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Industry 4.0 Implementation Projects: The Cleaner Production Strategy—A Literature Review

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Abstract: The industrial impacts on the environment need to be minimized to reduce climate change, which will benefit human beings. Industry 4.0, the new production paradigm, promises productivity gains for companies that manage to implement it, but it is also dependent on natural resources, impacting the environment. The aim of this study is to identify and analyze possible cleaner production strategies associated with Industry 4.0 to optimize manufacturing systems in Industry 4.0 implementation projects, in addition to reducing the environmental impacts of these companies. Through a literature search, cleaner production strategies associated with Industry 4.0 were identified and classified into ten dimensions (strategy, waste, recycling, life cycle, resources, energy, production, work, performance and environment) contributing to the theory. The possibilities of using Industry 4.0 technologies were analyzed to meet each dimension. The relevance of this study lies in presenting possibilities for using and developing technologies and applications to meet these dimensions of cleaner production and helping those involved in Industry 4.0 projects to implement it more stably, contributing to the theory and practice.

Keywords: cleaner production; sustainability; operations; Industry 4.0; networks; circular economy; projects

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1. Introduction

Industry 4.0, the new production paradigm, promises to improve the productivity of the companies that manage to implement it [1–4], but like other production paradigms, it is dependent on natural resources. Cleaner production strategies can be used to optimize or reduce the use of resources [5], representing a gain for the companies involved in Industry 4.0 implementation projects, which is the object of this study.

Cleaner production aims to increase the efficiency of production lines, reducing risk to people and to the environment, through the use of preventive environmental strategies for products, services and processes [5,6]. The adoption of cleaner production practices helps to preserve energy, water and raw materials, eliminating or reducing the emission of toxic material and residues in the production process [5,7]. Cleaner production strategies can also increase the energy efficiency of production lines by harnessing the residual heat generated by the operations, reducing energy consumption [8].

Despite the apparent complexity that cleaner production can represent initially, there are several ways to achieve cleaner production, such as by reducing the effects of greenhouse gases [9], reducing the volume of water discharged into the environment [10], minimizing water consumption [11,12] and using other methods.

For cleaner production to spread across all companies and countries, the involvement and support of government representatives and industrial decision-makers [13], universities [14], consultants and non-governmental organizations (NGO) [15,16], leaders and people in general is required. This joint effort could guide the establishment of public policies [17], regulating the emission limits of pollutants in the air, soil and water [5], in addition to stimulating the adoption of technical standards such as ISO 14000 [18,19], related to the protection and preservation of the environment, to prevent pollution and the potential problems that this can bring to the economy and society. It is also relevant that the government, banks and other financial institutions can provide financial incentives to encourage companies to adopt cleaner production [5], with privileged interest rates if possible.

Industry 4.0, the new industrial paradigm, has received much attention due to the possibility of improving the productivity of companies that can implement it [20]. In order to optimize the production process to increase productivity, Industry 4.0 uses high technology to integrate automation and information systems to exchange information and data between humans and machines [21,22].

Although Industry 4.0 can bring about opportunities for companies, the implementation process involves barriers and risks [1–4]. The adoption of a cleaner production strategy in the Industry 4.0 implementation process is defined as the use of cleaner production practices in production systems for the companies to reach the Sustainable Development Goals (SDGs) through this process [3].

To guide this implementation process, some models have been developed, but in most of these models cleaner production practices are not considered or mentioned. Few models consider cleaner production practices as essentials tool in the implementation of Industry 4.0 [3]. Shayganmehr et al. [23] proposed a model that sees Industry 4.0 as an instrument to strengthen the circular economy and cleaner production to increase the quality of the products or services available to the market. Amjad et al. [24] developed a model combining lean manufacturing, lean green manufacturing, the circular economy and Industry 4.0 to minimize waste and maximize production. Lu et al. [25] suggested that the environmental, legal, philanthropic, economic and ethical aspects should be analyzed at all phases of the Industry 4.0 implementation processes. Ma et al. [26] suggested a model to use Industry 4.0 technology to save energy costs; in a similar approach, Rajput and Singh [27] developed a model to reduce energy consumption with Industry 4.0, helping to reach cleaner production and circular economy goals. In some models, cleaner production is the antecedent, while in others it is the consequent. In these models, the cleaner production strategy is superficially addressed, a gap that this study intends to analyze. Therefore, the following research question was formulated.

