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Link Between Sustainability and Industry 4.0: Trends, Challenges and New Perspectives

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ABSTRACT The increasing number of studies that underline the relationship between industry 4.0 and sustainability shows that sustainability is one of the pillars of smart factories. Through a bibliometric performance and network analysis (BPNA), this research describes the existing relationship between industry 4.0 and sustainability, the strategic themes from 2010 to March 2019, as well as the research gaps for proposing future work. With this goal in mind, 894 documents and 5621 keywords were included for bibliometric analysis, which were treated with the support of Science Mapping Analysis Software Tool (SciMAT). The bibliometric performance analysis presented the number of publications over time and the most productive journals. The strategic diagram shown 12 main research clusters, which were measured according to bibliometric indicators. Moreover, the network structure of each cluster was depicted, and the patterns found were discussed based on the documents associated to the network. Our findings show the scientific efforts are focused to enhance economic and environmental aspects and highlights a lack of effort relating the social sphere. Finally, the paper concludes the challenges, perspectives, and suggestions for the potential future work in the field of study relating to industry 4.0 and sustainability.

INDEX TERMS Industry 4.0, sustainable manufacturing, sustainability, bibliometric, strategic intelligence, co-word analysis, SciMAT.

I. INTRODUCTION

In the Brundtland Report in 1987, the purpose of sustainable development was to "meet the needs of the present without compromising the ability of future generations to meet their own needs" [2]. However, societies are facing difficulties in conducting sustainable development, due to climate change [3], energy consumption [4], overpopulation, agricultural crises [5], food demand [6], water supply [7], [8], production waste [9], [10], among others. These issues demand improvements to sustainable policies, metrics [11], assessment techniques [12] as well as for implementation of new technologies. Such challenges are pushing organizations to adapt and reinvent how they meet customer needs from a sustainable perspective. In the future, an organization's success will depend on how well it deals with sustainability challenges [13]. Industry 4.0 (I4.0) presents an excellent opportunity for building sustainable organizations [14]. The

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I4.0 concept is complex to describe, since there are more than 100 distinct meanings in literature [15]. However, I4.0 is commonly described as the use of emerging technologies (internet of things, big data, cloud computing, among others [16] to enable autonomous systems. This is accomplished through self-organization and diagnosis, real-time monitoring and optimization as well as the capacity of a systems to learn and adapt according to environmental changes [17], [18]. Although I4.0 promises benefits [19], the concept and its full understanding is immature, therefore researchers are attempting to understand the positive and negative implications of I4.0 technologies in economic (cost reduction, productivity, etc.), social (unemployability, skills training, etc.), and environmental aspects (energy consumption, environmental impact, etc.) [20], [21]. Despite this, researchers highlight the lack of studies in this area and the need for future works in the field [22]–[24].

To address this need, several systematic literature reviews (SLRs) were performed in order to highlight the status of I4.0, guide future research in the field and propose a framework for a sustainable manufacturing (SM) [25] and highlight research challenges and opportunities for future works [26]. As well, an SLR to link of I4.0 and sustainable supply chain management were conducted, suggesting changes in systems and managers to develop a sustainable supply chain [27]. Through the analytical hierarchy process method, the main challenges such as technological, strategic, legal and ethical issues were presented [28]. A SLR explored the state of art of I4.0 and showed that sustainability is one of the main clusters in the field of research of I4.0, pointing future research in the field [29]. Although several studies have explored the research field of the link between I4.0 and sustainability, no study performed a complete analysis of the field of research. Therefore, a complete review still needed to contribute to the research in continuation. This review will utilize a bibliometric performance and network analysis (BPNA) approach, which is used to understand a field of research from a holistic observation. It relates the scientific works of several researchers over time, creating a strategic map of knowledge that can create new comprehension into the field of study [24], [30]–[34].

The objective of this research is to conduct a BPNA of the relationship between I4.0 and sustainability, in order to identify insight into prominent themes and their interrelationships, for the purpose of articulating challenges, perspectives and suggestions for future works. To perform this BPNA, we used the software Science Mapping Analysis Software Tool (SciMAT) [31]. The creation of a strategic diagram enables a reader to identify the most important scientific themes (motor themes, basic and transversal themes, emerging or declining themes, and highly developed and isolated themes) will be identified and classified according to their importance (centrality) and development (density). This result will highlight which topics the scientific community is putting the most efforts into, and what are the most promising for future research. The thematic network structure of each theme will be presented to investigate the relationship among themes, providing a holistic view of the field of research. As well, future challenges, perspectives and future directions will be developed and discussed to enhance future decision-making in the field of I4.0 and sustainability.

The paper is organized as follows: Section 2 presents the methodology and procedures used to achieve the objectives. In section 3 the analysis of data and discussions is presented, followed by the analysis of strategic themes and its thematic network structure in section 4. In section 5 we discuss the challenges, perspectives, and suggestions for future work in the field of study, ending with the conclusion and limitations in section 6.

