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Challenges of implementing Industry 4.0 in developed and developing countries: A comparative review

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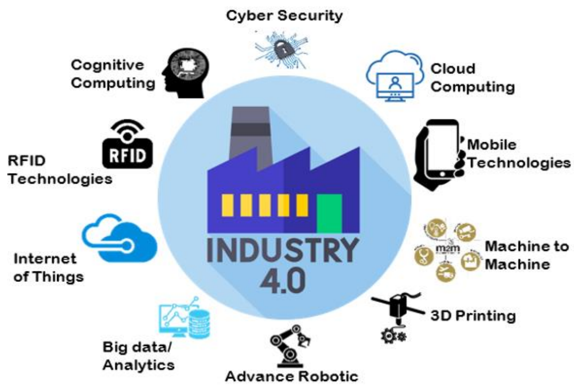
This article contributes to:
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
SUSTAINABLE DEVELOPMENT GOALS



Highlights:

- Indonesia is striving to adopt Industry 4.0 despite challenges like high costs and uncertain returns.
- The study compares Industry 4.0 readiness between developed countries (Germany, Singapore) and developing countries (China, Malaysia, Indonesia).
- INDI 4.0 reveals that Indonesia's industries are at a moderate level of readiness in technology and operations.

Abstract

Indonesia could transform the manufacturing industry by making Indonesia 4.0, despite the many uncertainties of implementing Industry 4.0 due to high investment costs and unclear returns. Therefore, looking at neighboring countries such as Germany, the country that initiated Industry 4.0, and China, the country taking the lead in implementing Industry 4.0, it is considered essential for the manufacturing industry in Indonesia to understand how towards the revolution and identify the development of the Industry 4.0 program. Germany is confident in its capabilities in the field of manufacturing technology. It makes the main challenge in carrying out Industry 4.0 'Investment Capital, Employee Qualifications, and Security of Data Transfer and Legislation'. On the other hand, China faces significant challenges in Manufacturing Capabilities, Research and Development (R&D), and Human Capital. To adopt the transformation technology and self-assess the internal resources, Indonesia created a tool, namely the Indonesia Industry 4.0 Readiness Index (INDI 4.0). This article presents a comparative review of the Industry 4.0 readiness index from the perspective of Germany and Singapore as a developed country compared to developing countries such as China, Malaysia, and Indonesia. This study aims to provide awareness related to the readiness index, which can be used to inform industries whether they are suitable for applying Industry 4.0 and how to measure whether their employees are capable of it. In general, the INDI 4.0 measuring instrument shows the readiness of companies in Indonesia, and according to the recent assessment, the industries in Indonesia are at a moderate level, especially in the field of technology application and operation.

Keywords: Industry 4.0; Intelligent manufacturing; Readiness index

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1. Introduction

The Industry 4.0 revolution represents an unstoppable global movement with profound implications for businesses, economies, and governmental operations. This transformative industrial shift has catalyzed a cascade of political upheavals, social movements, cultural shifts, and economic fluctuations projected to unfold throughout the 21st century [1]. The advent of the fourth industrial revolution has particularly impacted the industrial sector, leveraging the full potential of information and communication technology [2]. These technologies have been integrated into the production process and across the industrial value chain to enhance efficiency, productivity, flexibility, and product quality. Consequently, mastering technology, the primary driver of competitiveness in the Industry 4.0 era, becomes imperative, especially within national industrial sectors [3].

The aftermath of the third industrial revolution saw the widespread proliferation of digital technology. In contrast, the fourth industrial revolution is characterized by the convergence of software, biological, and physical innovations [4]. Key technologies driving this revolution include cyber-physical systems (CPS), big data, artificial intelligence (AI), cloud computing, digital twin, and the Internet of Things (IoT) [5]–[12]. This technological advancement has reshaped traditional industrial engineering strategies, paving the way for smart manufacturing characterized by intelligent sensing, networking, and identification capabilities [13]. As a result, complex manufacturing management can be monitored and synchronized in an integrated manner, enabling real-time visibility and process optimization [14], [15]. Moreover, Industry 4.0, marked by digitalization and hyper-connectivity, is revolutionizing production processes and manufacturing management practices, driving significant changes across industries [16], [17].

Currently, the manufacturing industry is profoundly influenced by Industry 4.0 management, as evidenced by the proliferation of intelligent services, the emergence of simple products based on smart technology, and the integration of the Internet of Things (IoT) into intelligent production sites. Lin et al. [18] have categorized published papers on Industry 4.0 into three main sectors. The first sector focuses on analyzing the impact of the fourth industrial revolution on production conditions, including investigations into the potential influence of technological innovation disruptions on social responses [19]. The second sector emphasizes information provision, architectural configuration, and system reconstruction [20]–[22]. The third sector examines the communication perspective of Industry 4.0, considering its impact on human resources, such as competency levels and education [23], [24]. However, recent research highlights a dearth of empirical studies on technology applications in intelligent manufacturing [25], [26].

While manufacturing operations based on sophisticated systems have been implemented globally, including in Indonesia, there remains room for improvement to align with Industry 4.0 standards [27]–[29]. The anticipated benefits of Industry 4.0 adoption have spurred extensive research, encompassing government reports, academic investigations, and practitioner studies [30]–[32]. Industry experts assert that fourth industrial revolution technologies enhance various aspects of organizational structure, including business model development, service and product innovation, and manufacturing management expansion [33]–[37]. This transformation fundamentally alters how employees work and organize their activities [38], [39]. Despite the emphasis on knowledge-based approaches in Industry 4.0, the role of human workers in direct manufacturing production and problem-solving remains essential for enhancing operational performance [40].

Many researchers have extensively documented the evolution of manufacturing companies towards Industry 4.0, particularly in developed countries. However, the fourth industrial revolution has also permeated and impacted local manufacturing firms in developing nations. Crucially, the success of Industry 4.0 hinges on the rapid adaptation of its technologies, both horizontally and vertically, within company management structures worldwide. Vertical integration involves connecting automation components, such as sensors and motors, with systems like Supervisory Control and Data Acquisition (SCADA) and Enterprise Resource Planning (ERP). Conversely, horizontal integration links various value chain sectors, including raw material supplies, procurement, maintenance, operation, and distribution. This comprehensive integration approach underscores the essence of Industry 4.0 implementation, which aims to connect all elements involved in the manufacturing process, including individuals, tools, and data (as illustrated in **Figure 1**).

The pervasive integration of Industry 4.0 and notable digital progressions are set to overhaul corporate tactics and transform workforce dynamics across multiple industries. To maintain competitiveness, manufacturing entities must emphasize innovation. Nonetheless, firms face assorted obstacles, contingent upon the socio-economic landscapes of their operating countries, when deploying technology and Industry 4.0 endeavors. Hence, conducting a thorough global assessment of the fourth industrial revolution's deployment, particularly in developing nations, is crucial.

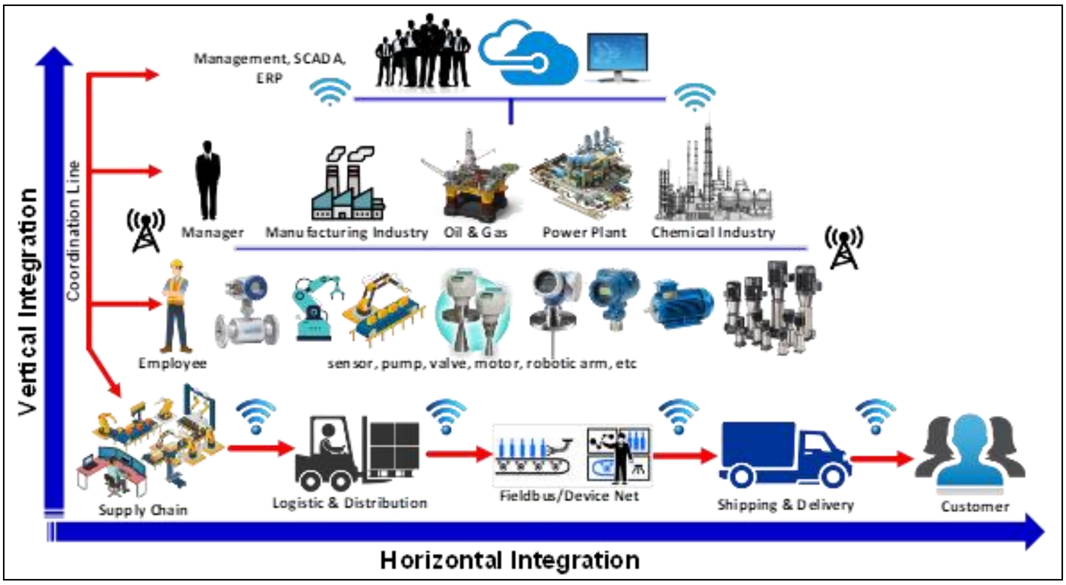


Figure 1. Connectivity in Industry 4.0 systems

The focus on implementing Industry 4.0 in developing countries was emphasized at the 2019 World Economic Forum (WEF). Given the concentration of manufacturing industries in these nations, addressing Industry 4.0 implementation is a collective effort. Originating from the German Government's concept of a smart factory in 2011, Industry 4.0 signifies the adoption of cutting-edge technology to enhance productivity, efficiency, and product quality through connectivity and digitalization.

In 2018, Indonesia, a developing nation, formally embraced Industry 4.0 under the decree of its President. The Making Indonesia 4.0 roadmap, introduced to commemorate this proclamation, aims to elevate Indonesia to the top 10 global economies by 2030. Indonesia's active participation as the official country partner of the Hannover Messe 2011: Digital Edition, Indonesia demonstrates its commitment to Industry 4.0. The Ministry of Industry meticulously selected seven sectors, including food and beverage, textile and clothing, automotive, chemical, electronic, pharmaceutical, and medical devices, to execute Making Indonesia 4.0 [30].

The fourth industrial revolution promises to propel Indonesian manufacturing into the digital sphere, necessitating a robust ecosystem of infrastructure, innovation, and policy frameworks. While Industrial Revolution 4.0 has the potential to reshape Indonesian manufacturing [41], uncertainties persist regarding Industry 4.0 applications, primarily due to high investment costs and unclear returns [42]. Thus, it's vital for Indonesia's manufacturing sector to examine neighbouring countries' experiences with Industry 4.0 to navigate this revolution effectively and enhance readiness across all industry elements. This paper aims to elucidate the strategies adopted by various countries to confront the challenges posed by the fourth industrial revolution and assess Indonesia's preparedness. It's structured as follows: Part 2 provides a brief overview of Industry 4.0, Part 3 outlines several countries' activities in addressing Industry 4.0 challenges, and Part 4 delves into the strategies employed by the Indonesian Government in adopting Industry 4.0. Finally, Part 5 presents conclusions through country comparisons, contributions, and recommendations for addressing Industry 4.0 challenges.

This paper presents a comparative review of challenges in implementing Industry 4.0 in developed countries and developing countries. The developed countries are represented by Germany, China, and Singapore, while the developing countries are represented by Malaysia and Indonesia. The category of developed and developing countries in this paper is based on the economic growth profile and the year when the country announced the government regulation and started implementing Industry 4.0.

This review article follows a structured progression. Section 2 presents research methodology which adopted in current study. Section 3 provides a brief description of Industry 4.0. Section 4 presents development of Industrial 4.0 in selected developed and developing countries. The challenges faced in each developed and developing country is also described. In Section 5, focussed on the development of Industrial 4.0 in Indonesia as a developing country. Section 6 presents further comparison study, Government regulation and readiness assessment of Industrial 4.0. Finally, Section 7 presents the conclusions of the review study.

2. Research Methodology

All academic research endeavours, regardless of field, begin with constructing a foundation on and making connections to prior knowledge. For this reason, educators must prioritise getting this right. But the complexity of this endeavour is growing. The business research community is producing new knowledge at a dizzying rate, yet that knowledge is scattered and doesn't adhere to any one discipline. Because of this, it is challenging to stay abreast of cutting-edge research, remain at the vanguard of a field, and evaluate the body of evidence in a certain field. That's why it's more important than ever to conduct a literature review as part of your research. Collecting and summarising past research in an organised fashion is what a literature review is all about [43]. The advancement of information and the facilitation of theory building are both bolstered by a review that is both successful and well-conducted as a research procedure. The effectiveness of a literature review lies in its ability to answer research questions in a way that no single study can. Providing an overview of regions where research is scattered and cross-disciplinary is another useful application. A comprehensive literature review is also an important part of developing theoretical frameworks and conceptual models since it allows researchers to synthesise study findings at a meta-level to demonstrate evidence and identify gaps in knowledge. However, conventional approaches to literature description and representation frequently lack rigour and are not systematic in nature. As a result, it's hard to tell what the accumulated research is trying to prove or suggest. This creates a substantial possibility that researchers construct their work on faulty premises. Research issues arise when scientists cherry-pick the evidence they use, neglecting findings that go counter to their hypotheses. Moreover, there are often concerns about what makes a good contribution even when the process of the reviews is valid [43].