RQ1: What are the possible cleaner production strategies associated with Industry 4.0 to optimize manufacturing systems in Industry 4.0 implementation projects?

Given that Industry 4.0 uses cutting-edge technologies to improve production, why not use these technologies to improve the cleaner production strategies as well? Thus, the following research question was formulated.

RQ2: How can Industry 4.0 technologies and applications be developed and used to meet these cleaner production strategies?

Using a literature search, cleaner production strategies associated with Industry 4.0 were identified and classified into ten dimensions, and Industry 4.0 technologies and applications are suggested for development and use to address these cleaner production strategies.

This study, which aims to contribute to cleaner production and to the Industry 4.0 body of knowledge, is divided into sections. After this introduction, Section 2 presents the literature review on Industry 4.0 and cleaner production. Section 3 discusses the methods used; Section 4 presents the dimensions of cleaner production strategies; and Section 5 addresses the conclusions, limitations and future study directions.

2. Literature Review

2.1. Industry 4.0

Although some authors question whether the evolution of industrial systems occurred by evolution or revolution [28,29], until now four industrial revolutions have been studied.

The first industrial revolution, or Industry 1.0, was possible with the use of steam power and the mechanization of the weaving loom around 1780, when industry managed to reduce the dependence on human physical strength, reaching new levels of productivity [3,30].

The second industrial revolution, or Industry 2.0, took place around 1870, due to the mass production; the division of labor; and the use of assembly lines, electricity [30,31] and steel mills, enabling the intensive use of steel.

The third industrial revolution or Industry 3.0 began in 1969, with the use of electronics, robotics, telecommunications and computing, enabling automation in production systems. The milestone was the emergence of the first programmable logic controller (PLC) [32,33].

The fourth industrial revolution or Industry 4.0 emerged in 2011, launched at the Hannover Fair, as part of a high-tech program by the German government with the aim of enhancing the competitiveness of German companies [34–40], based on three pillars: the Internet of Things (IoT), cyber–physical systems (CPS) and the Internet of Services (IoS) [2,21,41–45].

There are also concepts that support Industry 4.0, including horizontal integration, vertical integration, modular production, service orientation, virtual applications, real-time capabilities, interoperability, decentralized systems and virtual applications [46–49].

The integration of automation and information technologies is a pillar of Industry 4.0 [49,50], enabling information and data to be processed, monitored, controlled and analyzed in real time in order to increase operational efficiency [51–55], helping to manage production [56] and the entire company efficiently [57] and allowing better decision-making [58] with flexibility [59–80].

Supply chains can be restructured with Industry 4.0 to supply components and raw materials from different sources [33,81–83], allowing for better inventory control of work-in-process and finished goods [56,81,82], simplifying production planning and control [84–90] and assisting managerial functions and operations for the effective use of human resources [91].

For Industry 4.0, the core technology is the Internet, not the computer [92]. It is expected that by 2030, every economic person with Internet access will use digital data once every 18 s, or 5000 times a day [93,94].

Industry 4.0 can reduce costs, provide customized products and services to customers and increase sustainability and productivity [33,82,95], improving process and product quality [46,47,96], increasing production efficiency [2,3,43,45,49,82] and enabling mass customization [97].

Society is putting pressure on the private sector to become effective and efficient and to reduce environmental pollution and climate change, with Industry 4.0 being critical in this process [98], although it consumes more electricity than previous production paradigms.

The world economy has been affected by the difficulty of accessing reliable energy sources. Currently, approximately one-seventh of the people around the world still do not have access to electricity [99]. It is estimated that by 2030, the global demand for energy will increase by 30% [93].

2.2. Industry 4.0 Technologies

Industry 4.0 is an umbrella term that incorporates several technologies [100,101], some of which are presented below.

1. Cyber–physical systems

Through the integration of technologies, the cyber–physical systems (CPS) promote interdependencies and interconnections between networked cyber components and physical components [37,41]. CPS can be considered embedded systems that allow the exchange of data between humans and physical or mechanical systems, through software controlled by actuators, controllers, sensors and smart objects [41].

2. Internet of Things

The Internet of Things (IoT) enables humans to interact with machines, mobile devices, sensors and actuators, supporting humans in their daily activities [28,102]. In IoT, objects are animated via computation, actuation and sensing, so they can be accessed and controlled from anywhere around the world [41].

