

Key requirements for establishing dark factories as a pillar of technological development and the digital transformation of the global economy

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Received: 18/01/2026

Accepted: 10/03/2026

Published: 27/03/2026

Abstract:

The research has shed light on one of the most important technological developments, which is dark factories, which are considered one of the most important applications of the Fourth Industrial Revolution in recent decades, as they provide solutions to some of the problems that traditional factories suffered from. The research has concluded that in order to establish and develop dark factories, some requirements must be provided, the most important of which is that the human element does not interfere in the production process or reduces its interference. It complements its activity by providing some technological equipment and programs for construction and development and thus developing the global economy.

Keywords: Dark Factories; Global economy; Artificial Intelligence; Internet of Things; Production process.

Jel Classification Codes : O31, F02, O33, L86, L23.

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1. INTRODUCTION

Dark factories are manufacturing facilities characterized by high levels of automation, designed to operate with minimal to no human intervention. Within the framework of the Fourth Industrial Revolution, these facilities represent a significant shift in production paradigms, integrating advanced robotics and the Internet of Things (IoT) to enhance operational efficiency. As the global business environment becomes increasingly characterized by rapid technological change, the adoption of such automated systems is often viewed by industrial organizations as a strategic response to maintain competitiveness in a globalized market.

The rapid expansion of dark factories presents multifaceted challenges for economic institutions, necessitating strategic adaptations in infrastructure and development. Adopting such automated systems is often driven by the need to align with evolving global demand and to mitigate the structural limitations inherent in traditional manufacturing models.

1.1 The main problem of the Research :

In order for economic institutions to adopt dark factory technology through construction and development to keep pace with the rapid changes and developments in the global economy:

What are the requirements for establishing and developing dark factories, which are considered a pillar of technological development and the digital transformation of the global economy?

1.2 Importance of the Research :

The significance of this research lies in its examination of dark factories as a prominent technological development within the framework of the Fourth Industrial Revolution. Through a systematic analysis, this study seeks to identify the core technical and operational requirements necessary for the establishment and advancement of these fully automated facilities in the global economy.

2. The Origin and Concept of Dark Factories:

No direct human involvement in core production processes. While the aspiration toward highly automated production systems can be traced back to early twentieth-century industrial automation efforts, the contemporary notion of dark factories has emerged more clearly within recent decades as digital technologies have matured.

Dark factories represent an advanced stage in the evolution of manufacturing technologies. Their accelerated development is closely associated with progress in key technological domains, particularly communication technologies, the Internet of Things (IoT), artificial intelligence, and advanced robotics. These enabling technologies have provided the technical infrastructure necessary to support autonomous, interconnected, and data-driven production environments.

Accordingly, the major stages in the development and emergence of dark factories can be outlined as follows:

- **Before 1990 :** At this stage, the idea of building factories that can operate without lights emerged in the early 1980s, that is, building factories in the dark to carry out production operations because they do not need light, as they operate in the presence of robot workers. The first company that sought to embody the idea was the Japanese company "FANUC" ;
- **Between 1990 and 2000 :** This stage was marked by the inability to implement the idea due to several technical challenges. Among the most significant obstacles were the limited research in the technological field, particularly regarding internet development and speed, artificial intelligence, and other highly technical aspects related to the robots performing the production process ;
- **After 2000 :** This stage witnessed tremendous development in various technological fields, in which the Fourth Industrial Revolution and all the technologies accompanying it appeared, so more realistic and intelligent dark factories were established by integrating robotic machines with artificial intelligence and machine learning, in addition to the Internet of Things and fifth generation networks for automatic self-monitoring, for

automatic self-intervention.

From all of the above, the term dark factories are considered an emerging and modern term that reflects a very advanced application of technology in the process of producing products. The most important definitions of this term are:

- The innovation and strategy consultancy firm "Stellarix" defines the dark factory (or dark factories) as a fully automated environment where all manufacturing processes are carried out by machines without any human intervention, from raw material procurement and processing to shipping and storage. In other words, the entire manufacturing or production process is performed by machines. The term "dark" means that these factories do not require lights or other energy uses are required. The minimal lighting is reserved for monitoring and surveillance systems and highly sophisticated sensors ; (Stellarix, 2025, p. 1)
- A dark factory, or "automated factory", is a fully automated factory that requires minimal or no human intervention. It works almost completely with very advanced technologies, primarily artificial intelligence, robotics, and the Internet of Things (IoT). To achieve optimal production, the factory operates without any human intervention. This process maximizes production efficiency, minimizes production costs, and reduces errors to the lowest possible levels ; (ATS, 2025)
- An automated factory (or dark factory) is a place for manufacturing or production where raw materials enter and finished products leave, with little or no human intervention. (Jacques Mezhrhid, 2023)