Several rules for writing literature reviews already exist, as was previously indicated. Each review style has its place and can be useful in certain situations, but it all depends on the approach required to accomplish the review's objective. The phase of the review determines whether a qualitative, quantitative, or mixed-method approach is appropriate. Previous research has been critically examined here using a comprehensive literature review method. A systematic review can be defined as a strategy for locating and evaluating studies that are relevant to a topic, as well as a procedure for gathering and analyzing data from these studies [43]. In order to answer a specific research question or test a specific hypothesis, a systematic review seeks to locate all available empirical data that meet the inclusion criteria. Using explicit and systematic processes to examine articles and all relevant evidence can help reduce bias and produce more trustworthy findings on which to base choices. Simple procedures include:

- To what extent are analyses feasible? Statistics, such as meta-analysis, are frequently used to combine the findings of the included research, however, this is not always the case.
- A meta-analysis is a statistical technique for comparing and contrasting the findings of several research on the same issue in order to weigh and compare them and to detect patterns, disagreements, or relationships.
- In a meta-analysis, results from individual studies are summarized and standardized so that a single metric can be used to determine aggregate effect size. However, in order to conduct a meta-analysis, the studies included must use the same statistical metrics (effect size) to make comparisons.

Therefore, it is difficult to conduct a meta-analysis on studies that use varying research methods. However, simple ways are straightforward to consider, and that is the approach taken here. This includes the number of publications in journals, conferences, book chapters, etc. Apart of introduction in Section 1 and research methodology adopted in current study presented in Section 2, other content of this review study is illustrated in **Figure 2** that include a brief description of Industry 4.0 in Section 3, a review of Industry 4.0 in developed and developing countries presented in Section 4, and at last is a discussion of Industry 4.0 in Indonesia that presented in Section 5.

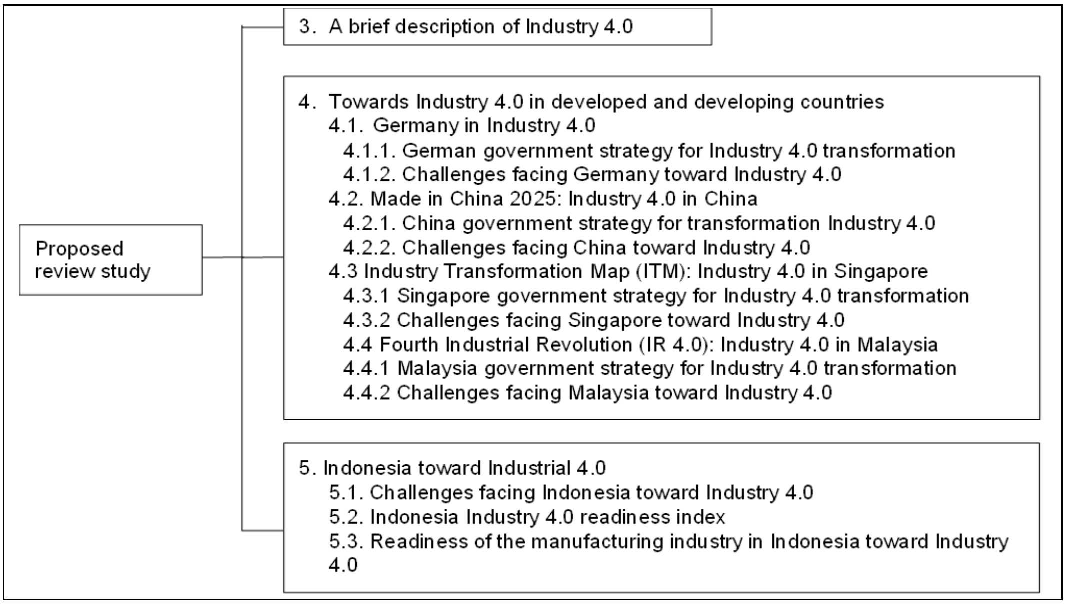


Figure 2. Flowchart of the main content of the proposed review study

3. Brief Description of Industry 4.0

James Watt who invented the steam engine changed the face of industry in England in the 1770s and spread all over Europe and America in the 19th-century world [44], later known as the first industrial revolution. Previously, products were produced in family-scale workshops by a workforce of craftsmen and their assistants. The invention of the steam engine in the first industrial revolution as illustrated in **Figure 3** required human resources to mechanize the process of mass production in factories, which required the workers of millions of people who migrated from rural agriculture to urban life.

The application of the Second Industrial Revolution concentrates on the mass production of goods and manufacture. Revolution is defined as the implementation of a mass production system using conveyors and electric power as illustrated in **Figure 3**. The driving factor begins in the automotive sector, especially the car manufacturer, Ford. When the market demand for Ford's Model T soared sharply, the company faced difficulties in fulfilling orders. With the use of this mass production system, very large production cost efficiencies are obtained. However, the price of the car has fallen drastically. This makes the purchasing power of the middle class increase because many people can afford to buy their cars. This in itself will cause the mobility of goods and people to become wider. The implementation of the mass production concept with conveyor belts was then imitated by many other industries. Hendry Ford (the founder of the Ford car factory) implemented the conveyor belt concept which was inspired by the production system at a slaughterhouse in Cincinnati, where after the process of slaughter, the pig is hung on a walking rack which makes the slaughtering process more efficient. Furthermore, breakthrough production process innovations with mobile assembly lines were discovered by utilizing continuous electrical energy to build a large number of standard products by organizing specific work areas and skills while reducing unit costs. Manufacturing jobs are available in large numbers in this second revolution, where workers get good pay and increase the welfare of economically weak people [45].

The digital revolution often called the third industrial revolution, is strongly influenced by computer technology, information technology, and widespread digitization [46]. Knowledge of digital engineering has enabled the automation of production and services. The manufacturing industry has transformed from large-scale production to mass custom modifications, a machine-aided product manufacturing strategy that can be programmed to produce standard products with a certain degree of flexibility in supporting assembly or finished goods.

The 3rd Industrial Revolution was marked by the integration of computer technology with production machines as illustrated in **Figure 3**. This integration led to the realization of an automation system, namely the existence of machines controlled using computers. For example, the invention of computer numerical control (CNC) machines, industrial robots, and programmable logic controller (PLC) systems. Broadly, the implementation of Industry 3.0 has been proven to make the production system at the factory more efficient and increase productivity which will affect the product quality to be more consistent/precise.

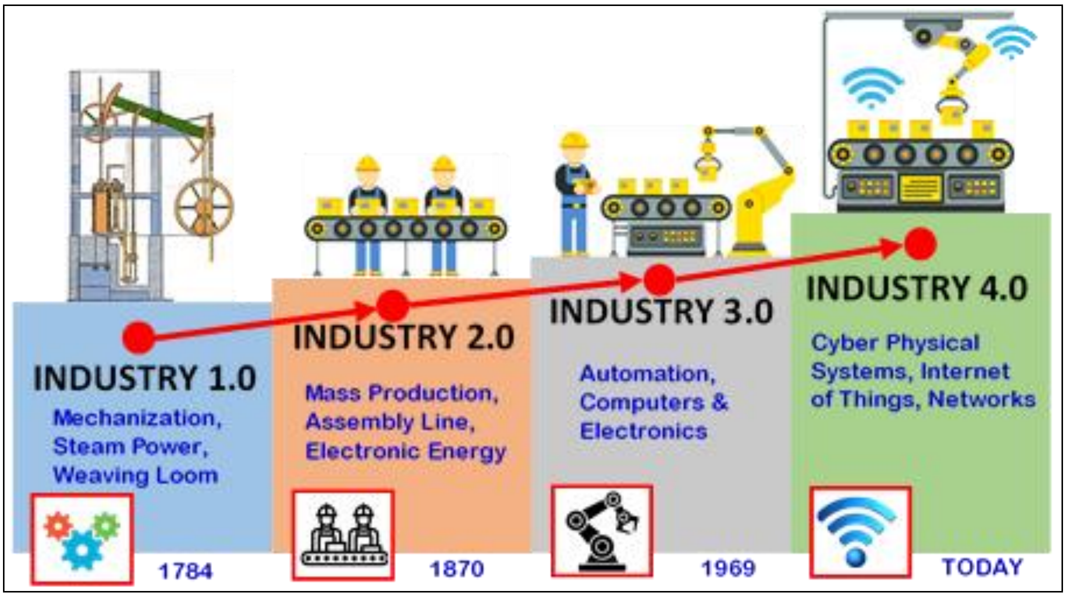


Figure 3. The development of the Industrial Revolution 4.0. Adapted from [47]

The term "Industry 4.0" was first discussed in an article written by the German authorities in late 2011 resulting from efforts on modern technology strategies for 2020 [48]. Industry 4.0 was first introduced by the German government in April 2013 with a focus on cyber-physical systems (CPS) and smart factories integrated with high technologies such as data exchange in manufacturing technology, automation systems, advanced cloud computing, Internet of Things (IoT), 3D in printing technology, smart products, and competent human resources, as illustrated in **Figure 4** [49]. This manner of the integrated industry includes various forms currently consisting of decentralized automated organizing capabilities, cyber-physical systems, smart factories, advanced systems in procurement and distribution, systems of products and services to be personalized, and obligations to the community in the form of corporate social responsibility (CSR). Germany Trade and Investment [50], the economic development agency of the Federal Republic of Germany, expressed the core idea of "Industry 4.0", an integrated system where the German government provides a platform with regulations supporting becoming a smart industry. Herman et al. [51] divide them into integrators for physical systems and essential software, integrators for supporting branches and sectors of the economy, and integrators for supporting industry and other industry types. This way, the downstream and upstream sector industries are monitored for supporting data to produce final products for consumers. Ganzarain et al. [52] define "Industry 4.0" as the ability of companies to control the entire production process from raw materials to final products with a more accurate and precise atomic system using computers and the internet. Meanwhile, Schröder [53] defines it as a leap in digital technology in industrial processes with modern networks that are reliable and computer-integrated.

In addition, with the implementation of Industry 4.0, it is hoped that there will be an enhancement in the quality of the current manufacturing process that can be seen from the economic, environmental, and social aspects. The interconnection of horizontal integration networks in Industry 4.0 offers new opportunities for more efficient processes that enable coordination between products, materials, energy, and water flows throughout the product life cycle. This enables cooperation between factories to achieve a competitive advantage by exchanging energy, materials, and products. For instance, Siemens, based in Munich, Germany, is Europe's largest industrial manufacturing company, with many branch offices worldwide. The German tech giant is known for its best-in-

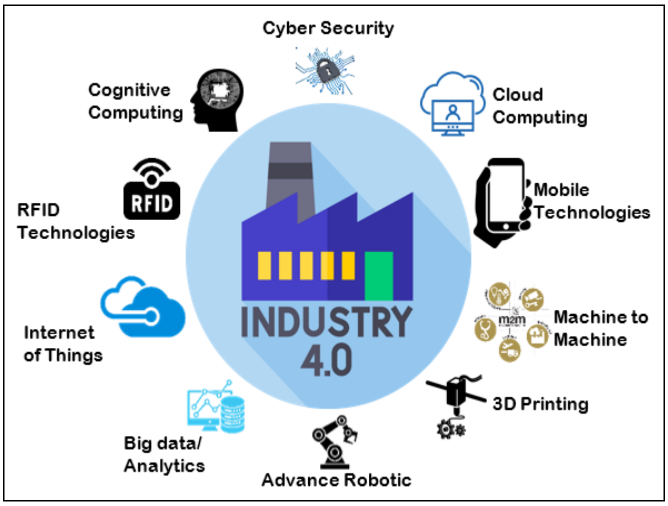


Figure 4. The main technology supporting Industry 4.0. Adapted from [54]

class AI, IIoT, and edge computing solutions for the manufacturing, healthcare, transportation, logistics, and energy and power industries. Siemens specializes in smart infrastructure (smart factory solutions and smart buildings and networks), the Internet of Things, cybersecurity, and digital twins. The Siemens Digital Industrial Software Platform is based on a fully digital business model that enables 3D and 2D product lifecycle management and offers advanced robotics, cloud connectivity, and additive manufacturing solutions.

Another opportunity from the implementation of Industry 4.0 is the reduction in the number of product defects. This is because the implementation of Industry 4.0 based on artificial intelligence makes each process able to optimize its ongoing processes to produce flawless products. In addition, Industry 4.0 is also beneficial for reducing machine breakdown, reducing machine set-up time, and reducing redundant logistics, which in the end increases company productivity. Krolczyk et al. [55] have investigated the flow of logistics materials by optimizing the distribution of raw materials for the manufacturing production process using the Bloch-Schmigalla method. The investigation has resulted in potential production cost savings and improved company performance effectiveness. In the Industry 4.0 era, it is required to carry out intelligent optimization applied in the production process including the flow of raw materials as the main factor in intelligent manufacturing [56].

In China, Industry 4.0 is named “Made-in-China 2025” which is comprised of three phases. The first phase is in the period from 2015 to 2025, in this period, China targets to become a country that has world-class manufacturing capabilities. Then in the second phase with a period of 2026 to 2035, China wants to make sure its manufacturing strength lies in an intermediate position at the global level. Furthermore, in the third phase the period from 2036 to 2049, China aspires to have the leading manufacturing capability which was announced when the People's Republic of China celebrated its 100th independence [57].

