

Lights-out manufacturing between Industry 4.0 and Industry 5.0: efficiency benefits, risks and socio-economic implications

Claudia Isac¹

¹Faculty of Economics, University of Petroșani, Romania, ORCID: 0000-0002-8429-4231

E-mail: claudiaisac@upet.ro

Abstract. This theoretical paper examines lights-out factories as an advanced stage of smart manufacturing at the intersection of Industry 4.0 and Industry 5.0. Building on recent literature, the study conceptualizes lights-out manufacturing as a cyber-physical production paradigm in which automation, robotics and artificial intelligence enable highly autonomous operations, particularly in repetitive, hazardous or ergonomically unfriendly processes. The paper synthesizes the main technological and economic benefits – higher efficiency, extended operating time, improved quality and better safety – while highlighting structural barriers such as high upfront investments, technological complexity and cybersecurity risks, especially for SMEs. Furthermore, it discusses the evolving role of human work, arguing that lights-out factories do not eliminate labour, but shift it towards design, supervision, data analysis and system integration, in line with the human-centric agenda of Industry 5.0. The article concludes that lights-out factories should be understood not only as a technological option, but as a strategic choice with significant implications for employment, skills development and social cohesion in manufacturing-based economies.

Keywords: *lights-out manufacturing, dark factories, Industry 4.0, Industry 5.0.*

Introduction

Currently, digitalization and artificial intelligence are evolving rapidly and driving a technological transformation with profound effects on businesses and industries, enabled by advanced technologies such as automation, the Internet of Things (IoT), artificial intelligence (AI), smart factories and cyber-physical systems [1]. Digital technologies refer to the integration of these technologies into a firm's operations in order to achieve its objectives, and they support a wide range of activities, including strategic planning, general administration and IT management, marketing, advertising and communication, as well as complex production and logistics processes [2].

This digital integration is central to the success of Industry 4.0 and relies mainly on two essential factors: the integration of industrial automation systems, such as cyber-physical production systems, which enables advanced and innovative functionalities by creating complex networks between the actors involved, and interoperability, which plays a crucial role in facilitating production processes, including in situations characterized by lack of continuity, both within organizations and across their boundaries [3].

Industry 4.0 primarily refers to the concept of factories in which machines are complemented by intelligent and autonomous systems and represents a revolutionary era of computers, machines and their interconnectivity with human resources, aimed at higher production efficiency, sustainable environmental outcomes and an improved quality of life [4]. However, what reveals the true potential

of Industry 4.0 is the connection and communication established between computers and machines, which allow decisions to be made without any human intervention. Consequently, the network formed by these interconnected machines and the large amount of data they generate constitutes the real value of Industry 4.0 [4]. Industry 4.0 has fundamentally transformed the traditional factors of production, simultaneously reshaping labour, capital, technology and organizational structures. Building on this, Industry 5.0 places emphasis on sustainability, resilience and the centrality of the human factor, so that production factors are no longer assessed exclusively in terms of economic efficiency, but also in relation to their social and environmental impact. The evolution of these factors of production from traditional industry to Industry 4.0 and Industry 5.0 is presented in the following table.

Table 1. The evolution of production factors under the influence of Industry 4.0 and Industry 5.0

Production Factor	Traditional Role	Industry 4.0	Industry 5.0
Human Capital/ Skills	Traditional technical skills	Advanced technical and digital skills for the workforce [5]	Sustainability, resilience and the centrality of the human factor, with a creative role [6,7]
Capital/ Machinery	Mechanised and semi-automated machines	Interconnected smart equipment and advanced robotics, with the role of production machinery reshaped by connectivity and autonomy [7]	Sustainable and interoperable equipment, with integration of green energy [7,9]
Technology	IT separated from operations	Digital integration with IoT, AI, real-time Digital twins and operational optimization [10]	Ethical, explainable and transparent intelligent systems that support human-machine collaboration, protect data and integrate ESG principles [7]
Information	Historical or isolated data	Complex data collection and predictive analytics for processes and decisions [10]	Responsible decisions, security, data protection and interoperability [7]
Organization / Management	Hierarchical and procedural structures	Organizational changes, interoperability and agile management for the adoption of new technologies [10]	Resilience, distributed decisions, sustainability

In conclusion, we are witnessing the profound digital transformation of production, based on connecting physical systems with the digital environment to create smart factories and, ultimately, fully automated production formations and paradigms, sometimes referred to as "lights-out manufacturing".

Literature review

Since the beginning of the 21st century, information technology has grown explosively [11], and human intelligence continues to play an important role as real-world factory life is increasingly complemented by the virtual reality of so-called lights-out manufacturing. Although the idea of lights-out manufacturing has its origins in General Motors' Lights-Out experiments of the 1980s, which demonstrated the potential of autonomous operations, it has only become a practical reality with the maturation of digital technologies and the evolution of Industry 4.0 [12].