From the previous definitions, the concept of dark factories has become clear, and can summarize the definition as follows:

Dark factories are manufacturing places for the production of finished products from the beginning by introducing the raw material to the end by finishing and storing. The manufacturing process is fully automated by integrating very advanced technologies and helping with that. There is no human intervention, or the intervention is at its lowest limits. These factories also operate without lighting and without other uses of energy that

are used to provide the appropriate atmosphere for work, because the workers are robots. These factories have positive effects on productivity and lower costs and errors.

Integrating advanced technologies enables a more comprehensive conceptualization of the transition from conventional manufacturing facilities to autonomous dark factories, as illustrated in the figure below.

Fig.1. Transition from ordinary factories to dark factories



Source: Prepared by the researchers based on: (YuanYuan Liu & Jun-Ho Huh, 2025, p. 338)

3. Tools for setting up dark factories and their benefits :

For dark factories to operate, certain important Tools must be provided to ensure smart and technologically advanced manufacturing. Among the most important of this Tools are :

- **A range of automated and specialized robots :** Dark factories must have a range of fully automated robots, tailored to the specific needs of the factory's operations, to perform assembly, production, inspection, and material handling activities. This includes autonomous vehicles ;
- **Highly advanced sensor equipment for monitoring and surveillance :** Sensors must be installed throughout the dark factory's operational areas. These sensors accurately transmit signals representing all movements within the dark environment ;
- **Modern communication networks :** Everything in the dark factories must be connected to 5G networks via IoT sensors to enable real-time data transfer and exchange between the system and various machines ;
- **Manufacturing Execution System :** A comprehensive system for integrating all machines and robots with pre-programmed schedules to

monitor the production process in real time ;

- **Performance Planning** : Planning processes for both raw material intake and finished product output, and programming all input-output operations ;
- **Digital Twin Installation** : For testing, simulating, and optimizing operations within darkened factories in real time ;
- **Artificial Intelligence and Machine Learning** : For monitoring, identifying, and minimizing defects, and predicting all internal requirements of dark factories ;
- **Digital Maintenance Systems and Monitoring Platforms** : Digital maintenance systems must be implemented to track all equipment, machines, and robots operating within dark factories for predictive maintenance requirements, such as the status of spare parts for these machines, and platforms that enable real-time remote monitoring by sending alerts after data analysis.

The dark factories are among the most important applications of technological development and digital transformation in the manufacturing sector. This is due to the benefits they offer to the global economy, which can be summarized as follows: (Stellarix, 2025, pp. 3-4)

- **Operational efficiency**: The use of artificial intelligence helps reduce resource waste and minimize defects;
- **Massive production**: Production in dark factories is known for its very high volumes. This is due to continuous operation without downtime for months at a time, as the production process is carried out by robots;
- **Stable production**: Dark factories provide stable production because they do not operate on shift systems, nor are they subject to rest periods or holidays, unlike conventional factories that rely on human labor;
- **Minimizing costs**: Dark factories offer significant cost savings because they rely on machinery and not human labor. Furthermore, they provide additional savings due to their low energy consumption requirements, as the machines operate without requiring a suitable working environment, unlike human workers ;
- Efficient energy use**: Dark factories use energy solely for production

processes and not for other purposes;

-Enhanced workplace safety: Dark factories rely on machinery for their production processes, operating in confined spaces as required by production demands, and under harsh conditions in temperature and exposure to potentially harmful substances. This ensures safety and reduces the risk of injury;

-Strategic flexibility: These factories are also easy to establish, requiring no strategic location. They can be built anywhere, unaffected by labor availability or living conditions.

Dark factories have a very positive impact on the production process. The following table summarizes the impact:

Table 1. Impacts of Dark Factories on the Production Process

	Impacts	Percentage
01	Production Quantity	50% or More
02	Cost Reduction	Between 20% and 45%
03	Reduction of Production Defects	Less than 0.02%
04	Reduction of Operating Waste	Up to 30%

Source: Prepared by the researchers.