4. Towards Industry 4.0 in Developed and Developing Countries

Not surprisingly, although the concept of Industry 4.0 is still a new thing, both developed and developing countries are ready to welcome it, of course for different reasons. For developed countries, Industry 4.0, a term that was first coined in Germany, could be a way to restore infrastructure competitiveness, especially for Western European countries [58]**.** For developing countries, Industry 4.0 can help simplify the production supply chain, which in this case is urgently needed to control the increasing labour costs. For example, China's 10-year plan announced in May 2015 entitled "Made in China 2025", targeted core sectors such as robotics, information technology, and energy, to turn what is now known as a "manufacturing giant" into a "manufacturing powerhouse world”, for this reason, China will beat the value of R & D investment to 2.938% of the total manufacturing revenue in 2025 [59]. China refuses to be labeled as a developed country according to the wishes of the United States, which wants it. This Bamboo Curtain country insists on maintaining its status as a developing country recognized by the World Trade Organization (WTO) and other international agreements. Many research reports state that China is a developing country, such as research in the fields of digital finance [60], monetary policy [61], industrial innovation [62], energy transition [63], and emissions trading [64].

4.1. Germany in Industry 4.0

One of the world's leading industrial countries, Germany launched a strategic plan "Industry 4.0" in 2013 [65], [66]. Several important industries in Germany with high brand prestige, such as Volkswagen, BMW, and SAP, have implemented innovative strategies that have led them to find the dignity of the company's identity. The fourth Industrial Revolution is an example of the efforts of German manufacturers to be able to compete in the new era of the manufacturing industry whose core activities are integrity [50], [67], digitization-based manufacturing [68], CPS [69], artificial intelligence (AI) and internet of things (IoT) [70]–[72].

Renowned worldwide, German products are lauded for their design and quality. Seven companies constitute a significant portion of Germany's GDP and are major profit generators. Notably, three prominent automakers, including Volkswagen, Germany's largest car company, Daimler, the second-largest, and BMW, the third-largest, dominate the global market. Notably, General Motors Co. oversees Volkswagen's operations in China, the world's largest auto sales market. German brands like BMW and Mercedes are esteemed luxury car manufacturers globally

[64], [69]. In the field of electronics and industrial automation, Germany is very strong and dominates the world market through the Siemens brand. Siemens is a German corporation with main businesses in the energy, manufacturing, infrastructure, and healthcare industries. Another world-class company, BASF is a chemical company in Germany that has an annual sales profit of more than $80 billion. The main areas of BASF's corporate enterprise are chemistry, agriculture, and other industrial fields [68], [73]. Germany is also dominant in the financial sector, with the establishment of Deutsche Bank, a large bank spread across Europe. Another financial sector in the insurance sector, Germany has the Allianz financial group, even though the company does business in the world market with a business focus on financial services [56].

There are twelve facts about Germany's Industrie 4.0 policy initiative as presented by Digital Transformation Monitor [69]. Among all facts, the most interesting thing is the policy lever(s) which stated that the policy made by the government related to industrial 4.0 is a publicly backed and steered initiative that is implemented by the stakeholders. **Figure 5** shows selected facts for Germany's Industrie 4.0 policy initiative that could be useful information for developing countries.

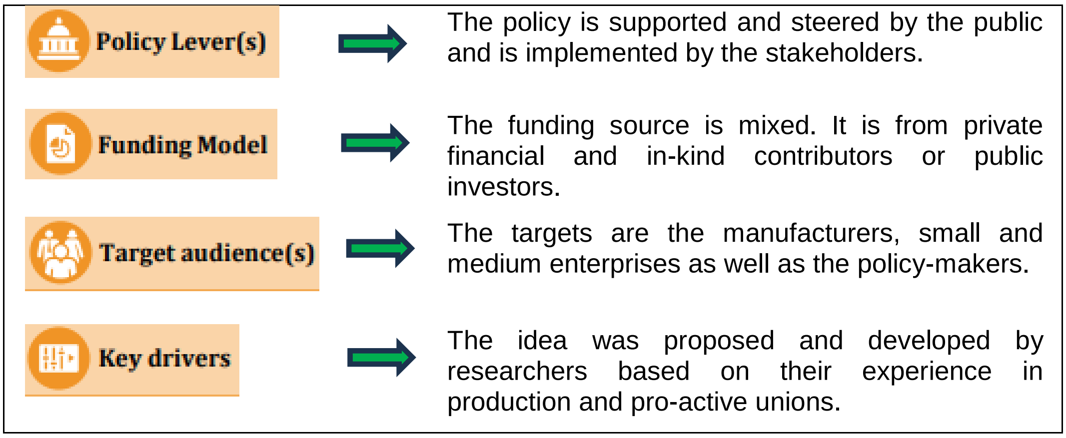


Figure 5. Selected items of fact box for Germany's Industrial 4.0. Adapted from [74]

4.1.1. German Government Strategy for INDUSTRY 4.0 Transformation

Advanced information and communication technologies have developed rapidly and initiated real innovations, in fields such as industrial control engineering, cloud computing, big data, and high mobility internet. These technologies drive major changes in production processes and grow the manufacturing industry. Although Germany is blessed with great manufacturing industrial machinery and equipment used throughout the world, especially the embedded equipment to control systems, the manufacturing industry faces some threatening challenges [71]. Müller, et al [75] have investigated and analysed the influence of the Industrial Revolution 4.0 which drives changes in the style of MSMEs (small and medium enterprises) in the manufacturing business and the importance of the role of MSMEs because they play a major role in maintaining and developing significant industrial values in Germany. In addition, the development of supporting equipment and machinery is very competitive, not only America is aggressively revitalizing the manufacturing industry, but also Asia is producing equipment and machinery that strictly follows global progress and undermines German brand manufacturing plants. In the area of internet technology and software, this could be a weak point for the German manufacturing industry. The German government and entrepreneurs are aware of these relative weaknesses, so Germany conceptualizes its own INDUSTRIE 4.0 revolution strategy to remain in a position of excellence as a global manufacturing equipment company, taking advantage of the position of the leading embedded system supplier and always ready to meet the challenges of the new industrial revolution era and study the influence of Industry 4.0 on changes in the behaviour of SMEs in running their business. Kiel et al. [76] show that for the manufacturing industry to continue to develop sustainably, the Internet of Things (IoT) requires the support of the Triple Bottom Line (TBL) which is already firmly rooted in three sectors consisting of big data and broad information, well known to the public and technically integrated. Furthermore, based on the TBL concept, they conclude that the main point is related to the creation of a sustainable manufacturing industry spirit, where IoT has a strong influence on social, ecological, and especially economic behaviour.

Encouraged by the German Academy of Engineering and other academics, the Fraunhofer Association, one of the major "Siemens" companies and other manufacturing industries, the German Federal Ministry of Education and Research, and the German Federal Ministry of Economy and Technology decided on INDUSTRIE 4.0 to be one of the 10 projects Leading Futures Education and Leading Research in 2020 [3]. The agenda of important projects with projections into the future is a concentrated part of the policy of leading research and breakthrough innovations and crucial goals will be achieved within a period of 10-15 years. The German government with the House of Representatives has budgeted funds of up to EUR 200 million to identify 10 flagship projects and strategic steps to realize INDUSTRIE 4.0 in the 2020 High Technology Strategic Action Plan [77].

The strategic steps to achieve the goals of important future-looking projects have been synchronized between relevant German ministries and departments of the German federal government. Project design planning involves stakeholders from academia and manufacturing industry players to determine tactical steps. Crucial factors such as complementary cooperation and intensive consultation from both stakeholders will determine the success of strategic high-tech businesses. Furthermore, Verband Deutscher Maschinen-und Anlagenbau, VDMA or German Mechanical Engineering Industry Association launched the INDUSTRIE 4.0 platform. One of the largest technical-scientific societies in Europe, TRIE or e.V.Verband der Elektrotechnik, Elektronik und Informationstechnik has published online the first German standardization roadmap for Industry 4.0. Based on the conclusion of the INDUSTRIE 4.0 preparatory group in 2013 which was tasked with implementing the INDUSTRIE 4.0 revolution plan to ensure Germany's superiority in the manufacturing industry competition, the German government has the following strategy: expanding the network, focusing only on two main themes, achieving integration of three fields and eight the main sector of development throughout Germany [3].

The INDUSTRIE 4.0 Architectural Model reference, RAMI 4.0 [78], provides an overview of the three-dimensional coordinate system that represents the influential elements to support INDUSTRIE 4.0. With this method, complex and interrelated problems can be clustered into small and simple cases. German government appoints leaders in the executive sector for INDUSTRIE 4.0, the German Ministry of Economic Affairs, and research institutes with the main task of developing the standardization of INDUSTRIE 4.0. The first strategic step in November 2015, Germany announced the second version of RAMI4.0 as the reference standard for achieving INDUSTRIE 4.0 for all institutes in Germany all these developments became important reports for the International Electronics Committee, and Germany aggressively promoted digital products as a standard and encourage coordinated execution. The second step was the development of the German roadmap 'standardization of INDUSTRIE 4.0 version 2', in addition, at the same time, an illustration map demonstrating the implementation of INDUSTRIE 4.0 was announced and succeeded in capturing 202 projects implementing INDUSTRIE 4.0 [79].

Changing geopolitical conditions, climate change and the global crisis in Europe pose significant challenges for companies in Germany. For example, industry must be able to react to disruptions to supply chains or energy supplies due to Russia's war with Ukraine. In addition, the trading system in Europe is tightening emission reduction regulations to increase economic sustainability. Germany initiated the Manufacturing-X initiative, which aims to carry out digital and ecological transformation towards a sustainable data network in the industry for multilateral data exchange. However, individual companies or trade associations cannot implement Manufacturing-X alone. Manufacturing-X is more than the sum of many individual projects. This initiative creates a broad alliance between companies, associations, academia, and politics. They actively shape digital data ecosystems across industries as a public-private innovation partnership [80].

4.1.2. Challenges Facing Germany Toward Industry 4.0

Industry 4.0 creates a manufacturing industry with a strong foundation to reach digital platforms and strengthen the intelligence of its entire supply network. Manufacturing digitization seeks to integrate digital technology with existing manufacturing processes, which emphasizes planning, analysis, and reorganizing processes and products with the help of advanced and integrated information technology to meet customer requirements. The commitment to maintain strong cooperative relationships between suppliers, producers, and customers is the main capital, to achieve the goal of the industrial revolution [81].

Research conducted by Geissbauer et al [82] reveals that investment is a serious challenge to implement the revitalization of Industry 4.0. While experts can measure the required investment costs, in contrast, they have difficulty projecting profits from the investment results. Both of these reasons were reported as formidable challenges faced by the surveyed companies, as reflected in the report by Geissbauer et al [82] where 46 percent said the size of the investment and the difficulty of predicting earnings. Most of the companies that took part in the survey did not carry out a plan that was specifically applied to deal with Industry 4.0, so they did not expand their investment. Company management is aware of the declaration of the industrial transformation movement in Germany, but they seem to be taking a wait-and-see attitude from other companies that have adopted Industry 4.0 before deciding to invest their capital.

The second challenge faced by companies to apply Industry 4.0 is the ability of human resources due to changes in worker qualifications which are labor requirements in the industrial revolution era. Meanwhile, in terms of regulatory standards, there are no globally or regionally accepted standards to implement these regulations. The third challenge is related to data transfer security and legal regulations that do not support the security of data owners and data users, especially for external purposes, so the development of technology and regulations is very ambiguous. In addition, there are many questions related to Internet technology that make companies and workers feel safe and comfortable, including data security. Frère et al. [83] analyzed the development of Industry 4.0 in Germany and found that many companies lack support from management and are not a top priority for running Industry 4.0.

a. Challenge in investment capital

The fourth Industrial Revolution involved huge investment capital with the risk of capital loss not being returned [84] because the rapid transformation of technological evolution invested high risk [3], [85]. Birkel et al. [86] have presented a large and unclear investment cost in terms of the payback period to adopt Industry 4.0, on the other hand, a manager must have the courage to invest, especially in SMEs. In addition, financial problems are a big challenge in implementing the fourth industrial revolution, especially for financing advanced infrastructure development and sustainable innovation breakthroughs [87]. Some researchers such as Kagermann et al. [3], Calabrese et al. [88], Müller et al. [89], Schneider [85], and Birkel et al. [86] found and highlighted the lack of internal capacity for financial capital resources causing companies to face problems with external investment capital which further exacerbated the situation.

The reorganization of all business capabilities [90] and the application of potential resources [91] to adopt the Industrial 4.0 technological revolution offer benefits, at least a low cost of capital when compared to significantly increased revenues. Many companies are reluctant to improve by introducing Industry 4.0 technology and do not plan to conduct research, feasibility studies, and dig up information because they have not received concrete evidence regarding their advantages or disadvantages [43], [75], [92], may argue that the company's operations are running smoothly without the front transformation of the industrial revolution and do not require investment towards Industry 4.0 [86], [93]–[95].