3. Internet of Services

The Internet of Services (IoS) can be considered as the new possibility for relationships with stakeholders or the general public to offer new services that can be found, used and paid for online, bringing about new business models [41].

4. Computer simulation

Computer simulation, also known as virtual commissioning or digital twin, involves the virtual simulation of a system or object to study their movements, interferences and handling in order to optimize them, reducing potential problems before their implementation and production [103].

5. Additive manufacturing

Additive manufacturing (AM), 3D printing or additive layer manufacturing (ALM) is a technology that allows the manufacture of three-dimensional objects via the deposition of successive layers of material, commanded by software [104,105].

6. Collaborative robotics

Unlike the robots designed during Industry 3.0, in Industry 4.0 the robots are designed to work or interact with humans, reducing human risk and effort while working [37].

7. Virtual reality

Virtual reality (VR) is characterized by the creation of a virtual environment, making the user feel as if the virtual universe is a reality, generating an immersive experience through observation [37,106].

8. Augmented reality

Augmented reality (AR) is a technology that allows virtual objects or data to be introduced into the observer's visual field, expanding the physical environment, so that human beings can interact with them in a superior way [1,37].

9. Radio Frequency Identification

Radio frequency identification (RFID) technology is used in a wide variety of products to allow remote identification and better control [1,107].

10. Big Data analytics

Through big data analytics, it is possible to collect, manipulate, compile and analyze large amounts of data from many different sources [108].

11. Artificial intelligence

Artificial intelligence (AI) is a system capable of interpreting and learning from external data and using this learning process to reach specific tasks and goals while adjusting to different conditions or situations in a flexible way [109].

12. Cybersecurity

It is important that systems that support Industry 4.0 can be protected from cyber-attacks, as the Internet is the main vehicle for communication and data exchange in Industry 4.0 [1,102].

13. Integrated system

The many different systems from various equipment manufacturers need to communicate with each other; therefore, these systems must be integrated to make the equipment interoperable [41].

14. Cloud computing

The data received from the various devices, IoT objects, sensors and actuators can be stored and processed in servers that can be located anywhere in the world; therefore, such data are said to be in the "cloud", as one has no idea where the server is located [102].

2.3. Cleaner Production

To minimize climate change, companies are pressured by non-governmental organizations, policymakers and customers to reduce the operational impacts of their operations on the environment [110–112].

The expression cleaner production was first used at the Council of the United Nations Environment Programme (UNEP) in 1989 [113–120]. According to the UNEP [114–120], cleaner production can be defined as a preventive environmental strategy that is constantly applied to production processes, products and services to improve overall efficiency while minimizing risks to humans and the environment.

Cleaner production is an umbrella term that includes terms such as green productivity, pollution prevention, eco-efficiency [111,121,122], green manufacturing [123–125], environmentally benign manufacturing and sustainable manufacturing, among others [123].

Cleaner production can be implemented not only in any industrial process, but also in the products themselves, as well as in the most diverse services offered to society [110–113]. While increasing industrial efficiency, cleaner production protects the consumer, the environment and the worker, increasing competitiveness and profitability [116]. Production planning and control is an important ally when implementing cleaner production strategies in a company [45,119].

The focus of cleaner production is "prevention", avoiding unnecessary costs and reducing the use of natural resources and the production of waste, moving towards a more sustainable and safe society [124].

The aims of cleaner production are the minimization of pollutant emissions and waste generation [112,126–128], the efficient use of energy and water and the reuse of waste [111,114,127–131], while minimizing operating costs [128], increasing the environmental performance [112,125], improving the operational performance by optimizing production resources, increasing the quality of products and services made available to society [101], improving occupational health and safety [132–134] and minimizing the use of non-renewable natural resources and the production of pollution resulting from manufacturing processes [113,114,118–122,129].

These possibilities allow the implementation of cleaner production to increase the economic performance of companies, contributing to the value of the company in the market [132] and economic gains while cooperating for the development of a culture of environmental protection [3,20,113].

2.4. Cleaner Production Strategy

The integration of Industry 4.0 technologies and cleaner production practices and strategies enables people involved in the implementation of Industry 4.0 to implement sustainable business models [115]. The adoption of Industry 4.0, cleaner production practices and circular economy initiatives can increase the sustainable performance of manufacturing organizations [134].