The concept of the "lights-out factory" has long been an aspiration for both industrialists and futurologists, with its roots in the early stages of industrial automation [13]. It was first introduced by Null in the 1980s and refers to a production system in which all manufacturing activities are carried out entirely by robots, using robotic technology, artificial intelligence and internet-based technologies, thus eliminating the need for a human workforce, lighting or windows [14].

This concept is also referred to as a *black factory* by some authors, such as Lengsfeld (2019). He defines a “dark factory” as a fully automated industrial production site, from the delivery of raw materials to the plant up to the dispatch of finished products, where production takes place without any direct human intervention at the shop floor [15]. Regardless of the label used, most authors view lights-out manufacturing as an advanced extension of the smart factory, in which deep automation, robotics and autonomous systems enable production with no significant human intervention [16]. It is worth noting that, while some authors [14, 16] argue that lights-out manufacturing can operate entirely without a workforce, most emphasize that human involvement remains necessary under specific conditions: without direct human intervention at the production site [15], without significant human intervention [16], or through the provision of information and supervision at a distance via virtual systems [12].

In a more recent paper, Liu (2022) argues that in the era of Industry 4.0, although the term “lights-out factory” is increasingly used, it does not imply the complete absence of human intervention; on the contrary, human intelligence becomes even more visible, especially in customized and adaptive production [12]. In the long run, however, Nadimpalli (2025) suggests that significant technological progress may progressively reduce, and potentially even completely eliminate, the human presence in this type of factory [13].

Indifferently of these differing views, Wang et al (2025) recently argued that lights-out factories represent the pinnacle of progress in the field of manufacturing, relying on automation, digitalization and smart technologies, as well as advanced tools such as process control systems, intelligent sensors and industrial robots [16].

Technological and economic dimension of lights-out manufacturing

Lights-out systems offer clear advantages for improving production efficiency and are frequently highlighted in the specialised literature. A well-known benefit of lights-out technology is its ability to operate during the night, which allows for extended working hours. Other authors emphasise that, beyond enhancing safety, lights-out factories improve production performance, support high-quality development, offer unmatched precision and significantly reduce the number of defective parts [13,16, 17, 18]. Another important advantage is the deployment of lights-out manufacturing in production sectors where working conditions are dull, dirty or dangerous for employees, such as environments with high temperatures, toxic gases or heavy loads, including applications like furnace operation, paint lines or carbon fibre cutting.

At the same time, lights-out manufacturing leads to a significant reduction in labour costs by removing employees from repetitive or routine operations that are prone to breaks and human error, while continuous operation without the need for lighting or climate control designed for human presence contributes to energy savings and lower operating costs [17,18]. Consequently, beyond the direct gains in labour and energy efficiency, the progressive diffusion of lights-out technologies is expected to reshape the competitive landscape, including for small and medium-sized enterprises.

In addition, Lee (2018) argues that another advantage of lights-out technologies is their growing accessibility [22]. Although lights-out manufacturing may currently appear to be the preserve of large firms, over time it is expected to become increasingly attainable for SME, which in the coming years are likely to adopt industrial robots on a wider scale. The effects of the expansion of lights-out manufacturing are directly linked to its efficiency, particularly in industries able to implement it more rapidly, such as plastics manufacturing, electronics assembly and food processing, that is, sectors with strong potential for SME development [17,18].

Consequently, there are valid reasons to ask whether lights-out manufacturing could become a widespread economic structure in the near future and whether its potential drawbacks might outweigh its current benefits. In this context, it is argued that, even though future technological advances are expected to further accelerate the development of lights-out factories, there remain significant financial barriers related to high upfront investment costs, as well as risks associated with cybersecurity and

extended downtime, which may pose serious challenges for many firms and even for entire industries [16].

Moreover, even though these technologies can have a substantial positive impact on profits, an increasing number of experts argue that the challenges of digitalization go beyond technological efficiency and cost reduction, drawing attention to their broader socio-economic implications. As a result, the black factory is seen not only as a technological model but also as a strategic issue, with potential social drawbacks in terms of employment and social cohesion. This perspective has guided the European Commission’s interest towards the Industry 5.0 paradigm, which envisions a sustainable, human-centric and resilient European industry [19,20]. It shifts the focus from purely economic performance to values and a more balanced transition, placing the wellbeing of industrial workers at the centre of the production process. Consequently, firms are required to adapt to new organizational forms and to implement innovative human-resource strategies, ensuring access to employees with a comprehensive understanding of the technological potential while safeguarding social objectives.