II. METHODOLOGY AND DATASET

In this section we define the criteria for selecting the databases, period, types of documents, search terms and bibliometric software. For this search, we used the Scopus, Web of Science and Science Direct databases. The terms related to I4.0 used were: ('industry 4.0' OR 'industrie 4.0' OR 'the 4th industrial revolution' OR 'the fourth industrial revolution' OR 'smart manufacturing' OR 'smarter manufacturing' OR 'smart production' OR 'smart factory' OR 'smart factories' OR 'intelligent factory' OR 'intelligent factories' OR 'digital manufacturing' OR 'smarter factories' OR 'ubiquitous factories' OR 'ubiquitous manufacturing' OR 'real-time factory' OR 'real-time manufacturing' OR 'factory-of-things') which were used by other sources [22], [24], [35]. Next, we define the terms related to sustainability: ('sustainability' OR 'sustainable' OR 'sustainab*') which were used by [36], [37].

The period analyzed was from 2010 to March 2019, since I4.0 started to gain momentum in 2011 [38], [39]. Documents must contain the search terms in the title, abstract or keywords. Also, we considered articles, articles in press and reviews. Finally, only documents in English were used. The date of the export of the documents was 03/18/2019. For the bibliometric analysis, we used the SciMAT (Science Mapping Analysis Software Tool), which allows the complete bibliometric process, from data processing to analysis [31], [32], [34], [40]. The steps to perform this research is shown in Fig. 1 (below).

In the data collection, 1081 documents were selected for bibliometric analysis of the Scopus, Web of Science and Science Direct databases, which presented a total of 5947 keywords. In preprocessing, words representing the same concept were grouped, such as "life-cycle assessment" and "LCA", "smart city" and "smart cities", among others. Words such as "industry 4.0" and "sustainability" were excluded because we wanted to identify unfamiliar words. 187 duplicate documents were then excluded, totaling 894 documents associated with the selected keywords. Moreover, misspelled words have been corrected, as well as meaningless words such as "things" have been removed. The development of the BPNA of this research takes place over the period between 2010 and March 2019.

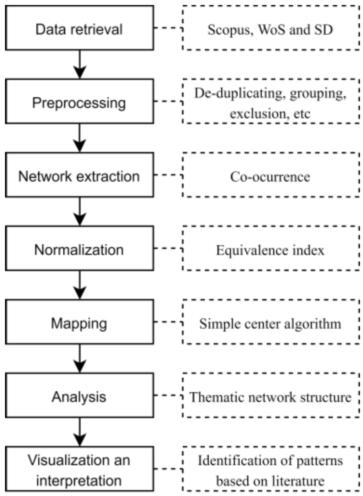


FIGURE 1. Workflow of science mapping.

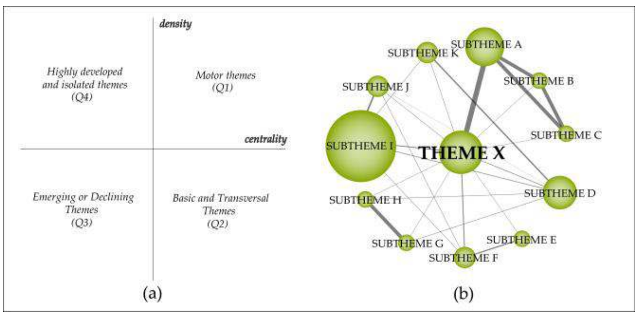


FIGURE 2. Matrix depicting density and centrality axes and thematic network structure.

894 documents and 5621 keywords were included for bibliometric analysis. The clusters were plotted in a bi-dimensional diagrams based on co-occurrence of keywords [41] and the similarity was calculated using the equivalence index that calculates the clusters' binding strength. The simple center algorithm was used for the clustering of themes [42]. The diagram is composed of four quadrants, where the 'y-axis' represents density and the 'x-axis' represents the centrality of clusters [41], [34]. In this context, research themes can be classified into four groups (Fig. 2 (a), below): a) Motor themes (First quadrant, Q1): High centrality and density (important themes for the field of research with high development); b) Basic and transversal themes (Second quadrant, Q2): High centrality and low development (tend to become motor themes in the future due to their high centrality); c) Emerging or declining themes (Third quadrant, Q3): Low centrality and density (need for qualitative analysis to define whether it is emerging or declining); d) Highly developed and isolated themes (Fourth quadrant, Q4): low centrality and high development (no longer important due to a new concept or technology) [24], [30]–[34], [40]. The thematic network structure (Fig. 2 (b), below) shows the co-occurrence among themes and highlights the degree of interactions (centrality) and internet strength among themes (density).

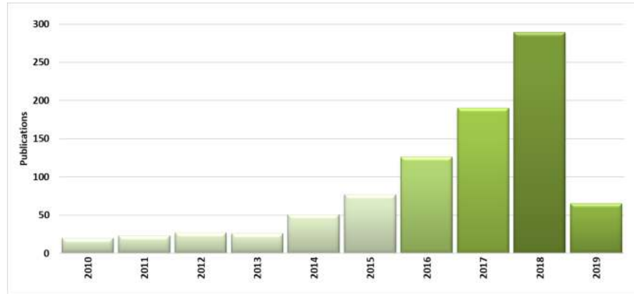


FIGURE 3. Number of publications over time (2010 – March 2019).

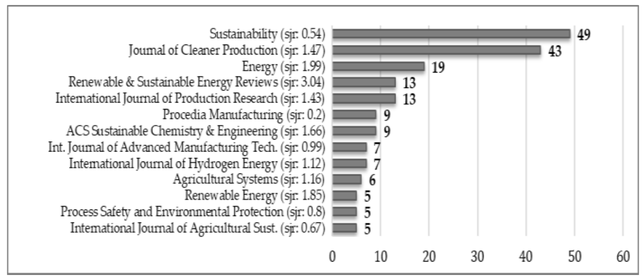


FIGURE 4. Journals that publish studies related to industry 4.0 and sustainability.