Large corporations are adopting Industry 4.0 and cleaner production strategies to increase their performance and innovate faster, while preserving the environment [135]. Industry 4.0 technologies can be used to reinforce cleaner production strategies in organizations, providing competitive advantage to these organizations [22,23,27], due to the optimizations of the utilization of resources and the possibility of increasing the follow-up of the product life cycle [136].

In the holistic and sustainable model for implementing Industry 4.0 [3], the cleaner production strategy and social stakeholders, composed of unions (workers and employers), governments, academic institutions, banks, private companies and other organizations and institutions, are the basis to consider in the implementation process, not a consequence (see Figure 1).

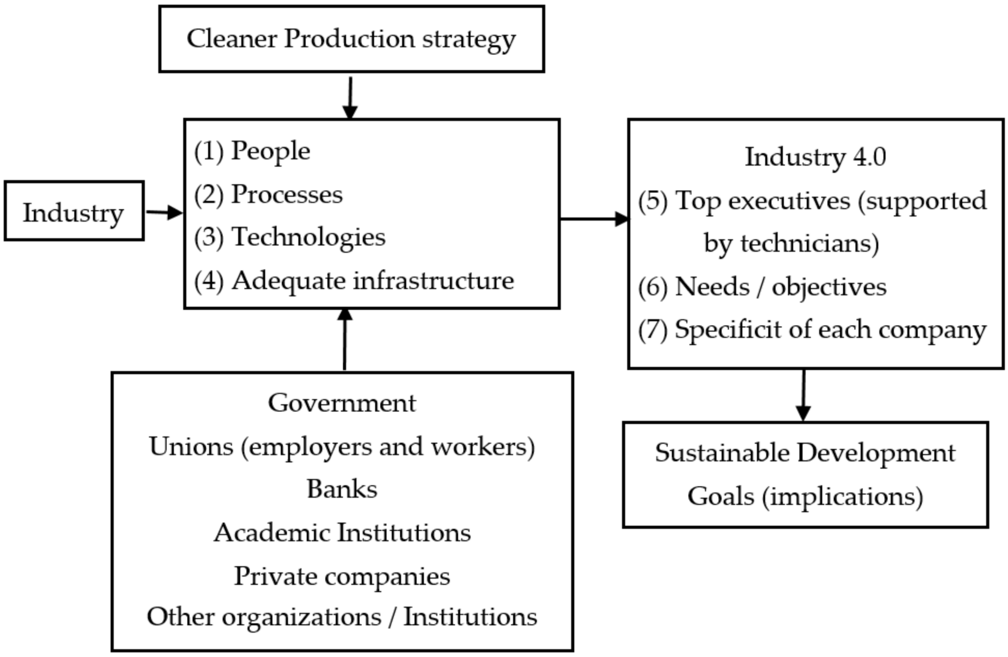

Figure 1. Holistic and sustainable model for implementing Industry 4.0 [3].

Other models that emphasize the cleaner production strategy or practice as a pillar to be taken into account for implementing Industry 4.0 are also superficial about this pillar. It is relevant to highlight which cleaner production strategy should be considered, to help those involved in Industry 4.0 projects to implement it more stably, thereby contributing to the theory and practice, the objective of this study.

3. Materials and Methods

The literature search was employed as research method to identify and analyze possible cleaner production strategies associated with Industry 4.0 to optimize manufacturing systems in Industry 4.0 implementation projects.

The Scopus and Web of Science databases were used in the literature search, as presented in Table 1, when no filter was used.

Table 1. Numbers of documents in Scopus and Web of Science database.

Search String	Scopus	Web of Science
"cleaner production"	4767	33,617
"Industry 4.0"	23,864	18,427
"cleaner production" AND "Industry 4.0"	35	103

The largest number of documents found in the Web of Science database was due to an error in the search software, which considered the name of the journal in the search field along with title, abstract and keywords.

After excluding duplicates and filtering to choose only journals, 73 journals were identified for full reading, so 32 papers were selected where there were proposals for cleaner production strategies to optimize manufacturing systems in Industry 4.0 implementation projects.

This reduced number of documents found with the theme of this study (32) in relation to "cleaner production" and "Industry 4.0" points to the scarcity of the theme.

4. Results

Table 2 presents possible cleaner production strategies associated with Industry 4.0, as found in the literature research, to optimize manufacturing systems in Industry 4.0 implementation projects, in addition to reducing the environmental impact of these companies.

