (AI), Internet of Things (IoT), and big data analytics.
    - Cybersecurity and systems interoperability.
3. *Human Capital and Educational Transformation*:
    - Reformed education systems with emphasis on STEM and ICT fields.
    - Programs for upskilling, reskilling, and lifelong learning.
    - The role of universities and research institutes in knowledge transfer.
4. *Innovation Ecosystem and Public–Private Partnerships*:
    - Development of industrial clusters and technology parks.
    - Strategic partnerships with global companies and support for startups.
    - Investment in research and development (R&D) and innovation promotion.

4.4. Key Lessons for Developing Countries

Drawing from this framework and the empirical analysis, the following key lessons are proposed as guidelines for countries aiming to modernize their industrial sectors [57]:

- *Lesson 1*: A high level of robotization is meaningful only when embedded within a broader digital transformation strategy.
- *Lesson 2*: Public policy must serve as a catalyst through effective financial and regulatory instruments.
- *Lesson 3*: Human capital development is a foundational prerequisite for an inclusive and sustainable transition.
- *Lesson 4*: Strong collaboration between government, industry, and academia accelerates technological progress.
- *Lesson 5*: Countries should strategically prioritize sectors in which they hold comparative advantages, rather than replicating a one-size-fits-all model.

This framework does not offer a universal solution, but rather a flexible model that developing countries can adapt to their specific institutional, economic, and industrial contexts. While still emerging, technologies such as quantum computing and high-order AI could further optimize manufacturing planning, real-time control, and security in smart factories. Quantum algorithms can enhance supply chain optimization, while high-order AI enables autonomous learning in complex industrial systems.

4.5. The Influence of Culture and Economic Policy on Robotization

Cultural norms and economic models play a significant role in shaping the approach to industrial automation in both countries. The Republic of Korea's Confucian-influenced culture values hierarchy, discipline, and technological advancement, facilitating centralized, large-scale industrial transformation. The structure of chaebols (large industrial conglomerates) allows for rapid and broad implementation of robotics across multiple sectors. By contrast, Singapore adopts a pragmatic and efficient governance model that fosters a flexible, innovation-driven ecosystem. With a smaller number of large manufacturers, Singapore relies heavily on foreign direct investment (FDI) and strategic alliances to advance automation. Its open economy, business-friendly regulatory environment, and strong integration of government, academia, and industry support a collaborative framework for technological progress. Cultural traits such as adaptability, meritocracy, and long-term planning have enabled Singapore to rapidly adopt advanced robotics in specialized, high-tech domains. Recent empirical studies further emphasize that robotization tends to shift labor demand toward higher-skilled jobs, accelerating structural changes in the workforce. Hu et al. [58] demonstrate that robot adoption can lead to both job displacement and upskilling, depending on national labor policies and sectoral characteristics. Japan's approach, driven by aging population concerns, prioritizes service and healthcare robotics, while Germany emphasizes cyber-physical systems and SME digitalization. These models provide alternative paths toward smart industrialization.

4.6. Contributions of the Study

This study makes several key contributions to the academic and practical understanding of industrial robotization and its role in shaping smart manufacturing systems [59]. The main contributions are outlined as follows:

- *Empirical Insight:* Provides a longitudinal, data-driven comparative analysis of industrial robot implementation in Republic of Korea and Singapore between 2013 and 2023.
- *Policy-Oriented Framework:* Proposes a conceptual framework that integrates institutional, technological, human capital, and innovation ecosystem dimensions for successful robotization.
- *Benchmark Models:* Establishes Republic of Korea and Singapore as distinct but complementary benchmarks for countries aiming to implement Industry 4.0 technologies.
- *Sectoral Perspective:* Offers detailed insights into the sector-specific application of robotics (e.g., automotive and electronics), highlighting differences in strategic focus.
- *Lessons for Emerging Economies:* Identifies key actionable lessons for developing countries, emphasizing the importance of tailored industrial strategies, public–private partnerships, and educational transformation.
- *Theoretical Integration:* Applies and extends Technology Diffusion Theory and National Innovation Systems (NIS) frameworks to explain successful technological adoption in national contexts.