According to the survey carried out by Statista Research Department [96] in Germany in 2023 among 364 respondents, the high investment cost is the major challenge in the application of Industri 4.0 in their company. The second and third challenges are the demands of data protection regulations and the lack of specialists. A detail of the survey results is presented in **Figure 6**.

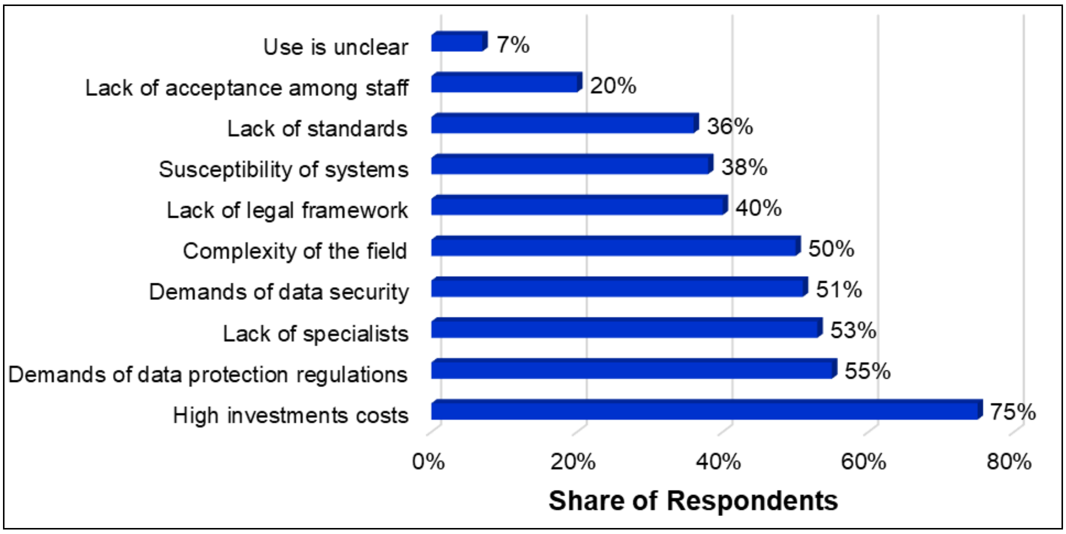


Figure 6. Challenges encountered regarding the Industry 4.0 application in Germanies companies. Adapted from [96]

b. Challenge in employee qualification

Human resources are the main obstacle in efforts to carry out the fourth industrial revolution because they are constrained by the ability to deal with cultural and technical changes [86], [93]. Therefore, all members of the organization must maintain a culture of learning and adapt quickly to improve the technology so that the team is ready to face the industrial revolution. However, many employees from manager level to permanent workers do not want to change their habits of work strategies and main production tasks [90], and usually for many reasons resist changes to new systems and technologies [97]. Several reasons revealed that advances in technology, especially information technology, have disrupted their privacy, including confidential personal data about expenses, financial arrangements, household secrets, and information on health problems and employees are worried that Industry 4.0 technology may always monitor their movements and make them uncomfortable in their working [98]. The Industry 4.0 era will provide opportunities for creative and dedicated employees to become pillars of the company [99] because the effects arising from the application of this technology require the ability of personnel to innovate continuously [100]. Certainly, creative innovation breakthroughs make it possible to answer customer needs [101]. Companies do not provide knowledge and skills [86] while implementing the fourth industrial revolution requires new knowledge [102], [103] and employees with the skills to manage the entry of information with production processes, and the ability to work together to find solutions [99], [104]. Therefore, the lack of employee skills is the main challenge facing the Industrial Revolution 4.0 [105]–[107]. Furthermore, the collaboration of all employees from various divisions through a guided interconnection network is the most important requirement for adopting Industry 4.0 [87], [92]. Several researchers have also proven that employees with various skills and different levels of ability can support improving company performance [108].

c. Challenge in data transfer security and legal regulation

Innovative breakthrough legal issues to realize the fourth industrial revolution need to face legal regulations. New manufacturing production technologies and processes are examined by legal analysis based on applicable regulations and investigated for their legal basis. Technology has developed and is widely used in society, while the law protecting it came too late. As a result, adjustments to legal aspects are really difficult to apply, especially for the implementation of Industry 4.0 because the Cyber-Physical System (CPS) transmits data between companies and supply chains globally, which can cause various technical and legal problems that interfere with each other between companies, employees and customers. For example, handling data transfers where the use and ownership of corporate or personal data for internal, and external purposes do not have an integrated and holistic legal basis. Supposedly, legal regulations should not limit a person's human rights and freedoms, for example, an employee employment contract with a long duration and detrimental to one of the parties, therefore, a clear and comprehensive legal contract design is needed [83].

Manufacturing production plants undergo a complex and long process of becoming smart factories based on Industry 4.0 and are complicated by the problem of the unclear legal basis for ownership and responsibility, personal data, and intellectual property protection [86]. In addition, on an international scope, regulations and laws apply in different countries causing the fourth industrial revolution to experience possible vulnerabilities [109]. Therefore, regulatory laws are still urgently needed to regulate various matters such as regulations to cover bilateral and multilateral company cooperation and trade, employee health, work area safety, and length of working hours [3], [97]. Furthermore, security certainty in using and sharing personal or company information data against violations of the law is a special challenge in the legal area of Information and Transaction Electronic, ITE [92].

In addition, **Table 1** contains a list of papers that express the opinions or empirical conclusions of several researchers regarding the challenges of Investment Capital, Employee Qualification, and Data Transfer Security and Legal Regulations.

Table 1. List of literature challenges Industry 4.0 in German (last five years)

Challenge field	Supporting literature
Investment capital	Max et al, 2021 [110]; Stentoft et al, 2020 [95]; Raj et al, 2020 [90]; Galati et al, 2019 [111]; Müller et al, 2018 [89]
Employee qualification	Glitz et al, 2021 [112]; Eisebith et al, 2021 [113]; Guzmán et al, 2020 [114]; Alcácer et al, 2019 [115]; Küsters et al, 2017 [116]
Data transfer security and legal regulation	Mirtsch et al, 2021 [117]; Nakagawa et al, 2021 [118]; Breda at al, 2020 [119]; Horváth et al, 2019 [93]; Hentschel et al, 2018 [120]

4.2. Made in China 2025: Industry 4.0 in China

China's economic reforms aimed to lift the Chinese population out of poverty began in 1978. The results of these reforms were successful in changing the welfare of the Chinese people. China's manufacturing development entered a new era after the development of the economic sector lasted for 30 years. Like the sides of a coin, challenges and opportunities arise with various environmental and resource constraints, increasing material and labour costs, and increasing demands for environmental responsibility. On the other hand, foreign investors poured direct investment into local companies while export growth slowed. Thus, group discussions to plan manufacturing strategies are inevitable. The industrial revolution "Industrie 4.0" in China is illustrated in **Figure 7**.

Figure 7. Industry 4.0 in China [121]

Countries around the world have passed legislation to promote smart manufacturing to attract investors, and are making every effort to transform and improve their manufacturing industries. Chinese is no exception, a country with big ambitions to become the number one manufacturing country. The Chinese government has announced the strategic plan "Made-in-China 2025" as a reaction to the global industrialization movement and Germany's modern technology strategy with 'Industry 4.0'. "Made-in-China 2025" is China's version of Industry 4.0 which was released in May 2015. This plan sets the main points for economic development for 10 years from 2016 to 2025. The details of the plan are printed in a blueprint developed by China's Ministry of Science & Technology (MOST), National Development and Reform Commission (NDRC) with additional advice from the Ministry of Industry and Information Technology (MIIT), and other related institutions [122].

Made-in-China 2025 targeted several sectors such as electrical equipment technology, farming machines, development of new materials, energy-saving methods, and new energy vehicles technology, numerical control tools and robotics, information technology, aerospace engineering equipment, railway equipment, ocean engineering equipment, high-end vessels, and medical and clinical devices as presented in **Figure 8**. Among all targets, robotics, information technology, and clean energy are centralized targets [123].

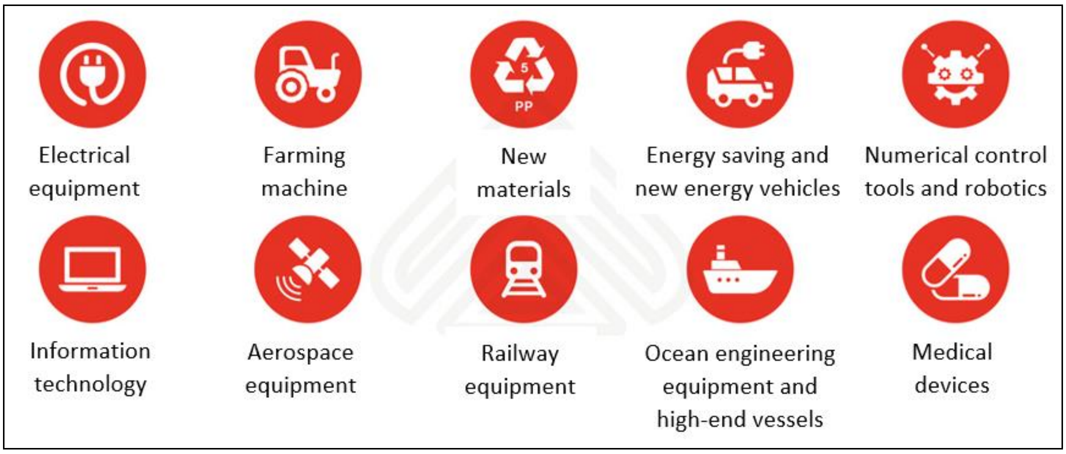


Figure 8. Target sectors of Made-in-China 2025. Adapted from [123]

4.2.1. China Government Strategy for Transformation Industry 4.0

The strategic plan "Made-in-China 2025" is a reference roadmap for the development of China's revitalisation of Industry 4.0 over 10 years. China intends to realize the industrial revolution from an employee-intensive to a technology-intensive manufacturing industry and produce breakthroughs at high speed. The "Made-in-China 2025" strategic plan is the first section of the "three-phase" master plan, to guide China's goal of becoming the world's manufacturing parameter center from garage-class workshops to large-scale production in today's world-class enterprises. The focus areas in China's plan consist of improving the quality of Chinese products, producing global Chinese brands, developing state-of-the-art modern technology based on solid manufacturing capabilities, discovering new materials, and being able to manufacture parts and key components from own machine production. With the Industry 4.0 revolution, the Chinese government prioritizes ten industries including high-tech machinery and automation, advanced information technology, maritime support equipment and high-tech shipbuilding, aerospace, and aviation equipment, unprecedented new materials, spare parts and rail support, energy-efficient vehicles, electrical equipment and parts, agricultural machinery and equipment, and bio-medical equipment [56].

The Chinese version of Industry 4.0 under the name Made-in-China 2025 contains three revitalization phase periods toward the leading manufacturing industry. The first phase period is to shift China from a large manufacturing country to a strong country by 2025. The challenge of this first step is related to the review in 2020, where the consolidation of the potential strength of the manufacturing industry as a basic reality of industrialization and the development of information technology substances should always be monitored. On the other hand, in-depth mastery of important technological fields should be carried out because it could increase the value of competition and the quality of manufacturing industrial products. Another improvement, in the field of digitizing the manufacturing industry process, is becoming more networked and higher in artificial intelligence. Major industrial values will increase their units, significantly reduce material and energy consumption, and degrade exhaust emissions. The targeted achievements in 2025 consist of improving quality in all areas of manufacturing, escalating innovation breakthroughs, increasing labor productivity and efficiency, and achieving a more modern integration of information technology with industrialization. The values of the main industries, consumption of energy and materials, and exhaust emissions are expected to reach the level of developed countries. Further achievements in 2025, the creation of multinational companies and industrial city clusters with international competitiveness are targeted to improve China's level in the manufacturing industry sector and supply chain globally. The second phase period is the ability of China's manufacturing industry to compete with developed country powers in 2035. The empirical challenge in this phase is China's industry must be able to make breakthrough innovations in the main fields to answer global demand and world-class leading capacity, increase competitiveness in all fields because it will be more stringent, and realize industrialization comprehensively. The third phase period is to target China's position as a leading manufacturing industry by 2045. The empirical challenge in this third phase period is that the manufacturing industry must have a real competitive and innovative value, after advancing the technology of the internationally leading manufacturing industry [124].

China is experienced a lot in carrying out strategically important plans for the national interest. China's economic reform measures in 1978 by building a Special Economic Zone (SEZ) city in Shenzhen as a model pilot area. The economic zone in the form of a special city became an experiment to implement free market business activities by making special policy regulations for the state and it turned out to provide extraordinary tax benefits that were able to attract foreign entrepreneurs to invest in China [125]. The port city of Ningbo was chosen as the first model city to implement the Chinese government's version of Industry 4.0 by accelerating industrial capabilities and mobilizing the city's manufacturing production, integrating with regional government innovation and flexible policy systems, the education system for its human resources, ability to support a healthy environmental ecosystem and diversity synergies in all fields. Furthermore, the Chinese government will determine a second group of cities consisting of 20 to 30 cities to join the Made-in-China 2025 grand plan [56].