The ten dimensions that classify cleaner production strategies are addressed below, answering RQ1.

Cleaner Production Strategies for Industry 4.0 Implementation

1. Strategy

The strategy dimension covers the selection of the process and technologies to be used in the implementation of Industry 4.0 [121,137–146]; that is, this selection must be made to meet cleaner production strategies, so that cleaner production can guide the implementation project from the beginning, not as a consequence as presented in some implementation models.

2. Waste

This dimension encompasses the minimization of emissions or pollutants [22,25,27,57,96,134] and the optimization of waste disposal [121,137–148] and management [48,57,82,119,124,147,148], which should be a concern from the beginning of the implementation of Industry 4.0.

3. Recycling

The recycling dimension addresses the waste recycling [93,94,119,148,149], the possibility of digitally identifying the materials that make up the products, facilitating their disposal or reuse [121,150–152], and the possibility of recycling materials in company [147], contributing to the reduced use of new raw materials and industrial costs.

4. Life cycle

The life cycle dimension ranges from designing to extend the life cycle of a product [121,147,150–159] to using Industry 4.0 to manage the entire life cycle of a product [22,26,57,119,124,148,160–170], supporting the production of differentiated products.

5. Resources

The resources dimension includes the use of Industry 4.0 to manage resources efficiently [26,57,119,124,147,148,169,171] and optimize resource utilization [172], preserving the environment while improving productivity.

6. Energy

This dimension addresses the management of a renewable energy grid system [57], as well as the reuse of the heat generated by the company in the operations and offices [98] and the use of Industry 4.0 to optimize energy consumption [26,27,57,82,96,151,168,169,173,174], reducing industrial costs and carbon footprints.

7. Production

The production dimension encompasses the largest number of cleaner production strategies. It considers the use Industry 4.0 to manage or map the supply chain [25,135,170], control the inventory of in-process and finished goods [23,27], manage production efficiently [3,22,25,45,49,57,124,151], enable production system integration [23,96], manage production and maintenance through energy consumption [119], allow production integration throughout the organization [23,25,96] and optimize the production planning and control processes [27] and the utilization of human resources [151], with the aim of increasing productivity while reducing the environmental impacts.

8. Work

Coming second in the number of cleaner production strategies, the work dimension covers the use of Industry 4.0 to improve work safety [172], collaborative working [47], knowledge-sharing [47] and workplace conditions [171], focusing on providing a better working environment.

9. Performance

The performance dimension uses Industry 4.0 to engage all stakeholders to optimize the organizational performance [25], showing the need to unite ideals to achieve the implementation of Industry 4.0.

10. Environment

The environmental dimension, which encompasses all of the other dimensions, is formed by the use of Industry 4.0 to increase environmental management [25,48], with the aim of reducing the environmental impacts of these companies while optimizing manufacturing systems.

Table 2. Cleaner production strategies associated with Industry 4.0.

Dimension	Cleaner Production Strategies	Studies
Strategy	Selection of an adequate process considered environmentally friendly	[121,137–139]
	Selection of technologies considered environmentally friendly	[121,137–139]
Waste	Use Industry 4.0 to minimize emissions/pollutants	[22,25,27,57,96,134]
	Optimization of waste disposal	[121,137]
	Use Industry 4.0 to manage waste	[48,57,82,119,124,147,148]
Recycling	Use Industry 4.0 for waste recycling	[93,94,119,148,149]
	Digitally identify the materials that make up the products, facilitating their disposal/reuse	[121,150–159]
	On-site recycling	[147]
Life cycle	Design to prolong the life cycle of products	[121,147,150–152]
	Use Industry 4.0 to manage life cycle	[22,26,57,119,124,148,160–170]
Resources	Use Industry 4.0 to efficiently manage resources	[26,57,119,124,147,148,169,171]
	Use Industry 4.0 to optimize resource utilization	[172]
Energy	Management of a renewable energy grid system	[57]
	Reuse of the heat generated by the company (operations and offices)	[98]
	Use Industry 4.0 to optimize energy consumption	[26,27,57,82,96,151,168,169,173,174]
Production	Use Industry 4.0 to manage/map the supply chain	[25,135,170]
	Use Industry 4.0 to efficiently manage production	[3,22,25,45,49,57,124,151]
	Use Industry 4.0 to control in-process and finished goods inventory	[23,27]
	Use Industry 4.0 to manage production and maintenance through energy consumption,	[119]
	Use Industry 4.0 to enable production system integration	[23,96]
	Use Industry 4.0 to enable production integration across the organization	[23,25,96]
	Use Industry 4.0 to optimize production planning and control	[27]
	Use Industry 4.0 to optimize the utilization of human resources	[151]
Work	Use Industry 4.0 to improve work safety	[172]
	Use Industry 4.0 to improve collaborative work	[47]
	Use Industry 4.0 to improve knowledge-sharing	[47]
	Use Industry 4.0 to improve workplace condition	[171]
Performance	Use Industry 4.0 to engage all stakeholders to optimize organizational performance	[25]
Environment	Use Industry 4.0 to increase environmental management	[25,48]