4. Reasons for the Spread and Market Reality of Dark Factories :

The reasons for the widespread use of dark factories as a cutting-edge technology in production processes are linked to a variety of factors, the most important of which are :

- Labor shortages and rising costs: Most major industrialized nations face a labor shortage due to aging populations. Furthermore, labor costs have been steadily increasing. Economic institutions have sought to establish these factories to address these challenges, as they are not affected by demographic changes and offer relatively stable costs over time ;

- The need for continuous and efficient production : The increasing global demand for finished products has led to difficulties for economic institutions in keeping pace, resulting in long waiting periods for orders. Dark factories provide continuous production, 24 hours a day, seven days a week, with very high efficiency and speed ;

- Reducing errors and lowering energy consumption : In Ordinary factories that rely on manual labor, errors increase as workers age or fail to

keep pace with technological advancements. These factories also consume a significant amount of energy due to their various uses. In contrast, dark factories minimize errors and reduce energy consumption to a minimum, as they do not require a suitable working environment like those created by human labor ;

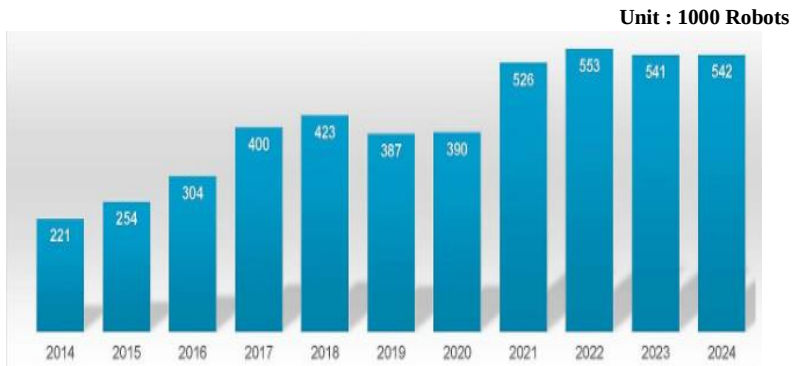
- **Conserving resources** : The global economy is characterized by resource depletion. Economic institutions, in their normal production activities, consume materials without rationalizing their use. Dark factories contribute to the rationalization of resources consumption and prevent waste. They also protect the environment by reducing carbon emissions ;

- **Worker exposure to illnesses and hazards** : Human labor is exposed to significant risks due to its involvement in production processes. It is also susceptible to illnesses and infections. For example, the COVID-19 pandemic, when global production came to a standstill. Dark factories can operate under extremely harsh conditions and are not exposed to significant illnesses and infections.

The dark factories market has witnessed remarkable development in the past few years. This development can be summarized by the following statistics:

- Dark factories depend entirely on machines (robots), they cannot work without them. The use of robots in production processes has increased significantly, until 60% of the world's economic institutions occupy them in at least two production lines. The development and increasing use of robots in production processes can be illustrated by the following figure:

Fig.2. The annual installations of robots



Source: (IFR Press Room, 2025).

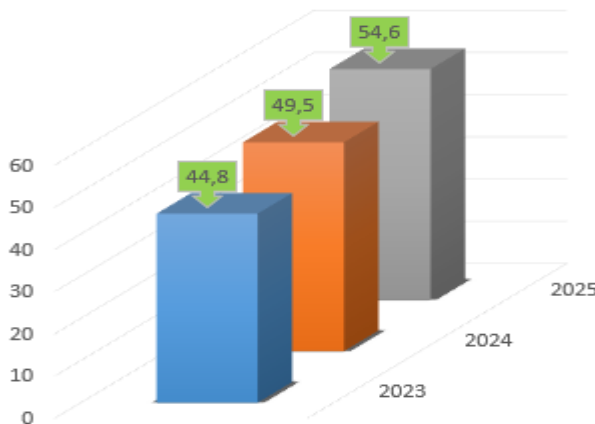
As shown in the previous figure, the number of robots used in the production process more than doubled between 2014 and 2024, a period of ten years. In 2014, there were 221,000 robots used in the production process, rising to 542,000 by 2024, representing a 245.24% increase. However, A significant decrease was observed between 2019 and 2020, which can be attributed to the repercussions of the COVID-19 pandemic.