4.2.2. Challenges facing China toward Industry 4.0

China has built a massively complex and complete manufacturing industrial system, which has pushed the progress of manufactured products toward modern industrialization since the late 20th century. However, when compared to the manufacturing industry of developed countries at the global level, the number of manufacturing industrial products owned by China is very large but does not have strong brands. So the first challenge that affects China's economic progress in the era of digital transformation is manufacturing capabilities. The second challenge indicator is the problem of Research and Development, R&D. The task is at the starting point of a new history of the Industrial Revolution 4.0 with advanced technology [57], [58].

China reacts quickly to boost economic development and progressively replaces scheduled work patterns for international manufacturing industries. China's strategic actions to overcome fundamental changes in the manufacturing industry with four comprehensive implementation efforts consisting of the realization of the manufacturing blueprint, maturation of all integrated planning, deployment to the future, and full effort through three periods of strategic planning, furthermore, the target in 2045, China appears to become a strong player in the global manufacturing Industry [126]. Of course, the plan requires human capital, the readiness of employees who are ready to work and skilled, so this becomes the third challenge Digitalization capabilities for manufacturing processes, continuous work on R&D, and large amounts of human capital have a major impact on the implementation of the "Made-in-China 2025" strategic plan [57].

a. Critical challenge in manufacturing capabilities

China is an active country leading in the Industrial Revolution 4.0 and actively promoting technology. Currently, China is targeted from the largest manufacturing country in the world to a country based on sturdy manufacturing. The manufacturing industry plays a major role in the foundational structure of the Chinese economy. According to official data from the National Bureau of Statistics of China, NBSC, value added with advanced manufacturing processes accounted for 29.4 percent of the Chinese government's GDP in 2018 [127]. Liu [128] revealed in his research that the Chinese manufacturing industry was only able to win the competition on low product prices and fast production. Chinese manufacturers tend to do manufacturing with a smaller value than developed countries [129]. For example, in global sales of Apple's iPad and iPhone, data reported by [130] shows the US-China trade deficit where the selling price of 1 unit in the US went from $229 to $275 and there was a $10 shortage of employee wages went to Chinese employees. Moreover, the production plants of the manufacturing industry generally produce exhaust gas pollution [131], [132].

b. Critical challenge in research and development

Breakthrough innovations by applying new technologies such as the Internet of things, cyber-physical systems, and process virtualization contained in Germany's "Industry 4.0" and China's version of "Made-in-China 2025" have proven to change the socioeconomic order in developing countries. Collaborative cooperation, patent law protection, and continuous research and development (R&D) in developed and developing countries have shown the right direction with applicable R&D results because of the varied knowledge and complementary capabilities of various countries to produce collaborative discoveries, it may not work if only one country. Furthermore, Research that is collaborative between countries allows the commercialization of research results to the downstream stage and ease of entry into global trade. Research projects in East Asian countries have made R&D collaborations across universities and countries to improve competence with reliable researchers and more advanced foreign science. In his research focus on the "legal value of international R&D", Su [133] investigates the value of international law on research collaboration and formal legal protection, between Japan-China, Korea-China, Taiwan-Japan, Korea-Japan, and Korea-Taiwan, for the results of the study that based on international law, R&D collaboration leads to violations of cross-border patent rules.

The application of science and technology through innovative breakthroughs is the driving wheel of a country's economy and the benchmark for measuring people's comprehensive capabilities. The innovative breakthrough capacity possessed by the community requires research and development with a large capital investment. China is still far behind the average of other countries when considering the percentage of R&D investment to GDP. Recently, market developments and economic capabilities tend to compete between digital technology and innovation breakthrough capabilities [134].

c. Critical challenge in human capital

Improving the quality of human resources is an important key to achieving the "Made-in-China 2025" target. Competent human resources with high discipline help the culture work together with the environment to create creativity and innovation breakthroughs. Competent human capital is the main capital to create mutually beneficial exploration practices [135]. A structured and healthy education produces quality human capital to utilize their talents and interests toward innovation based on quality research. Operators running "Made-in-China 2025" with Internet-Plus manufacturing systems and "Industry 4.0" with Cyber-physical systems must go through training and assessment to run the system. The transformation of Industry 4.0 by improving the quality of education to produce graduates who are ready to work is a very important step for the crew for further processes.

The description containing the Challenges facing China towards Industry 4.0 has presented several researchers who agree that China has the following main challenges: Manufacturing, Research and Development, R&D, and Human Capital capabilities, furthermore, **Table 2** lists the other researchers who support these main challenges.

Table 2. List of literature challenges made-in-China 4.0 (in the last five years)

Challenge field	Supporting literature
Manufacturing capabilities	Li et al, 2021 [136]; Yuan et al, 2020 [137]; Li et al, 2020 [138]; Guo et al, 2019 [139]; Wang et al, 2020 [140]
Research and development (R&D)	Chin et al, 2021 [141]; Dai et al, 2021 [142]; Lin, et al, 2019 [127]; Kuo et al, 2019 [58]; Feng et al, 2018 [134]; Yi et al, 2017 [143]
Human capital	Chen et al, 2021 [144]; Scholz et al, 2020 [145]; Li et al, 2020 [146]; Müller et al, 2018 [147]; Li, 2018 [56]

4.3. Industry Transformation Map (ITM): Industry 4.0 in Singapore

Industry 4.0 in Singapore encompasses a holistic approach to manufacturing, blending advanced technologies like IoT, big data analytics, and artificial intelligence to enhance productivity, efficiency, and innovation across sectors. Singapore, a global hub for innovation and technology, has seamlessly embraced Industry 4.0 manufacturing initiatives. With a robust manufacturing sector contributing significantly to the nation's gross domestic product (GDP), Singapore actively integrates cutting-edge technologies. The government's strategic roadmap for Industry 4.0, known as the Industry Transformation Map (ITM), plays a pivotal role in guiding and coordinating Singapore's efforts towards digital transformation in key industries. Through the ITM, Singapore aims to drive innovation, enhance competitiveness, and ensure sustainable growth in the digital economy, positioning itself as a leading player in the global Industry 4.0 landscape [148].

4.3.1. Singapore Government Strategy for Industry 4.0 Transformation

As early as 2014, the Singaporean government recognized the immense potential of Industry 4.0 in driving economic growth and enhancing competitiveness. In 2016, they launched the Industry Transformation Maps (ITMs), which serve as clear roadmaps for companies to adopt Industry 4.0 technologies and best practices [149]. These ITMs focus on several key strategies [150]:

a) Advanced Manufacturing and Trade Clusters: Refreshed ITMs for five advanced manufacturing and trade clusters aim to uplift companies in Singapore and create at least 13,400 new jobs. These clusters cover sectors such as electronics, precision engineering, energy and chemicals, aerospace, and logistics, which together contribute about 80% of Singapore's annual manufacturing output.
b) Research and Development (R&D): The government emphasizes R&D, deep tech innovation, extensive digitalization, and environmental sustainability within these sectors. By fostering partnerships with larger international firms and institutes of higher learning, the ITMs help small and medium-sized enterprises (SMEs) adopt new technologies and capture global business opportunities.
c) Skills Development**:** The ITMs ensure that workers acquire relevant skills for emerging areas. These include additive manufacturing, robotics, artificial intelligence, digitalization, and sustainable product engineering. With Industry 4.0 adoption, Singapore's manufacturing workforce has evolved, with more professionals, managers, executives, and technicians (PMETs) in white-collar roles**.**

4.3.2. Challenges Facing Singapore Toward Industry 4.0

As Singapore embraces the transformative potential of Industry 4.0, characterized by the convergence of digital technologies and manufacturing processes, it encounters a myriad of challenges on its journey towards digitalization and automation. These challenges, ranging from workforce readiness to cyber security concerns, pose significant hurdles that must be addressed to ensure a smooth and successful transition. In this context, understanding and navigating these challenges is paramount for Singapore to capitalize on the opportunities presented by Industry 4.0 while mitigating potential risks and fostering sustainable growth in the digital age [151]. Singapore faces several challenges as it transitions towards Industry 4.0:

a) Workforce skills gap: There's a need to equip the workforce with the necessary skills for digitalization, automation, and data analytics. Upskilling and reskilling programs are crucial to ensure that workers can adapt to new technologies and roles.
b) Cyber security concerns: With increased connectivity and reliance on digital systems, Singapore must address cyber security risks. Safeguarding critical infrastructure and sensitive data against cyber threats is essential for maintaining trust and reliability in Industry 4.0.
c) Adoption by SMEs: Small and Medium Enterprises (SMEs) may struggle with the cost and complexity of implementing Industry 4.0 technologies. Support mechanisms, including funding and technical assistance, are necessary to facilitate SMEs' adoption and integration into the digital ecosystem.
d) Regulatory frameworks: As Industry 4.0 technologies evolve rapidly, there's a need for flexible and adaptive regulatory frameworks. Regulations must balance innovation with concerns such as data privacy, intellectual property rights, and ethical implications of emerging technologies like AI and automation.
e) Infrastructure and connectivity: Reliable infrastructure, including high-speed internet connectivity and robust digital infrastructure, is essential for the seamless operation of Industry 4.0 technologies. Ensuring nationwide access to such infrastructure is critical for equitable participation in the digital economy [152].

Addressing these challenges requires a multi-stakeholder approach involving government, industry, academia, and civil society to foster an ecosystem conducive to the successful adoption and implementation of Industry 4.0 initiatives in Singapore.

4.4. Fourth Industrial Revolution (IR 4.0): Industry 4.0 in Malaysia

Malaysia stands at the cusp of the Fourth Industrial Revolution (IR 4.0), poised to embrace the transformative potential of advanced digital technologies in its industries. With the advent of Industry 4.0, characterized by the convergence of cyber-physical systems, automation, and data analytics, Malaysia's economic landscape is undergoing profound shifts. This era promises unprecedented opportunities for innovation, efficiency, and competitiveness, while also presenting significant challenges in terms of workforce readiness, digital infrastructure, and regulatory frameworks. Understanding Malaysia's journey towards Industry 4.0 and its implications for economic development and societal advancement is essential for charting a path towards sustainable growth and prosperity in the digital age. Embracing Fourth Industrial Revolution (IR 4.0) initiatives, Malaysia is strategically positioning itself to leverage cutting-edge technologies and drive economic transformation across sectors [153].

4.4.1. Malaysia Government Strategy for INDUSTRY 4.0 Transformation

Malaysia's Strategies and Action Plans for Industry 4.0 encompass a multifaceted approach to address key areas crucial for digital transformation. This includes encouraging the deployment of converged networks, assessing and digitalizing government processes, strengthening workforce skills, fostering innovation through R&D initiatives, ensuring robust cyber security measures, and promoting smart manufacturing adoption to drive sustainable economic growth and competitiveness Top of Form [154]. Detailed strategies and action plans for Malaysia’s Industry 4.0 transformation are as follows:

a) Converged networks: Encouraging the deployment of converged networks essential for Industry 4.0 technologies is a key objective. Converged networks, which integrate data, voice, and video services, play a pivotal role in facilitating seamless connectivity between machines, sensors, and devices within the Industry 4.0 framework. This integration involves implementing 5G networks to enable ultra-fast data transfer, low latency, and reliable communication, alongside edge computing, which distributes computing power closer to data sources such as the factory floor for real-time processing. Furthermore, ensuring compatibility with Internet of Things (IoT) devices is crucial. The impact of converged networks is substantial, enhancing data exchange capabilities, enabling predictive maintenance practices, and supporting real-time decision-making processes [155].
b) Digitalization and integration of government processes: Assessing priority government-related

processes impacting manufacturing and supply chains is the objective, recognizing the significance of streamlining administrative processes for efficient manufacturing. This entails several actions, including process mapping to identify bottlenecks, paperwork, and manual steps in government procedures, as well as automation to digitize approvals, permits, and compliance checks. Additionally, ensuring interoperability to facilitate seamless data exchange between government agencies and businesses is crucial. The impact of these efforts is substantial, leading to reduced administrative burden, faster approvals, and smoother cross-agency interactions, ultimately enhancing the overall efficiency of manufacturing and supply chain operations [156].

c) Human capital development: Strengthening the workforce's skills to adapt to technological advancements is the objective of human capital development, recognizing the pivotal role of investing in human capital to ensure a skilled workforce ready for Industry 4.0. This entails various actions, including the development of training modules focusing on digital literacy, data analytics, and automation, as well as upskilling and reskilling initiatives aimed at equipping existing workers with relevant Industry 4.0 competencies. Moreover, fostering partnerships with educational institutions to align curricula with industry needs is essential. The impact of these efforts is profound, as a skilled workforce drives innovation, productivity, and competitiveness, thereby contributing to the overall success of manufacturing and industrial sectors in the digital age [157].

d) Research and development: Fostering innovation through Research and Development (R&D) initiatives is the objective, emphasizing the importance of encouraging collaboration between industry, academia, and research institutions. This involves establishing R&D hubs focused on emerging technologies such as AI and robotics, known as technology clusters, to facilitate interdisciplinary collaboration and knowledge exchange. Additionally, providing incentives for private sector R&D, including tax breaks, grants, and funding for innovative projects, incentivizes investment in research and technology development. Collaborative projects, such as joint ventures between industry and academia, play a crucial role in developing cutting-edge solutions and accelerating technology adoption. The impact of these efforts is significant, leading to accelerated technology adoption and the emergence of homegrown innovations that drive economic growth and competitiveness [155].

e) Cyber security readiness: Ensuring robust cyber security measures to protect digital infrastructure is the objective of cyber security readiness, recognizing the critical importance of addressing cyber threats in the context of Industry 4.0. This entails several actions, including conducting risk assessments to identify vulnerabilities and assess potential risks, as well as implementing industry-specific cyber security protocols to safeguard against various threats. Moreover, training staff on safe practices and threat detection enhances employee awareness and resilience against cyber attacks. The impact of these efforts is significant, as they contribute to safeguarding critical data, preventing disruptions to operations, and maintaining trust in digital systems and processes [158].

f) Promote smart manufacturing adoption: The objective is to promote the adoption of smart manufacturing practices among companies, recognizing the significance of data-driven decision-making and automation in enhancing operational efficiency and competitiveness. This involves several strategies, including conducting awareness campaigns to educate businesses about the benefits of smart technologies and the potential for increased efficiency and reduced waste. Financial incentives, such as tax breaks, are provided to incentivize the adoption of smart solutions. Additionally, collaboration platforms are established to facilitate knowledge sharing among industry players, fostering innovation and best practices in smart manufacturing. The impact of these initiatives is substantial, leading to increased efficiency, reduced waste, and enhanced competitiveness for businesses embracing smart manufacturing practices [155].