A performance analysis was utilized to measure the contribution of the entire research field to identify strategic themes (clusters) and establish the most important and impactful subthemes. To this end, bibliometric indicators were used such as of the number of publications, main authors, citations and h-index [43].

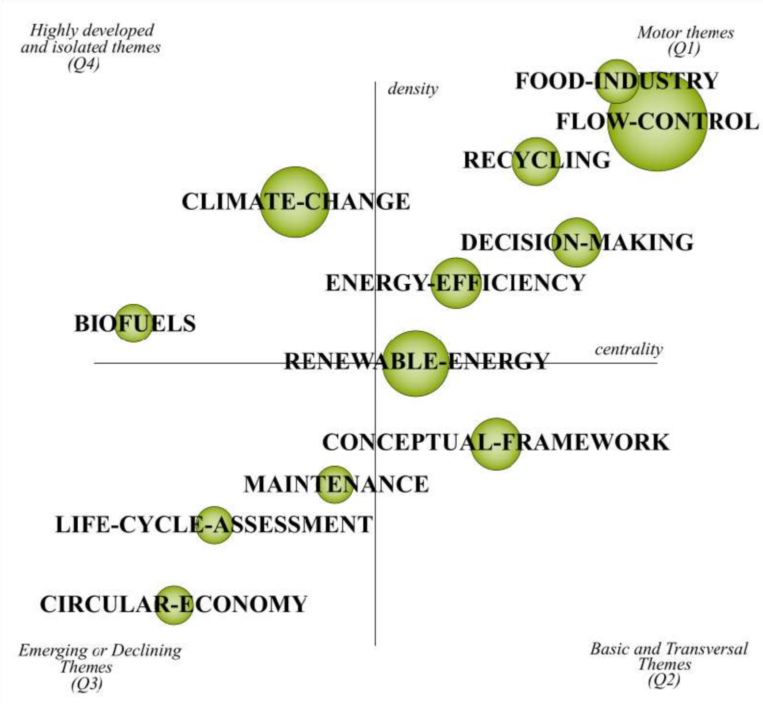
III. PERFORMANCE BIBLIOMETRIC ANALYSIS

Regarding the number of publications between 2010 and March 2019, Fig. 3 (below) presents a low number of publications of articles related to both I4.0 and sustainability between 2010 and 2015, but there is a significant increase from 2016, reaching 289 publications in 2018. However, there is a decline in 2019, which can be justified because 2019 is a partial year.

Fig. 4 (below) shows the journals that publish studies relating to I4.0 and sustainability. The Sustainability journal has the largest number of publications, followed by Journal of Cleaner Production and Energy. However, the journal with the highest SCImago journal rank (SJR) is Renewable & Sustainable Energy Reviews with 3.04. Although the number of studies relating I4.0 and sustainability is gaining attention from journals, the field of research is still immature, because the concept of I4.0 starts to appear only in 2011. This can partly be attributed to the creation of the "advanced manufacturing partnership" (AMP) by the USA government and the "High-Tech Strategy 2020" by the German government [44].

IV. ANALYSIS OF THE STRATEGIC DIAGRAM AND THEMATIC NETWORK STRUCTURE

Fig. 5 (below) presents 12 clusters, 6 of which are classified as motor themes ('FOOD-INDUSTRY', 'FLOW-CONTROL',



Theme	Core documents	h-index	Sum Citation	Q.	C.	D.
FLOW CONTROL	50	9	485	1	1	0.93
FOOD INDUSTRY	8	3	45	1	0.93	1
DECISION MAKING	12	3	46	1	0.86	0.71
RECYCLING	11	5	71	1	0.79	0.86
CONCEPTUAL FRAMEWORK	14	5	91	2	0.71	0.36
ENERGY EFFICIENCY	13	3	123	1	0.64	0.64
RENEWABLE ENERGY	25	11	1,057	1	0.57	0.5
MAINTENANCE	3	2	30	3	0.43	0.29
CLIMATE CHANGE	28	8	376	4	0.36	0.79
LIFE-CYCLE ASSESSMENT	3	2	8	3	0.21	0.21
CIRCULAR ECONOMY	4	2	11	3	0.14	0.07
BIOFUELS	4	3	44	4	0.07	0.57

Centrality (C.): degree of interaction of a theme with other themes. (importance of a theme in the development of the entire research field analyzed).

Density (D.): degree of internal strength of the theme with other themes. (capacity of the theme to sustain and develop over time in the field of research)

FIGURE 5. Matrix diagram depicting the performance of the research themes from 2010 to March 2019. Quadrant 1: motor themes. Quadrant 2: basic and transversal themes. Quadrant 3: emerging or declining themes. Quadrant 4: highly developed and isolated themes.