Global trends

Statistical data from the Dark Factories Industry Research Report indicate that, in 2024, the global dark factories market was valued at USD 119.19 billion, with a projected growth rate of 8.7% up to 2030, while China currently dominates the rankings with major developments in the electronics and automotive sectors [21]. The growth trend of lights-out manufacturing is further supported by the rapid increase in the use of industrial robots, the main indicator of manufacturing automation.

According to the International Federation of Robotics, the global stock of industrial robots exceeded 4.6 million units in 2024, while annual installations have surpassed 500,000 units for the fourth consecutive year, with Asia and Australia accounting for about 75% of new deployments in 2024, compared with 16% in Europe and 9% in the Americas. China installed approximately 295,000 robots in 2024, representing around 54% of global installations, followed by Japan with 44,500 units, while the sectoral composition has shifted from over 43% of industrial robot installations in automotive in 2014 to more than 53% in general industry in 2024. These dynamics strongly suggest that the accelerating adoption and diffusion of industrial robotics is laying the quantitative foundation for a broader transition towards lights-out manufacturing models in the coming decade [22].

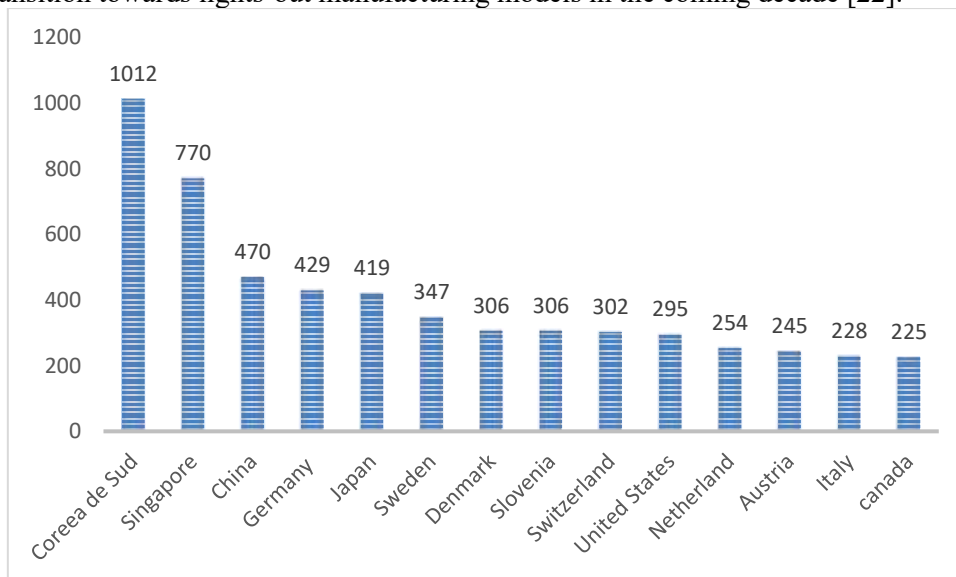


Figure 1. Robot density in the manufacturing industry 2023 [23]

Another key indicator is robot density, which doubled between 2016 and 2023, from 74 to 162 robots per 10,000 employees in the manufacturing sector, while South Korea and Singapore lead the global ranking in terms of robots per employee, reflecting the world’s most highly automated manufacturing

sectors relative to the local workforce (Figure 1). The steady increase in both the number of industrial robots and robot density reflects the accelerated adoption of automated and digital processes in production, representing a necessary step towards lights-out manufacturing structures.

Regardless of their medium- and long-term effects, industrial robotics can no longer be considered optional; it has become a major strategic issue for manufacturers. In a world facing labour shortages, supply-chain pressures and ageing industrial infrastructure, factory automation represents the most important lever for sustaining and enhancing industrial competitiveness.

At the same time, recent research in product design and digital innovation shows that the strategic role of automation is increasingly shaped by the integration of digital solutions, artificial intelligence and innovation methodologies such as TRIZ into Industry 4.0 environments [24]. These dynamics confirm that the transition towards lights-out manufacturing is not only a technological option, but a strategic decision for firms that pursue long-term sustainability and competitiveness by transforming their design and production processes.

Conclusions

In conclusion, lights-out manufacturing represents an advanced stage of smart factories, in which automation, robotics and artificial intelligence enable a high level of autonomy, especially in repetitive, hazardous or ergonomically demanding processes. The expansion of the dark factories market, the growth of the global stock of industrial robots and the doubling of robot density suggest that partially or fully “unmanned” factory models may shift from being exceptional cases to becoming a new normal in certain sectors and regions. At the same time, as technology costs decline, the integration of robotics and AI may transform lights-out manufacturing from a system specific to large corporations into an accessible option that can be progressively adopted by an increasing number of SMEs.

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