The new World Robotics 2025 statistics on industrial robots showed 542,000 robots installed in 2024 - more than double the number 10 years ago. Annual installations topped 500,000 units for the fourth straight year. Asia accounted for 74% of new deployments in 2024, compared with 16% in Europe and 9% in the Americas. And, "The new World Robotics statistics show 2024 the second highest annual installation count of industrial robots in history - only 2% lower than the all-time-high two years ago", says Takayuki Ito, President of the International Federation of Robotics. "The transition of many industries into the digital and automated age has been marked by a huge surge in demand. The total number of industrial robots in operational use worldwide was 4,664,000 units in 2024 – an increase of 9% compared to the previous year". (IFR Press Room, 2025)

-While precise statistics on the global dark factory market are unavailable, it has developed rapidly in recent years. In 2023, 2024, and 2025, this market reached a market value of \$44.8 billion, \$49.5 billion, and \$54.6 billion respectively, representing an increase of 121,875%. Over the past decade, this market has maintained an average annual growth rate of

between 9% and 10.3%. This reflects the adoption of dark factories by 60% of economic institutions across all economies. (Coherent market insights, 2025) This development can be summarized in the following figure :

Fig.3. Dark factories market development for the period 2023-2025



Source: Prepared by the researchers based on: (Coherent market insights, 2025).

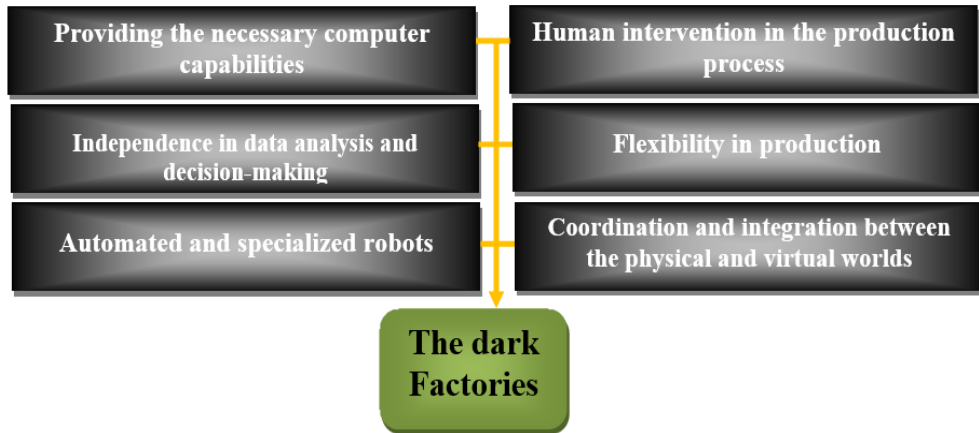
In 2025 : (Coherent market insights, 2025)

- The automotive sector led the market with a 40.8% share;
- The industrial robotics sector dominated the market with a 45.3% share;
- The startup sector achieved a 53.7% share;
- By region, Asia Pacific led the market with a 44.8% share. Latin America was the fastest-growing region with a 32.4% market share.

5. Key requirements for establishing and developing dark factories :

Various studies that have addressed the topic of dark factories have focused on some requirements that help in establishing and developing this type of factory. And the most important of these requirements in the following points :

Fig.4. The most important requirements for establishing and developing dark factories



Source: Prepared by the researchers.

- **Human intervention in the production process** : Human intervention in the production process takes place through two methods, intervention for the implementation of production, or intervention for management for the sake of administration. Through dark factories, this intervention is not available, at least from the implementation side. The factory must operate independently of human intervention except in necessary cases such as major and serious malfunctions and serious emergencies. Therefore, the role of humans in dark factories is limited to the monitoring function only ;
- **Flexibility in production** : The production efficiency in dark factories lies in the ability to deal with changes in the shape and components of products. The most advanced dark factories are not the dark factories that can produce products and allocate a separate production line for each product without any human intervention Rather, they are dark factories that can produce any type of product in the same production line without human intervention and can make internal and formal changes to the products according to requirements. To achieve this, dark factories must be supported by very technologically advanced and intelligent systems in order to be able to achieve the production flexibility that must be reached ;
- **Coordination and integration between the physical and virtual worlds** : In dark factories, there must be complete coordination between what is physical in the factory and what is virtual at the system level. To

reach this level of coordination, some very advanced technologies must be used, most notably digital twin technology, which is based on this coordination to control all the activities of the dark factory using smart sensors and systems that help it do so. If the dark factory reaches these technological applications, it becomes easy to access it in the global virtual world in order to bring some information related to production processes, such as benefiting from all research that can develop products to keep pace with market requirements ;