4.7. Environmental Sustainability Perspective

Although the primary focus of this study is on the technological and institutional aspects of robotization, it is essential to acknowledge the growing relevance of environmental sustainability within the Industry 4.0 paradigm

[60]. The integration of advanced robotics and digital technologies can contribute to more sustainable production systems in several ways:

- *Energy Efficiency:* Intelligent robots and automated systems can optimize energy consumption through precision control and predictive maintenance, reducing waste and operational inefficiencies.
- *Resource Optimization:* Data-driven manufacturing enables better forecasting, inventory management, and material usage, thereby minimizing overproduction and unnecessary resource depletion.
- *Circular Manufacturing:* Robotics and AI play a pivotal role in enabling remanufacturing, recycling, and closed-loop systems by automating disassembly and material recovery processes.
- *Emission Reduction:* Smart factories can track and reduce carbon footprints through real-time environmental monitoring, aided by IoT sensors and AI-based decision systems.

Despite these opportunities, environmental sustainability is not an automatic outcome of digitalization. If not guided by appropriate policies and regulatory frameworks, robotization may increase energy consumption or lead to unsustainable production scaling. Therefore, the integration of green manufacturing principles alongside robotization should be a priority in national industrial strategies. Future research should explore how digital-industrial convergence can support the broader goals of sustainable development and climate neutrality.

5. Conclusions

The comparative analysis of industrial robotization in the Republic of Korea and Singapore confirms the status of both countries as global leaders in the transition toward smart industry. The conclusions of this study are drawn directly from the longitudinal analysis of industrial robot implementation data (2013–2023) and the comparative assessment of national strategies in the Republic of Korea and Singapore. These findings support the research question, demonstrating that high robot density alone is insufficient without strategic integration within a broader digital ecosystem. This finding directly addresses the central research question of the study, which aimed to explore how high robotization levels, when integrated with other Industry 4.0 technologies, have enabled these countries to become exemplary models of future-oriented smart manufacturing. Key findings indicate that strategic government support, strong public-private partnerships, and continuous investment in education and innovation ecosystems are essential for the successful integration of industrial robots. While Singapore focuses on highly specialized robot applications in the electronics sector, the Republic of Korea demonstrates a broader distribution of automation across multiple industrial domains. These models clearly show that differentiated approaches aligned with national development priorities can lead to high levels of automation and sustained technological progress. A high degree of robotization brings numerous advantages, including increased productivity, improved product quality, and enhanced competitiveness in global markets. Automation also reduces dependence on human labor in routine and hazardous tasks, thus increasing workplace safety and operational efficiency. However, these benefits are accompanied by challenges such as the risk of job displacement for low-skilled workers, growing inequality in access to high-paying jobs, and the constant need for reskilling to meet the demands of the digital industry. For countries aiming to implement or enhance robotization processes, three key recommendations emerge. First, it is essential to establish a long-term development vision based on coherent and adaptable policies. Second, investments should be directed not only toward technological infrastructure but also toward human capital development through education, retraining, and innovation support. Third, collaboration between government, industry, and academia must be institutionalized to ensure that technological progress aligns with labor market needs. At the same time, social policies must be developed to mitigate the adverse effects of transition, ensuring that industrial transformation is both inclusive and sustainable.

While this study offers valuable insights into the role of robotization in the advancement of smart industry, several limitations should be acknowledged:

- *Scope Restriction:* The analysis is limited to two case countries—Republic of Korea and Singapore—which, although exemplary, do not capture the diversity of development trajectories in other regions, especially among low-income or resource-dependent economies.
- *Data Availability:* The study relies on secondary data from public sources such as the IFR, OECD, and national

reports. Although reliable, these data may not fully reflect micro-level operational realities within firms.

- *Lack of Qualitative Depth:* The research design is primarily quantitative and does not incorporate insights from interviews, fieldwork, or surveys, which could provide richer perspectives on organizational practices and barriers to robot adoption.
- *Environmental and Ethical Aspects:* Although the study includes a conceptual note on sustainability, it does not provide a detailed analysis of environmental or social implications, such as carbon emissions or workforce displacement.

Future research should consider:

- *Expanding the sample* to include a broader range of countries with diverse economic and industrial backgrounds.
- *Conducting mixed-methods studies* that combine quantitative data with qualitative interviews or case studies of specific industries or companies.
- *Investigating the long-term impact* of robotization on labor markets, education systems, and regional economic inequality.
- *Exploring sustainability metrics* to measure how robotization aligns with carbon neutrality goals, circular economy models, and ESG (Environmental, Social, and Governance) frameworks.

A more nuanced and multidisciplinary approach will be essential in future research to evaluate the broader societal, environmental, and institutional consequences of large-scale robotization.

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Conflicts of Interest

The authors declare no conflict of interest.

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