4.4.2. Challenges Facing Malaysia Toward Industry 4.0

Malaysia faces challenges in its transition towards Industry 4.0, including workforce skills gap, cyber security risks, and ensuring equitable access to digital infrastructure. Overcoming these hurdles requires concerted efforts in upskilling, cyber security preparedness, and infrastructure development to fully harness the benefits of Industry 4.0. Here is the comprehensive overview of the challenges facing Malaysia in its transition towards Industry 4.0 [159]:

a) Workforce skills gap: One of the primary challenges is the existing gap in the skills of the Malaysian workforce compared to the demands of Industry 4.0. There's a need to equip workers with digital literacy, data analytics, programming, and problem-solving skills to thrive in an increasingly automated and technology-driven environment.

b) Cyber security risks: With the increased adoption of digital technologies and interconnected systems in Industry 4.0, Malaysia faces heightened cyber security risks. Protecting critical infrastructure, sensitive data, and intellectual property from cyber threats such as hacking, data breaches, and ransomware attacks is paramount to ensure the integrity and security of digital ecosystems.
c) Infrastructure development: Ensuring widespread access to robust digital infrastructure, including high-speed internet connectivity and reliable communication networks, remains a challenge, particularly in rural and remote areas. Addressing infrastructure gaps is crucial to enable seamless connectivity and support the deployment of advanced technologies essential for Industry 4.0.
d) Regulatory frameworks: Malaysia needs to develop agile and adaptive regulatory frameworks to keep pace with the rapid advancements in technology and innovation associated with Industry 4.0. Balancing the need for innovation with concerns related to data privacy, cyber security, intellectual property rights, and ethical considerations presents a significant regulatory challenge.
e) Digital divide: Bridging the digital divide between urban and rural areas, as well as among different socioeconomic groups, is essential to ensure inclusive growth and participation in the digital economy. Efforts to improve digital literacy, provide affordable access to digital technologies, and promote digital inclusion programs are crucial to address this challenge.
f) Adoption by small and medium enterprises (SMEs): SMEs, which form the backbone of Malaysia's economy, may face barriers to adopting Industry 4.0 technologies due to factors such as limited financial resources, technical expertise, and awareness. Providing support mechanisms such as funding, training, and technical assistance tailored to the needs of SMEs is essential to facilitate their integration into the digital ecosystem.
g) Cultural and organizational change: Embracing Industry 4.0 requires significant cultural and organizational change within Malaysian businesses and institutions. Encouraging a culture of innovation, risk-taking, and lifelong learning, as well as fostering collaboration and knowledge sharing, is essential to drive successful digital transformation initiatives.

Addressing these challenges requires a coordinated and multi-stakeholder approach involving the government, industry players, academia, and civil society to develop comprehensive strategies and initiatives aimed at overcoming barriers and leveraging the opportunities presented by Industry 4.0 for Malaysia's sustainable economic growth and development.

5. Indonesia toward Industrial 4.0

To be involved in the Industrial 4.0 era, the President of the Republic of Indonesia launched a national initiative called "Making Indonesia 4.0" on April 4, 2018. This initiative aims to support the industrial transformation in Indonesia towards Industry 4.0. The long-term goal is to bring Indonesia up to become the 10th largest economy by 2030. The strategy presented by the Ministry of Industry of the Republic of Indonesia consists of returning the industry's net export level to 10 percent (the same level as in 2000), doubling the level of labor productivity above labor costs similar to India's pace of improvement where output is increased while managing costs, and allocates 2% of GDP to R&D with building local innovation capacity that contributes significantly to the progress of national industry (similar level to China) [160]. To achieve this, the Indonesian government has made a policy regarding ten national priority strategies consisting of improving material flows, structuring industrial estates, improving the capability of human resources, supporting Micro, Small, and Medium Enterprises (MSMEs), implementing technology investment incentives, establishing an innovation ecosystem, attracting foreign investment, harmonization of policies and regulations, building a national digital technology infrastructure, and accommodating sustainability standards.

One of Indonesia's strategies for entering the Industrial 4.0 era is to prepare five manufacturing sectors to serve as pilot projects for strengthening and empowering the fundamental structure of the national industry. The five sectors are the Food and Beverage Industry, Automotive Industry, Electronic Industry, Chemical Industry, and Textile Industry. Accordingly, this strategy will encourage the Indonesian Investment Coordinating Board or Badan Koordinasi Penanaman Modal (BKPM) to carry out its role in encouraging foreign and domestic investment, especially in the five industrial sectors mentioned above. Previously, BKPM data stated that the realization of investment in 2011 - 2017 was dominated by the secondary sector. The Food Industry accounts for the largest portion with a total realized investment (both domestic and foreign) of IDR 302.8 trillion. Followed by Basic Metals, Metals, Machinery, and Electronics in second place (IDR 299.0 trillion); Basic Chemicals, Chemicals, and Pharmaceuticals in third place (IDR 285.5 trillion); and other Transportation Industries in fourth place (IDR 160.3 trillion). The Textile Industry as the last component of the main sector of Industry 4.0 is in eighth place with a realized investment value of IDR 58.3 trillion. According to these records, Indonesia is already on the right track to welcome the Industry 4.0 era [160].

Currently, the implementation of the “Making Indonesia 4.0” initiative has been carried out consistently by the Ministry of Industry, Republic of Indonesia. The programs that have been successfully implemented are:

a) Awareness related to Industry 4.0 in around 2000 industries in Indonesia.
b) Certification and training of Industry 4.0 transformation managers in companies in Indonesia. By the end of 2019, around 300 people had received this training. More than 50% of the trainees have started the transformation in their respective companies.
c) The invention of INDI 4.0 (Indonesia Industry 4.0 Readiness Index), is an index to measure the readiness of industries in Indonesia to transform towards Industry 4.0. Currently, 600 companies have conducted assessments with INDI 4.0. From the results obtained, in general, the industry in Indonesia is quite ready to transform towards Industry 4.0.
d) The establishment of the Industrial Ecosystem 4.0 (SINDI 4.0), to accelerate the digital transformation that exists in each company.
e) The establishment of the Indonesian Digital Innovation Center (PIDI) 4.0, an innovation institution that functions as a research/innovation center, showcase center, capability center, ecosystem center, and delivery center.

With the “Making Indonesia 4.0 initiation, many industries in Indonesia are now aware of the transformation of Industry 4.0. Around 500 companies have started transformation projects toward Industry 4.0. Currently, there are already 2 companies in Indonesia that have become Lighthouse Industry 4.0 of the World Economy Forum (WEF) vision, which is PT. Schneider-Electric Manufacturing Batam and PT. Petrosea in East Kalimantan is presented in **Figure 9**. According to **Figure 9**, Indonesia is the only one that has Lighthouse Industry 4.0 in ASEAN until 2019. This reveals that Indonesia is ready to implement Industry 4.0. After implementing Industry 4.0, PT. Schneider Batam was able to increase labor productivity by 13%, reduce scrap costs by 40%, and increase operational efficiency by 12%. While PT. Petrosea East Kalimantan with the implementation of Industry 4.0 was able to reduce total costs by 12% and increase productivity by 32% [161].

From the initial results seen at the end of 2019, the implementation of the Making Indonesia 4.0 initiation showed positive results. However, to make the impact even bigger, a massive industrial transformation is needed. Therefore, a guidebook has been compiled as a reference in the transformation process in the company, so that it can be used as a reference for companies to transform their factories to Industry 4.0.

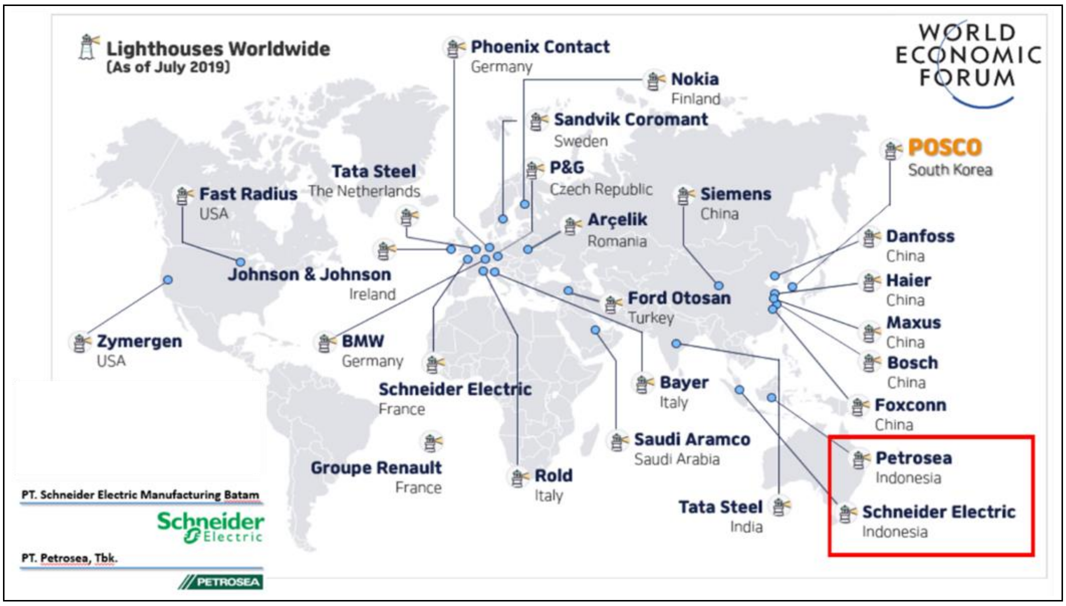


Figure 9. Lighthouse Industry 4.0 version WEF [161]

5.1. Challenges Facing Indonesia Toward Industry 4.0

Currently, Indonesia faces tough competition from other developing countries such as China, Vietnam, and Thailand. Many other challenges remain but the Indonesian government has adopted many positive strategies to meet these goals. There are four major challenges faced by Industry 4.0 in Indonesia, including capability issues, funding problems, lack of suppliers of digital technology systems and infrastructure for Industry 4.0, and overlapping regulations and policies that require further synchronization.

a. Developing local skills and talents

Technological developments will disrupt all business lines, including the requirement for manpower that leads to competent human resources in responding to the challenges of technological change and future needs. The government pays special attention to early childhood education considering that this period is a golden age for the development of the human brain as a prerequisite for being able to attend further education. The government has prepared an allocation of funds for education amounting to 20% of the state budget, mainly for increasing human resources that are economically competitive. The value for 2022 is around Rp. 541.7 trillion. Our problem is how to prepare a workforce that has the capacity [160].