5. Discussion

A discussion about the ten dimensions and their cleaner production strategies is presented here. Possible Industry 4.0 technologies and applications for development and use are also suggested to meet these cleaner production strategies, answering RQ2.

5.1. Strategy Dimension

The selection of an adequate process, as proposed by [121,137–146], and the selection of technologies, as indicated by [121,137,138,147], considered environmentally friendly should guide Industry 4.0 implementation projects, preceding all phases.

This is in line with the holistic and sustainable model for implementing Industry 4.0 [3], which considers that cleaner production strategies should be the basis for any process or technology selection; that is, the implementation of Industry 4.0 should consider cleaner production strategies antecedents and not consequences of the implementation processes.

In this way, the concern for the preservation of the environment guides the entire implementation of the Industry 4.0 strategy, also focusing on maintaining sustainable development.

5.2. Waste Dimension

Industry 4.0 technologies should also be considered to minimize emissions and pollutants [22,25,27,57,83,96,134], contributing to reduced waste generation [112,125].

The optimization of waste disposal [117,137–148] is another possibility with Industry 4.0, helping to improve occupational health and safety [131].

For example, bins equipped with sensors and actuators and accessed via an IoT application (i.e., smart bins) could inform users via the Internet when the bin is almost full, requesting its collection. They could also manage the generated waste rate by the week, day, hour or minute, triggering alerts when necessary.

The use of Industry 4.0 technologies to manage waste [48,57,82,119,124,147,148] contributes to moving towards a more sustainable and secure society [124].

5.3. Recycling Dimension

The technologies of Industry 4.0 can be used for waste recycling [93,94,119,148,149], optimizing the use of resources [136].

These technologies can also be used to digitally identify the materials that make up the products, facilitating their disposal or reuse [121,150–159] by providing adequate technical information to assist in the disposal or reuse process.

This could be facilitated by the use of RFID tags or QR codes inserted in strategic locations on the products, with instructions on how to disassemble and recycle the parts.

Another possibility for Industry 4.0 technologies is to perform on-site recycling [147], using cleaner production strategies and circular economy initiatives to increase the sustainable performance of manufacturing organizations [83,134,153–167].

5.4. Life Cycle Dimension

The cleaner production strategy should be used as the basis for implementing Industry 4.0, not just processes [121,137–139] and technologies [121,137,138,147], which should be selected to reinforce this strategy. Products should be designed to extend their life cycle [121,147,151,152], reinforcing the use of a preventive environmental strategy that is constantly applied to products and services to improve their overall efficiency while minimizing the risks to humans and the environment, as stated by the UNEP [120].

Industry 4.0 technologies should also be used to manage the life cycles of the products [26,57,119,124,148,160–170], using this management information as feedback to redesign products with superior efficiency [120], protecting the consumer, the environment and the worker, and increasing competitiveness and profitability, as stated by UNEP [120].

Enhancing these products with IoT, i.e., making them "smart", would allow the products to alert users over the Internet when maintenance is required or when an upgrade is possible to extend their life cycle.

5.5. Resources Dimension

In the implementation of Industry 4.0, the technologies and processes should be used to support the resources management efficiently [57,119,124,147,148,169,171], in order to reduce the use of natural resources and waste, contributing to a safer and more sustainable society [120].

Industry 4.0 technological applications should also be used to optimize resource utilization [172], thereby optimizing the productive resources [5,113,133], representing a gain for companies involved in Industry 4.0 implementation projects.

Artificial intelligence could be trained to control processes and big data analytics to help keep the processes optimized in order to use resources efficiently.