- **Providing the necessary computer capabilities:** The dark factory to perform its technological and digital functions to coordinate the machines and software it has, the necessary computer equipment capabilities must be provided so that the dark factories can carry out their normal activities. The dark factories must have at least large capacities to store data due to the huge amounts of data that comes to them for analysis and periodic decision-making. And on processors from the latest technological generations so that they can integrate and develop the activities of these factories, and software for artificial intelligence and machine learning that is always self-updating ;

- **Independence in data analysis and decision-making:** Dark factories have the ability to make operational decisions independently, and this can only be achieved by providing software that helps them to analyze the data. Therefore, in order for dark factories to exist, they must have all the capabilities to analyze big data, by providing them with it and securing them from any external penetration in order for them to have the ability to analyze and make decisions ;

- **Automated and specialized robots :** The production activity of dark factories depends on the automated element. Dark factories must be equipped with robots capable of completing all the activities of workers on the same type of production, and that they are in line with the specialization of dark factory production, without neglecting to have them periodically updated for maintenance and replacement with other types of automated robots that are more technologically advanced and capable of greater independence in production. Robots and machines must be more organized

within the factory in order to provide more harmony between them.

6. CONCLUSION

Literature indicates that dark factories—also known as lights-out manufacturing facilities—are environments designed for the autonomous transformation of raw materials into finished products through integrated end-to-end processes. These facilities leverage high-level automation and advanced robotics to minimize or eliminate the need for on-site human intervention. Consequently, such factories can operate without traditional environmental support systems, such as lighting or climate control, which are typically required for human labor. Technical analysis suggests that this model may lead to increased production consistency, potential cost reductions in energy and labor, and a decrease in error rates compared to conventional manufacturing methods.

These are very advanced technological applications of the Fourth Industrial Revolution, from artificial intelligence, digital twin technology, and the modern generation of communication, in addition to other modern technologies. These factories came to solve some of the problems suffered by ordinary factories that depend on the human element. The most important and foremost of these problems is keeping pace with the increasing global demand for final products quickly, and by working around the clock, rationalizing both resource and energy consumption, and reducing errors.

In order to establish and develop this type of factories, some recommendations must be applied as follows:

-The implementation of dark factories requires a comprehensive feasibility study to determine the necessary capital allocation. While the initial acquisition of advanced robotics involves significant capital expenditure (CAPEX), the long-term economic viability is often evaluated through the potential Return on Investment (ROI) derived from the reduction in labor and energy costs, alongside optimized resource utilization. Furthermore, to mitigate the financial burden of large-scale upfront investments, industrial organizations may explore alternative financing models, such as the leasing of robotic equipment from specialized providers;

- The operational efficiency of dark factories relies on the seamless technical and virtual integration of production processes. This integration is achieved through the deployment of cyber-physical systems that facilitate autonomous manufacturing. Such systems are typically underpinned by advanced communication protocols and software platforms, enabling real-time, digital execution of production cycles immediately upon order reception. A primary objective of this architectural design is the comprehensive automation of the entire value chain, encompassing automated storage systems and the synchronized movement of materials into production units without manual intervention;
- The integration of advanced Artificial Intelligence (AI) algorithms is a fundamental determinant of operational performance within dark factories. These systems facilitate the optimization of product design and the autonomous refinement of manufacturing workflows. By leveraging machine learning and predictive analytics, AI-driven architectures enable continuous process improvement and adaptive production strategies, thereby enhancing the overall industrial output;
- The alignment of production processes with international environmental standards facilitates a significant reduction in carbon emissions within dark factories. This transition towards sustainable manufacturing practices allows these facilities to integrate environmental sustainability into their operational framework, often resulting in a lower ecological footprint compared to conventional industrial models;
- A phased transition toward the implementation of dark factory models allows industrial organizations to systematically assess operational requirements and potential risk factors. By initially deploying pilot automated production lines, businesses can evaluate technical byproducts and process methodologies, facilitating a data-driven approach to scaling full-scale autonomous manufacturing.

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