In addition, the problem of distribution and quality of teachers, the process of teaching and learning through technology, as well as the content of education itself. The ratio of the number of teachers to students, around 18, is comparable to that of developed countries. However, teacher distribution and teacher quality are challenges. In terms of content, learning from Vietnam, Indonesia needs to create a simpler curriculum that focuses on reading, mathematics, and natural sciences so that children are less burdened but focus on what is important for them to be able to face a very fast world. Furthermore, the Indonesian government's policies are specifically carried out through several fiscal policies. Examples include, among others, the allocation of funds for the Family Hope Program, the Bidik Misi scholarship to provide opportunities for school-age children, especially from poor families, deduction tax for research, and double deduction tax for companies that provide HR training.

b. Funding advances Industry 4.0 manufacturing capabilities

The requirement of industrial financing cannot be met from policies that are only directed at providing industrial incentives, but a competitive industrial financing system is needed in particular. Several things need to be considered in order to increase the role of banking, such as: providing ease of application procedure; providing competitive loan interest rates or providing debt subsidy assistance mechanisms; and providing convenience in debt restructuring. Meanwhile, the problems of disbursement of funds in the manufacturing industry consist of Maturity mismatch, where banks only tend to provide short- and medium-term financing, because many sources of bank funding are dominated by short-term sources of funds; Limited human resources of banks who have expertise in the industrial sector; Limitations of financing schemes that can be financed by banks, especially in the form of project bases (banks tend to ask for collateral) and for businesses that are just starting (start-up business) as well as industries that are still in the early stages of development (infant industry) which require incentives for banks to dare to finance. In terms of the industrial sector, the limited use of bank credit is partly due to the relatively high-interest rates of banks because they are financed by short-term public funds, so it is necessary to establish a financial institution that can guarantee the availability of investment financing with competitive interest rates [162].

c. Lack of suppliers of digital technology systems and infrastructure

Most business people have not been able to fully implement Industry 4.0 practices due to the limitations of available technology, both for hardware and software. The lack of reliable technology providers in Indonesia means companies have to wait longer to get the technology they need, and this can result in significant missed opportunities. Opening access to technology providers from other countries such as Singapore, New Zealand, Taiwan, Japan, etc., and it will be very beneficial in accelerating the practice of Industry 4.0. Other countries have developed advanced technologies that combine physical, digital, and cyber-physical aspects to implement Industry 4.0. Some of the services offered include manufacturing research and development (R&D), lean manufacturing training, 3D printing, and the use of industrial robots. The application of Industry 4.0 allows a country to maximize its limited resources to meet optimal production volumes, efficiency, and safe practices.

Industrial Technology 4.0 generally prioritizes automation and integration of information technology that enables a better decision-making process, mitigates risks, and achieves targeted results such as efficiency, security, and consistency. One of the pillars of Industry 4.0 is factory operations, which can directly support the entire system. For example, Industry 4.0 allows factories to carry out preventive maintenance to reduce the risk of downtime. Data connectivity will help identify the condition of each part so that it can be repaired or replaced before a breakdown or damage occurs. In addition, with various new practices that have emerged as a result of the COVID-19 pandemic, safer operations are becoming increasingly important and are expected to continue in the future.

d. Overlapping regulations and policies that require further synchronization

Indonesia is a country based on the law as stated in the 1945 Constitution of the Republic of Indonesia, so any action must not violate the law. Meanwhile, related to Industry 4.0, Indonesia does not yet have a national law that regulates this problem. The existence of a law related to Industry 4.0 is important to regulate the standards used for companies, especially when the current conditions are increasingly progressive in using robots to replace or assist human work. If a robot commits an act that violates state laws, such as causing murder, then who will be held responsible for that action? It seems impossible to put the responsibility on the robots. Are robot makers, governments, or companies responsible for the actions of robots? These things are only a piece of doubt to face the new Industrial Revolution. Therefore, harmonization is needed for the rules and policies that have not been finalized by the Indonesian government.

5.2. Indonesia Industry 4.0 Readiness Index

To find out the work steps of industrial readiness level in Indonesia to transform to Industry 4.0, the author with the Industrial Research and Development Agency (IRDA) in Indonesia called Badan Penelitian dan Pengembangan Industri (BPPI), Indonesian Ministry of Industry in 2018 compiled an index called INDI 4.0. INDI 4.0 stands for Indonesia Industry 4.0 Readiness Index; a national index used to measure the readiness of industries in Indonesia to implement Industry 4.0. INDI 4.0 was compiled jointly by industry, Government, academics, experts, and consultants. With various considerations, it was decided that INDI 4.0 was compiled by the BPPI team in collaboration with related academics and experts. After the workshop in Batam, a core team of INDI 4.0 formulators was drawn up whose task was to compile the INDI 4.0 draft. The team then developed and drafted INDI 4.0. After that, discussions regarding the INDI 4.0 concept continued to be finalized after hearing input from experts, industry, and academics. In general, the work steps for the preparation of INDI 4.0 can be seen in **Figure 10**.

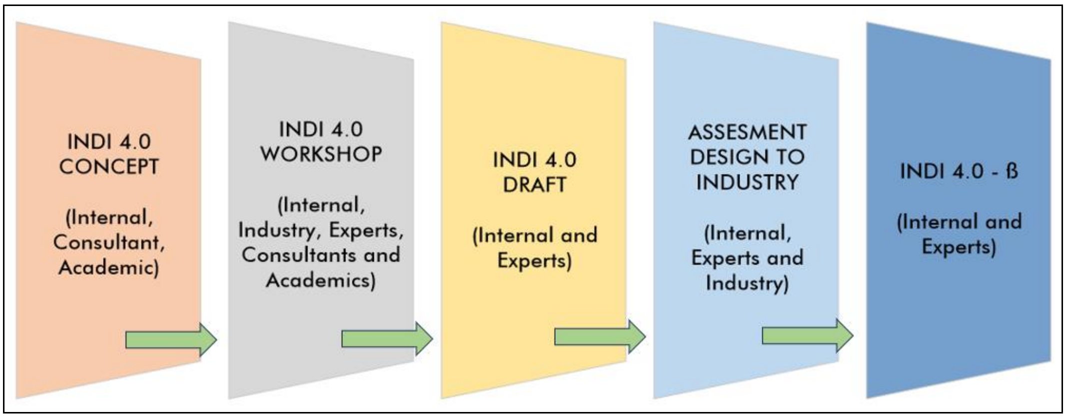


Figure 10. Work steps for the preparation of INDI 4.0. Adapted from [163]

After the INDI 4.0 draft was formed, socialization of INDI 4.0 was carried out to industry and related stakeholders. Furthermore, responses and input from the socialization event were used as input to improve the INDI 4.0 draft, especially related to survey methods and verification methods. There are five pillars that need to be measured in INDI 4.0, i.e., (1) management and organization structure, (2) people and culture in the industrial sector, (3) products and services improvement, (4) technology related to the research and development, and (5) factory operation and sustainability. The five pillars then were further divided into 17 fields. These 17 fields are used as a reference to measure the readiness of industries in Indonesia to be transformed into Industry 4.0. The front page of the INDI 4.0 book and the classification of its constituent criteria can be seen in **Figure 11**.

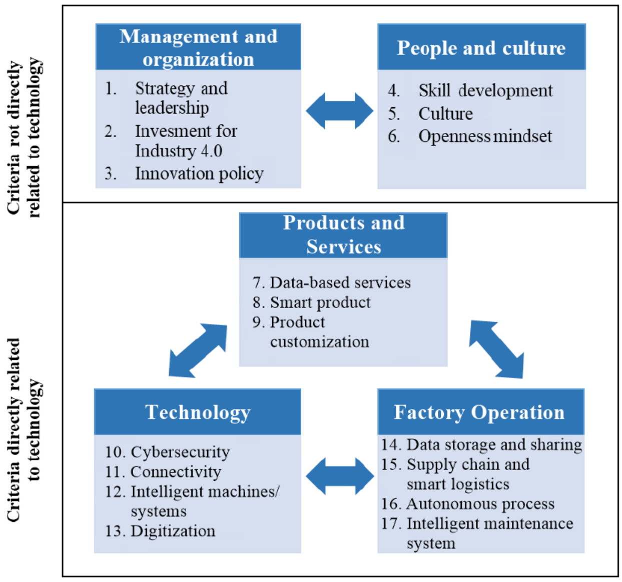


Figure 11. Classification of INDI 4.0 criteria. Adapted from [163]

The assessment method uses an online survey filled out by the industry followed by field verification conducted by experts. In INDI 4.0, the score ranges from 0 to 4 level. Level 0 indicates the industry is "not ready" to transform into Industry 4.0. The company assessed in level 1 means it is still at the "early readiness" stage. For level 2 result means the industry is at the "moderate readiness" stage. The assessed company with level 3 means a "ripe readiness" stage to transform into Industry 4.0. At last, level 4 means that the industry has "implemented" most of the concepts of Industry 4.0 in its production system as presented in **Figure 12**.

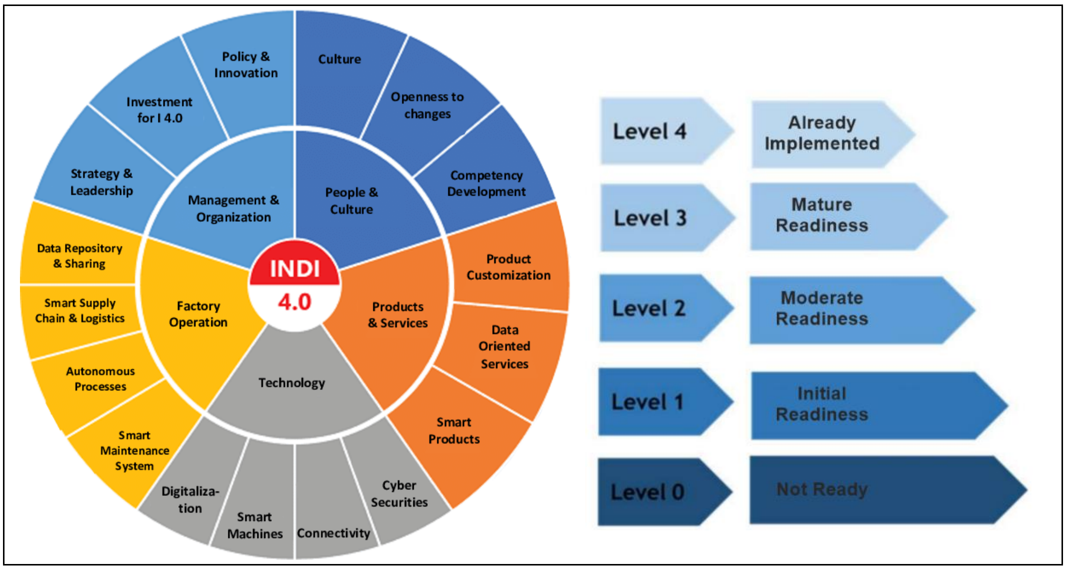
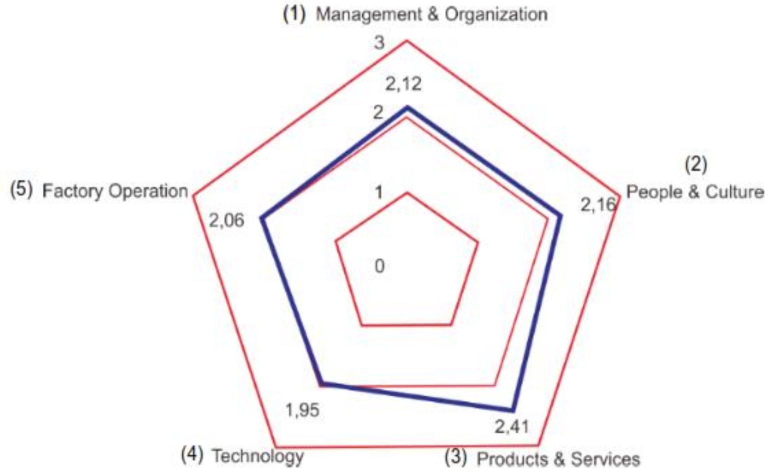


Figure 12. INDI 4.0 – Pillars and readiness index to transform to Industry 4.0. Adapted from [163]

5.3. Readiness of the Manufacturing Industry in Indonesia Toward Industry 4.0

There are five pillars in self-assessment to obtain an INDI 4.0 score i.e. (1) Management and Organization, (2) People and Culture, (3) Products and Services, (4) Technology, and (5) Factory Operation. From the self-assessment results conducted by a number of manufacturing companies in Indonesia in 2019 based on INDI 4.0 self-assessment pillars and tools, it is known that the average readiness index for Industry 4.0 transformation is at a moderate level i.e. 2.14 as presented in **Figure 13**. According to the spider chart of the five pillars presented in **Figure 13**, Technology pillar is the lowest self-assessment value with 1.95. In contrast, Products and Services pillar is revealed as the highest self-assessment value with 2.41.

As of April 2019, at least 326 companies have carried out self-assessments using INDI 4.0. From the data collected, at least it can get an overview of the readiness of the manufacturing industry in Indonesia to move towards Industry 4.0. Of the eight industrial sector categories, food and beverage, textile, chemicals, and EPC sectors are the industries that are almost ready to transform towards Industry 4.0 becuase it is above the INDI 4.0 average value. In addition, there are already 11 companies that have carried out self-assessment in the various sectors with an INDI 4.0 score at the level of 1.97 which slightly lower than the national average. For the highest participation is in the automotive sector with 196 industries, however, the INDI 4.0 score is lower that the average with 1.72 score.