5.6. Energy Dimension

In order to cooperate to reduce global energy increases [94], Industry 4.0 can be used to manage a renewable energy grid system [57], where the surplus of electricity generated can be offered to the public electric system, thereby benefiting society, as recommended by the UNEP [120].

Another way to reduce energy consumption is to reuse the heat generated by the company, as found various in operations and office equipment [98], thereby minimizing the operating costs [128] and increasing the environmental performance [112,125].

Industry 4.0 can also be used to optimize energy consumption [26,27,57,82,96,147,164,169,170], helping to save energy through its cleaner production strategy [5,7,113].

By identifying potential heat sources using sensors or IoT, they could be monitored to direct their surplus energy to the company's electrical grid.

5.7. Production Dimension

There are many possibilities to use Industry 4.0 technologies and concepts to improve operations systems effectively and efficiently.

Industry 4.0 can be applied to manage or map the supply chain [25,131,166], enabling individuals to manage production efficiently [3,22,25,45,49,57,120,147], minimizing the use of non-renewable natural resources and pollution resulting from manufacturing processes [113,118].

Industry 4.0 technologies can also be employed to control the in-process and finished goods inventories [23,27], enabling the provision of a better information service to the customer and society [101].

The control of production and maintenance management processes through energy consumption [119] is a possibility that Industry 4.0 presents [8].

The use of Industry 4.0 can allow the integration of the production system [23,96] and the use of this system throughout the organization [23,25,96], contributing to the unification of information, an important point when implementing sustainable business models [119].

Industry 4.0 technologies can lead to improved production planning and control [27,45,84–90,123], creating opportunities to implement cleaner production processes [45] and optimize the use of human resources [151,173–176], contributing to improving productive resources and lives [101].

Computer simulations could be used to improve processes, prior to their practical implementation, and integrated systems could be used to improve production processes through their optimization. Additive manufacturing could help in the production of customized products.

5.8. Work Dimension

Workplace safety can be improved using Industry 4.0 [172], enabling the improvement of collaborative working [47] and workplace conditions [171], increasing the occupational health and safety of workers [133] and collaborating toward cleaner production.

The knowledge-sharing opportunities provided by Industry 4.0 [47] can help people move towards a more sustainable, safe and educated society [124].

Virtual reality could be used to train workers and augmented reality could be used to help with their daily tasks or for special occasions when advanced features are need. Collaborative robots could be used to help workers with their tasks.

5.9. Performance Dimension

The integrated information provided by Industry 4.0 technologies can be used to engage all stakeholders to optimize organizational performance [25], while preserving the environment and enabling increased competitiveness and profitability, as recommended by UNEP [120].

IoS could help in this task, maintaining transparent communication with all stakeholders and providing real-time information about the company; what has been planned and accomplished; and its goals by year, month, week or day, among other factors.

5.10. Environment Dimension

There are diverse ways to use Industry 4.0 to increase environmental management [25] to contribute to achieving cleaner production, just as cleaner production strategies should be considered as a pillar to implement Industry 4.0, not its consequence [3], in order to minimize industrial impacts on the environment. Cybersecurity is an important concern in Industry 4.0; as with all data and information circulating over the Internet, attacks must be repelled.

6. Conclusions

This study aimed to identify and analyze possible cleaner production strategies associated with Industry 4.0 to optimize manufacturing systems in Industry 4.0 implementation projects, in addition to reducing the environmental impacts of these companies.

This paper contributes to the theory by identifying in the academic literature cleaner production strategies associated with Industry 4.0, classified here into ten dimensions. Each dimension was analyzed according to its cleaner production strategies, and based on this discussion some possibilities for developing technologies and applications to meet these dimensions of cleaner production have been presented, potentially influencing further research in this field.

The contribution to the practice is the identification of cleaner production strategies that could guide the Industry 4.0 implementation process, helping those involved in Industry 4.0 projects to implement it more stably. Policy-makers can use this study to guide Industry 4.0 implementation projects to adopt the cleaner production strategies identified here, and they could also stimulate researchers to develop the technologies and applications proposed here, such as establishing incentives for this line of research via initiatives in favor of the environment and manufacturing systems.

Although the cleaner production strategies presented here are not exhaustive, which is a limitation, this study could stimulate academics and professionals in general to develop or study other relevant cleaner production strategies to support Industry 4.0, contributing to reducing the environmental impacts of these companies.

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