Industry Sector	Total	(1) Management & Organization	(2) People & Culture	(3) Products & Services	(4) Technology	(5) Factory Operation	INDI 4.0 Score
1. Food and beverages	39	2.50	2.51	2.61	2.31	2.42	2.47
2. Textiles	10	2.70	2.50	2.77	2.26	2.30	2.51
3. Chemicals	30	2.34	2.33	2.41	2.13	2.33	2.31
4. Automotive	196	1.35	1.83	2.03	1.49	1.83	1.72
5. Electronics	28	1.47	1.89	2.24	1.63	1.90	1.84
6. Metal	11	1.50	1.70	2.03	1.15	1.41	1.57
7. Various	11	1.94	2.29	1.98	1.64	1.75	1.97
8. EPC	1	3.17	2.22	3.17	3.00	2.50	2.74
Total/Average	**326**	**2.12**	**2.16**	**2.41**	**1.95**	**2.06**	**2.14**

Figure 13. INDI 4.0 – Self-assessment results in 2019. Adapted from [164]

From the results of INDI 4.0, it is known that the Technology and Factory Operations pillars has a relatively low value compared to other pillars. This shows that the industry's readiness in Indonesia for the application of advanced technology is still lacking. In general, connectivity and digitization in various industries are still lacking. Connectivity means conditions between machines, between systems, as well as machines/systems with humans/employees. The basic philosophy of implementing Industry 4.0 is to connect all machines/systems/humans both in vertical integration and horizontal integration.

6. Further Comparison Discussion Between Developed and Developing Countries

6.1. Challenges Differ According to Country's Level of IR4.0 Development

The Indonesian government has decided to embrace the Industry 4.0 trend, naming it "Making Indonesia 4.0," to prevent lagging behind in the global economy. However, adopting a follower mindset risks detrimental blunders to Indonesia's economic growth, given each country's unique conditions, such as culture, environment, and behavioral characteristics. Based on the literature review, the challenges faced by Germany, China, Singapore, Malaysia, and Indonesia can be categorized in **Figure 14**.

Germany, China, Singapore, Malaysia, and Indonesia, the focus of this discussion, have all identified human resources as a challenge in embracing the Fourth Industrial Revolution. The synergy among employees with various competencies has been shown to enhance a company's competitiveness. Structured formal and informal training is necessary for employees to become more disciplined, creative, and dedicated to continuous innovation. Meanwhile, the Indonesian government has undertaken concrete steps to enhance education quality, including increasing fund allocation, ensuring equitable distribution and quality of teachers, adopting a more practical curriculum, and offering tax incentives to companies contributing to public education improvement.

In Germany, many companies are hesitant to transition to Industry 4.0 due to significant capital costs, particularly when operations and cash flow remain stable and profitable. In Indonesia, banks play a crucial role in providing capital loans to SME-scale companies, necessitating competitive policy breakthroughs. While challenges in capital investment are paramount, German SMEs argue against change when their companies are performing well. Conversely, Indonesia struggles with banking institutions' readiness to finance SMEs transitioning to Industry 4.0.

Each country prioritizes different challenges, reflecting varying needs and circumstances. Germany emphasizes resolving data transfer security and legal regulation to address global supply chain vulnerabilities. China focuses on enhancing research and development collaboration with developed countries to produce high-value research products. Indonesia seeks to increase digital technology suppliers and address legal gaps in regulating robotics in industrial environments, highlighting the need for comprehensive policy frameworks to navigate the fourth industrial revolution effectively.

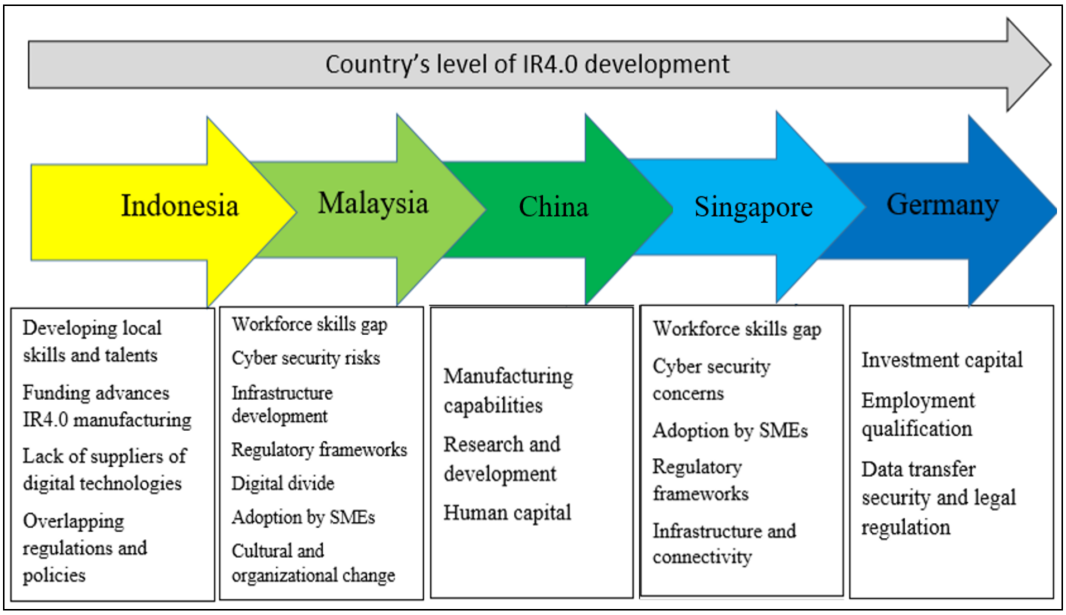


Figure 14. Different challenges according to a country's level of IR4.0 development

Each country prioritizes different challenges, reflecting varying needs and circumstances. Germany emphasizes resolving data transfer security and legal regulation to address global supply chain vulnerabilities. China focuses on enhancing research and development collaboration with developed countries to produce high-value research products. Indonesia seeks to increase digital technology suppliers and address legal gaps in regulating robotics in industrial environments, highlighting the need for comprehensive policy frameworks to navigate the Fourth Industrial Revolution effectively.

6.2. Government Regulation and Readiness Assessment of IR4.0 for Each Country

Government regulations and readiness assessments play a crucial role in facilitating the adoption and implementation of Industry 4.0 (IR4.0) technologies and practices across different countries. In Germany, the government has established comprehensive regulatory frameworks to guide companies in navigating the challenges and opportunities presented by IR4.0. These regulations encompass data protection, cyber security, intellectual property rights, and workforce training initiatives to ensure a smooth transition towards digitalization and automation. Additionally, readiness assessments, such as the Industry 4.0 Readiness Check, provide German companies with structured evaluations of their capabilities and readiness levels for IR4.0 adoption, enabling them to identify areas for improvement and develop tailored strategies. Similarly, countries like China, Singapore, Malaysia, and Indonesia have also implemented government regulations and readiness assessments to accelerate IR4.0 adoption and foster economic growth in the digital age, as presented in **Table 3**. These initiatives aim to create an enabling environment for businesses to thrive amidst the transformative changes brought about by IR4.0.

Table 3. IR 4.0 regulation and readiness assessment for each country

Country	Government regulation or program name	Year launched	Name of readiness assessment
Germany	Industry 4.0 [165]	2011	Industry 4.0 Readiness Check
Singapore	Industry Transformation Map (ITM) [150]	2014-2015	Singapore Smart Industry Readiness Index (SIRI)
China	Made in China 2025 [124]	2015	China Manufacturing 2025 (CM2025)
Malaysia	Fourth Industrial Revolution (IR 4.0) [166]	2016-2017	Industry 4.0 Readiness Assessment Framework
Indonesia	Making Indonesia 4.0 [160]	2018	Indeks Daya Saing Industri 4.0 (INDI 4.0)

The global transition to Industry 4.0 necessitates meticulous readiness assessments and supportive government regulations across various countries. Germany pioneered this movement with its Industry 4.0 Readiness Check, empowering companies to evaluate their technological infrastructure, digitalization strategies, and innovation capabilities through questionnaire-based assessments and personalized recommendations. China's Made in China 2025 (CM2025) initiative assesses manufacturing readiness through comprehensive on-site visits, interviews, and technology analysis. Sample activities within CM2025 include conducting on-site visits to manufacturing facilities, interviewing management and technical teams, and analyzing technology adoption levels and innovation strategies. Meanwhile, Singapore's Smart Industry Readiness Index (SIRI) evaluates companies holistically across technology, process, and organizational dimensions, employing workshops, interviews, and surveys. Sample activities encompass conducting workshops with industry stakeholders, interviewing key personnel to assess digitalization efforts and automation levels, and administering surveys to gauge workforce capabilities. Additionally, Malaysia's Industry 4.0 Readiness Assessment Framework evaluates digital strategies and talent development through interviews, workshops, and surveys, providing comprehensive recommendations for improvement. Similarly, Indonesia's Indeks Daya Saing Industri 4.0 (INDI 4.0) assesses readiness through surveys, focus groups, and on-site visits, offering tailored recommendations. These assessments and regulations serve as vital tools in guiding companies to implement strategic initiatives effectively, ensuring their competitiveness and success in the dynamic landscape of Industry 4.0.

7. Conclusions

A comparative review study on Industry 4.0 development has been conducted. The review study particularly analysed and presented the challenges in implementing Industry 4.0 in developed and developing countries. Germany, China, and Singapore were categoried as a developed country; while Malaysia, and Indonesia were categorised as a developing country. These categories were based on the year of implementing Industry 4.0 which has been presented in Section 6.2.

Germany and China prioritize manufacturing advancements through digitalization and IoT, reflecting their global competitiveness goals. Meanwhile, Singapore implements its Industry 4.0 strategy via the ITM, focusing on manufacturing, R&D, and skills. Similarly, Malaysia prepares for IR 4.0, emphasizing digital transformation across sectors. Challenges such as skills gaps and cyber threats must be addressed for successful Industry 4.0 adoption, ensuring sustainable growth and competitiveness. The convergence of these efforts underscores the global shift towards a digitally driven industrial landscape. Globally, numerous countries are embracing the ethos of Industry 4.0 revitalization, propelled by digital technology and the internet. According to Deloitte's predictions, the United States leads the world in manufacturing competitiveness and technological advancement, followed by China, representing European nations such as Germany, Japan, India, and South Korea, among others. Korea, representing Asia, Mexico for Latin America, and Taiwan, Canada, and Singapore, the latter being a small Southeast Asian country with the highest GDP, are also noteworthy players in the global manufacturing arena.

Germany is more confident with its technological progress because it does not consider manufacturing technology the main challenge. However, based on the literature study, we found that Germany considers the main challenges to be Investment Capital, Employee Qualifications, and Labor Security. Using Data Transfer and the Legislation that protects it. In contrast to China, which places Manufacturing Capabilities as the main challenge that must be answered with technology, the next challenge is that Research and Development, and R&D must be increased in intensity and quality, and Human Capital must be increased to meet the needs of industrial revitalization. China is still focused on low-value manufacturing production even though the quantity is large. This is related to the Chinese government's policy of protecting small industries such as MSMEs and small industries, which have survived amidst intense business competition. The Chinese government plans to become the world's leading manufacturing industry, as stated in "Made-in-China 2025". Singapore and Malaysia both grapple with multifaceted challenges in transitioning to Industry 4.0. Singapore focuses on workforce skills, cyber security, SME adoption, regulatory agility, and infrastructure. Malaysia addresses similar hurdles, including workforce skills, cyber security, and digital infrastructure access. Collaboration among stakeholders is crucial for both nations to develop adaptive regulations, bridge the digital divide, support SME integration, and foster cultural changes. A coordinated approach is essential for leveraging Industry 4.0 opportunities and ensuring sustainable economic growth.

The low labor productivity factor was one of the reasons for the initiation of Making Indonesia 4.0, the Indonesian version of Industry 4.0. The main objective of this fourth industrial revitalization is to make Indonesia a top ten global economic power by 2030. The implementation of the Making Indonesia 4.0 initiative shows a positive direction. However, this movement requires massive industrial transformation to have a significant impact. For companies in Indonesia, the average Industry 4.0 transformation readiness index is at a medium level with a value of 2.14 (INDI 4.0 scores range from level 0 to level 4) from the results of self-assessments carried out by manufacturing companies in Indonesia in 2019. The INDI 4.0 instrument revealed that the Technology and Factory Operations pillars had the lowest scores compared to other pillars. On the other hand, the workforce's quality is a challenge every country faces. Everyone applies training as the primary way to increase creativity and dedication without abandoning discipline and a good attitude.

Future works of this review study will present the Industry 4.0 assessment methods in other developed and developing countries. With more more dicussion on the Industry 4.0 assessment on developed, developing countries can benchmark and learn from the develop countries to achieve a better Industry 4.0 tranformation and application. With more comprehensive Industry 4.0 review study in developing countries, it can be revealed which pillar or criteria need to be improved. Transfer technology from developed countries to developing country will also an effect of the review study related to the Industry 4.0 in the future.

Author's Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation, and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials - We do not analyse or generate any datasets, because our work is a comparative review

Competing interests - The authors declare no competing interest.

Additional information – No additional information from the authors.

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