'RECYCLING', DECISION-MAKING', 'ENERGY-EFFICIENCY' and 'RENEWABLE-ENERGY'), 1 as basic and transversal theme ('CONCEPTUAL-FRAMEWORK'), 3 as emerging or declining themes ('MAINTENANCE', 'LIFE-CYCLE-ASSESSMENT' and 'CIRCULAR-ECONOMY'), and 2 as highly developed and isolated themes ('CLIMATE-CHANGE' and 'BIOFUELS'). The centrality "measures the strength of external ties to other themes, in other words this value as a measure of the importance of a theme in the development of the entire research field analyzed" [45] (p. 150) and the density "measures the strength of internal ties among all keywords describing the research theme, this value can be understood as a measure of the theme's development [45] (p. 150). Therefore "centrality" represents the importance of the theme for the field of research, in other words, it is an essential theme that have to be understood to any researcher involved in the area. "Density" indicates the capacity of the theme to predominate over time [24], [30]–[32], [41]. The size of each cluster is proportional to its number of core documents associated with the theme, followed by the sum of citations (in brackets). Fig. 5 (above) shows the performance analysis of the research themes and their respective core documents, sum citation, h-index, quadrant (Q.), centrality (C.) and density (D.). Fig. 6 - 17 (below) shows the thematic network structure of each theme. The clusters are discussed relating the most important subthemes.

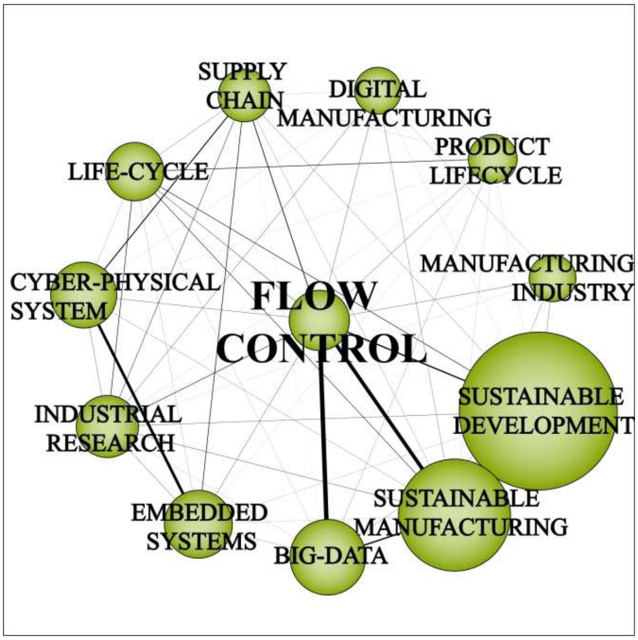


FIGURE 6. Thematic network structure of the cluster 'FLOW-CONTROL.''

A. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'FLOW-CONTROL'

The cluster 'FLOW-CONTROL' (Fig. 6, below) is a motor theme and the most important cluster in the strategic

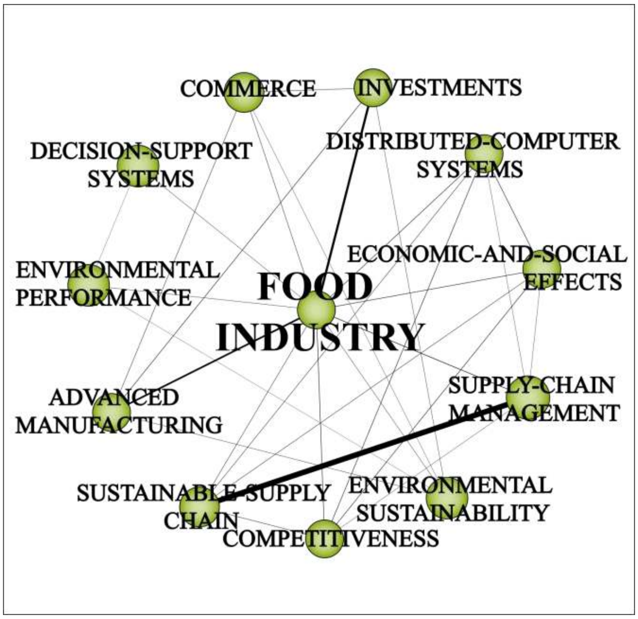


FIGURE 7. Thematic network structure of the cluster 'FOOD-INDUSTRY.'

FIGURE 8. Thematic network structure of the cluster 'RECYCLING.'

diagram due to its performance in terms of centrality. The flow control can be understood as the management of data flow among devices, computers and machines [46]. The relationship of this theme with the subthemes 'SUSTAINABLE-DEVELOPMENT', 'SUSTAINABLE-MANUFACTURING', 'BIG-DATA', 'CYBER-PHYSICAL-SYSTEMS' and 'EMBEDDED-SYSTEMS' highlights researcher's efforts to use and manage available data through I4.0 technologies. These technologies relate to real-time data processing and data analytics, in order to develop SM and achieve sustainable development [47], [48]. SM aims to solve problems and challenges related to energy, environmental, and natural resources issues and has attracted great attention from industry, government and the scientific community [49], [50]. It is one of the emerging trends in global manufacturing industries [51], [52]. This concept makes organizations more competitive by reducing costs, increasing profitability [53], creating clean processes and using renewable energy [54]. Thus, these SM related themes have strong relationships with I4.0, which has as one of its main objectives to promote more sustainable production [55].

B. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'FOOD-INDUSTRY'

The cluster 'FOOD-INDUSTRY' (Fig. 7, below) is also a motor theme and the second most important in terms of centrality, and the first in terms of density. This cluster highlights efforts to implement I4.0 technologies in order to improve efficiency of the food industry [23], [56]–[58], by the use of information systems that support research, design, production, and quality control, reducing time to market and manufacturing. The food industry is gaining attention from scientific community as the world's population is growing rapidly [5], which requires that industries produce more food [6]. However, more than a half of the produced food is lost or discarded during the production process [59], [60], and a third of already produced food is lost or wasted [9], [10]. In this sense, companies have been looking for technologies that ensure quality in food supply chain by using real time data monitoring system. The subthemes 'INVESTMENTS', 'SUPPLY-CHAIN-MANAGEMENT', 'ADVANCED-MANUFACTURING', among others highlights these efforts.

C. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'RECYCLING'

The cluster 'RECYCLING' (Fig. 8, below) is a motor theme and is directly related with the subthemes 'ADDITIVE-MANUFACTURING', 'SUSTAINABLE-PRODUCTION' and 'ENVIROMENTAL-IMPACT'. This relationship points out the use of recycled materials to use for three-dimensional (3D) printing [61] for a few applications. These works include the use of 3D printing to improve flexibility and efficiency, and reducing time to market and manufacturing costs [56] in order to develop a more sustainability production [62]. Additive technologies increase organizational capacity to develop complex products or parts, ensuring almost zero loss through process automation. The adoption of this technology impacts mainly in the use of raw materials, from the reduction of losses inherent to the production process, which in turn reduces environmental impacts, promoting improvement in the environmental pillar of sustainability [56], [63]. However, the adopting of 3D printing technologies requires innovative training for accelerating the implementation process [64].

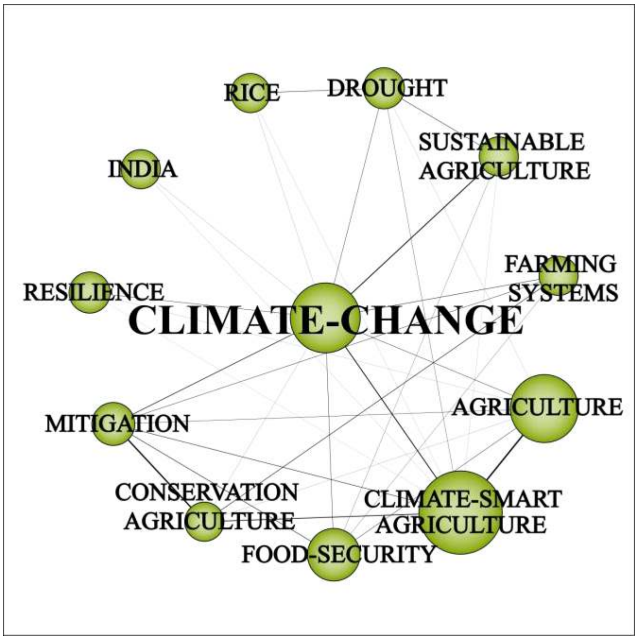


FIGURE 9. Thematic network structure of the cluster 'CLIMATE-CHANGE.'

FIGURE 10. Thematic network structure of the cluster 'DECISION-MAKING.'

D. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'CLIMATE-CHANGE'

The cluster 'CLIMATE-CHANGE' (Fig. 9, below) is a highly developed and isolated theme. It is gaining momentum since I4.0 technologies present high potential for climate change mitigation [65]. The cluster is directly related to subthemes including 'CONSERVATION-AGRICULTURE', 'FARMING-SYSTEMS', 'CLIMATE-SMART-AGRICULTURE', among others. In order that societies achieve sustainable development, the climate change issue must be addressed [3]. Also, in order for industries to be able to produce more food, agriculture must become more efficient, without compromising the climate. In this sense, it is possible to observe researcher's efforts to develop a more productive and sustainable agricultural production through climate-smart agriculture (CSA) [66]–[68]. This allows the use of various I4.0 technologies such as big data, simulation, among others [69]. Such technologies allow the development of Agriculture 4.0, which consists of using data generated by equipment, devices and machines to simulate scenarios for the optimization and better use of natural resources for planting, generating significant impacts throughout the agriculture supply chain [70].

E. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'DECISION-MAKING'

The cluster 'DECISION-MAKING' (Fig. 10, below) is a motor theme and is surrounded by subthemes related to I4.0 technologies such as 'VIRTUAL-REALITY', 'ARTIFICIAL-INTELLIGENCE', 'DATA-MINING', 'SENSORS', 'AUGMENTED-REALITY', 'ICT', among others. These links represent studies to develop a virtualized model to support decision making in smart industries [71]. A proposal of an end-of-life management framework for smart recovery decision making of economically and environmentally concerned products [50]. A nomenclature of performance indicators to support decision making in view of changes in I4.0 [72]. The association of lean production and simulation in the context of I4.0 [73]. A collaborative decision making in the pharmaceutical sustainable supply chain [74]. In this context, I4.0 technologies support decision making, as the company makes assertive decisions, resulting in improvements in operations management, such as product development, more efficient process management, cost reduction, waste reduction and rework, among others benefits [75]. Such improvements lead to increased profitability, and consecutively allows organizations to invest in social and environmental pillars, thus promoting sustainable development.

F. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'CONCEPTUAL-FRAMEWORK'

The cluster 'CONCEPTUAL-FRAMEWORK' (Fig. 11, below) is a basic and transversal theme. Its relationship with subthemes related to I4.0 ('INTERNET-OF-THINGS', 'INDUSTRIAL-INTERNET-OF-THINGS', 'ICT', 'BIG-DATA-ANALYTICS') highlights researches focused in the development of frameworks to implement SM [25] through real time data processing [47]. A framework to develop products that focus on sustainability in economic, social and environmental terms [23]. A Framework for production planning and control using carbon tax in I4.0 environments to reduce environmental impacts [76]. A Framework focused in human-centric cyber-physical production systems related to employee functionality to improve social sustainability [77]. A Framework focused in maintenance schedule optimization

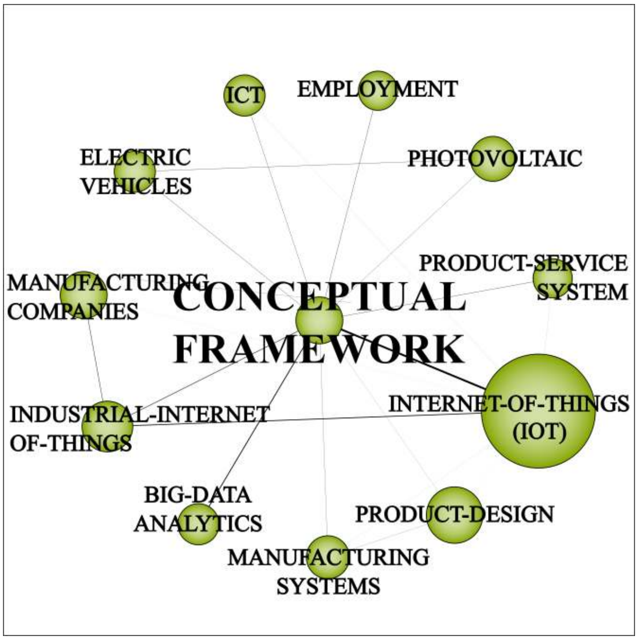


FIGURE 11. Thematic network structure of the cluster 'CONCEPTUAL-FRAMEWORK.'

FIGURE 12. Thematic network structure of the cluster 'ENERGY-EFFICIENCY.'

by the use of the big data analytics [78]. A Framework for end-of-life management of products with focus on economic and environmental aspects [50]. A training framework for accelerating the process of adopting 3D printing technologies [64]. A holonic framework for sustainable supply chain management [79], (holon is the combination of a physical and an informational part [80]).

G. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'ENERGY-EFFICIENCY'

The cluster 'ENERGY-EFFICIENCY' (Fig. 12, below) is a motor theme and its relationship with subthemes such as 'DIGITAL-TWIN', 'ROBOTICS', 'DIGITIZATION' and 'SUSTAINABLE-MANUFACTUIRING-SYSTEMS' highlights the relationship between I4.0 and sustainability. In this perspective, I4.0 technologies presents high potential to reach sustainable development by improving energy efficiency [65], [81]. Studies related to this cluster show the relationship between smart manufacturing and SM pointing to the impacts of I4.0 technologies on sustainable energy industries [3], [49], [50], [55]. Technologies such as real-time simulation and real-time control to manage energy resources and flexibilize the use of conventional and renewable energy in manufacturing systems gain prominence [82], [83]. Besides this, several researchers are focused on studies related to smart grids for generating, conserving and improving energy system efficiency [84]–[86].

H. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'RENEWABLE-ENERGY'

The cluster 'RENEWABLE-ENERGY' (Fig. 13, above) is a motor theme, and is related to the subthemes

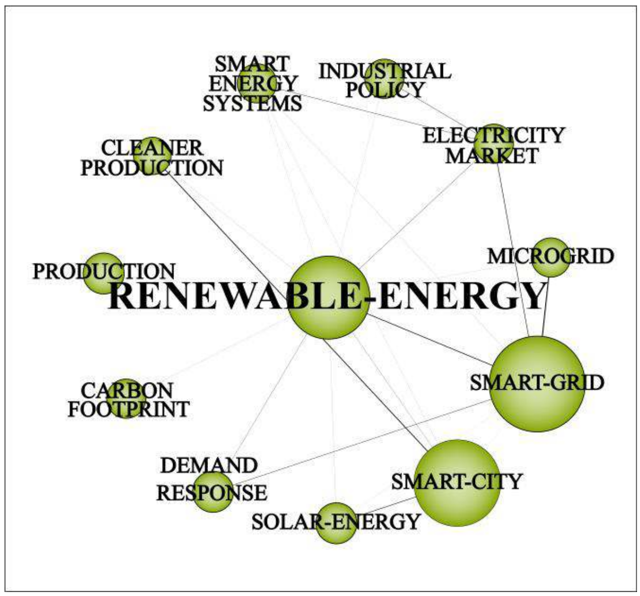


FIGURE 13. Thematic network structure of the cluster 'RENEWABLE-ENERGY.'

'SMART-GRID', 'MICRO-GRID', SMART-ENERGY-SYSTEMS' and 'SMARTCITY'. The energy theme is considerably discussed through the renewable-energy and smart grid clusters. The term smart grid is commonly used to describe a power grid that uses information and communication technologies to gather information and operate automatically to improve reliability, efficiency, economy and sustainability [87]–[89] energy production, distribution, transmission and consumption [90]–[95] aiming to achieve energy sustainability, environmental protection, large-scale failure prevention and cost savings [89]. These co-occurrence of keywords points to studies that use smart vehicle-grid to increase energy efficiency in electric cars [96], [97], smart electrical grid that uses renewable energy sources as an alternative to develop sustainable electrical systems in power plants. [98], industrial microgrid to develop more SM processes [99]. In other words, the cluster 'RENEWABLE-ENERGY' is mainly related to the energy sector through studies that address the use of renewable energies, as well as implementation of concepts such as smart grid and improving energy efficiency and development of smart cities.

I. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'CIRCULAR ECONOMY'

The cluster ('CIRCULAR ECONOMY') (Fig. 14, below) is an emerging or declining theme and highlights the beginning of the integration of circular economy (CE) with I4.0 technologies [63], [100]–[102]. The CE is a new perspective with focus on the correct use of resources, proposing sustainable organizational operations capable of generating benefits in the three spheres of sustainability [100]. The I4.0 technologies has been used to measure and collect data related to consumption, emissions and waste in production process, and this knowledge can assist decision making with a focus on sustainable production [103]. This relationship between these circular approaches and digital technologies is the necessary synergy to improve sustainable development and a regenerative economy [102]. The cluster CE is related to the subthemes 'BIOECONOMY', 'WASTE-WATER', 'REMANUFACTURING' and 'ONTOLOGY'.

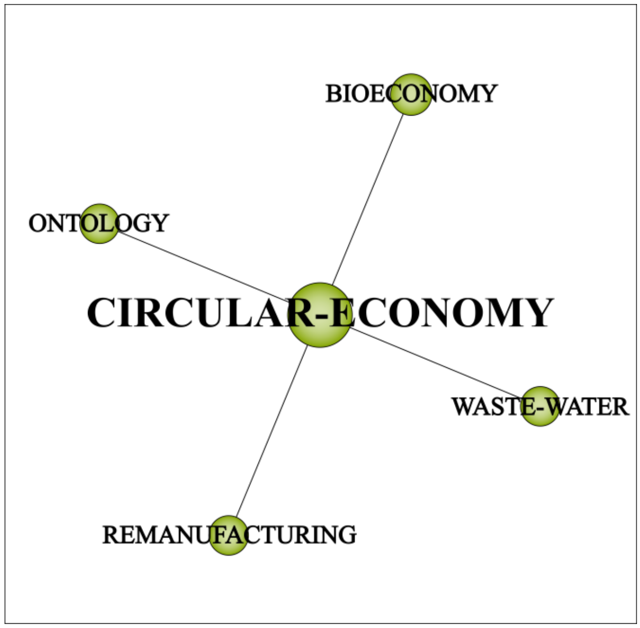


FIGURE 14. Thematic network structure of the cluster 'CIRCULAR ECONOMY.'

J. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'BIOFUELS'

The cluster 'BIOFUELS' (Fig. 15, below) is a highly developed and isolated theme and is related to the subthemes 'PHOTOSYNTHESIS', 'METABOLIC-ENGINEERING" and 'SYNTHETIC-BIOLOGY'. The cluster present discussions about ethanol production [104], artificial photosynthesis [105], and algal biorefinery [106] among others. The manufacturing process that use biological systems to produce biomolecules that can be commercialized and applied in different sectors such as industrial, agricultural and energy, among others, is referred to as biomanufacturing processes [107]. The use of biofuels can be a low carbon energy solution if produced correctly. Several technologies are used to assist in the generation of sustainable energy, such as photovoltaic and wind energy parks, smart grids for carbon sequestration and fuels produced by artificial photosynthesis and algae [108]. In the near future, biotechnology can become a key factor in the production of chemicals without the need to extract them from earth [109].

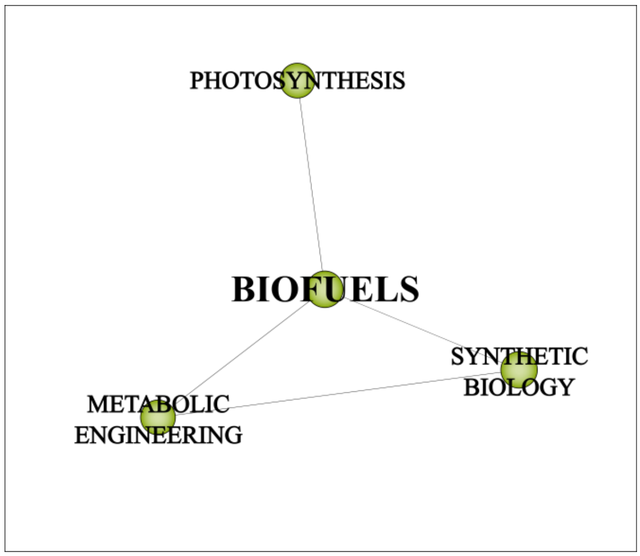


FIGURE 15. Thematic network structure of the cluster 'BIOFUELS.'

K. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'MAINTENANCE'

The cluster 'MAINTENANCE' (Fig. 16, below) is an emerging or declining theme and is gaining momentum through researches focused in efforts to understand the role of maintenance for SM and the relationship of maintenance with I4.0 technologies [26], [48], [78]. This cluster is related to the subthemes 'FORECASTING', 'SERVICE' and 'SOCIAL-SUSTAINABILITY' and characterizes the search for advanced technologies to optimize product life cycle through sustainable production. In many scenarios, big data and analytics is applied to develop condition-based maintenance and enable sustainable manufacturing. This approach reduces the uncertainty of the future through data analysis and makes it possible to minimize the use of resources and increase the reliability of the production process [78]. The

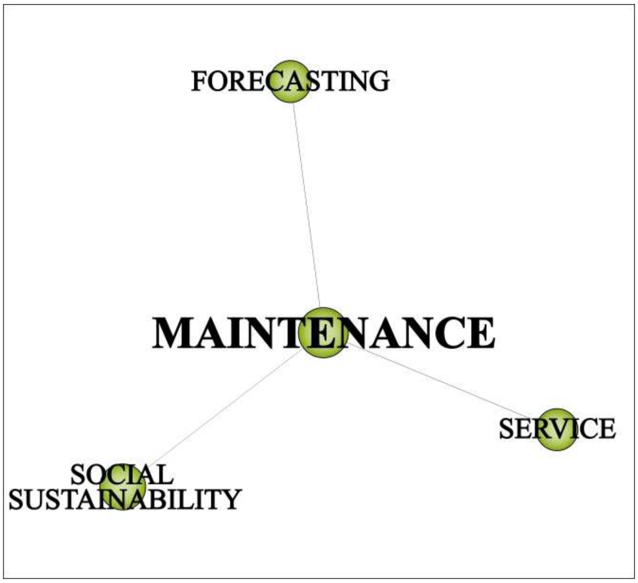


FIGURE 16. Thematic network structure of the cluster 'MAINTENANCE.'

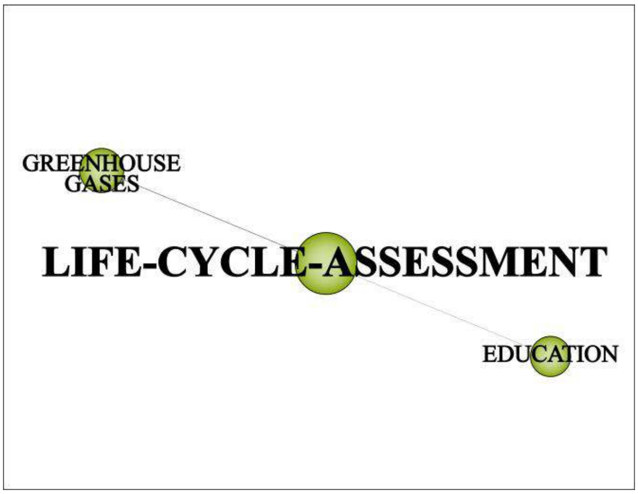


FIGURE 17. Thematic network structure of the cluster 'LIFE-CYCLE-ASSESSMENT.'

industrial systems are responsible for a large consumption of resources and emissions that impact the environment. In this sense, the maintenance process and I4.0 technologies contribute to the availability and reliability of data and productive resources, directly contributing to sustainable production [26].

L. THEMATIC NETWORK STRUCTURE OF THE CLUSTER 'LIFE-CYCLE-ASSESSMENT'

The cluster 'LIFE-CYCLE-ASSESSMENT' (Fig. 17, below) is an emerging or declining theme and relates studies by the use of I4.0 technologies with life-cycle assessment (LCA) as a strategy for reducing environmental impact focused in product life cycle [48], [110]–[112]. The cluster LCA is related to subthemes 'GREENHOUSE-GASES' and 'EDUCATION'. The LCA analysis has been applied in different scenarios such as healthcare [113], energy [114], agriculture [115] and manufacturing processes [116], and skills training of undergraduates about the understanding of LCA to promote SM [117].

The LCA and I4.0 technologies has been used to create products from the perspective of eco-design, with ecological redesign and prototyping. This allows the identification of critical points in the life cycle of products and the environmental impact for the implementation of sustainable production strategies [118]. The smart manufacturing and I4.0 technologies have potential to bridge the information gap between life cycle stages, specially between the product design and manufacturing processes [119].

V. CHALLENGES, PERSPECTIVES AND SUGGESTIONS FOR FUTURE RESEARCH

Considering the greenhouse effect, the emission of gases in the atmosphere and global warming have become crucial issues for societies [3]. In addition cities consume about 75% of global energy production and generate 80% of CO2 emissions [4]. The world's population will increase from 7 to 9-11 billion by 2050, with about half still dependent on using coal or biomass for domestic energy and 20% of the total lacking access to electricity [5]. As the population growths, world crop productivity remains stagnant, leading to agricultural crises, which represents one of the biggest scientific challenges in the coming years [120]. Moreover, meat demand is projected to increase by about 85% by 2030 [6], while water supplies will be 40% below global demand [7], [8]. Furthermore, it is estimated that up to 50% of food production is lost or discarded during the production process [59], [60], while a third of already produced food is lost or wasted [9], [10]. This information demonstrates some of the challenges and issues that need attention to promote sustainable development.

For nations to prosper, industries need to be flexible, transformative learning factories capable of innovation and economic development, as well as ecological and social concerns [121]. Therefore, in order to remain competitive, industries need to create sustainable value, i.e., to target the economic, social and environmental characteristics of TBL [122]–[124]. Although the number of studies in the area is increasing [125] (Fig. 3, above), it is still difficult to achieve a qualitative and quantitative combination of TBL dimensions, as these impact both the internal and external environment of the organization [122], [126], [127]. Environmental benefits are strongly related to the economic development of the organization [128] as they enhance the company's image and attract investors [129], while social efforts bring financial advantages when made public [130].

However, the dimensions of the TBL must be considered together and not in isolation [131] in order to consider sustainability as part of the company's organizational strategy [132], [133]. In this context, I4.0 impacts manufacturing in several ways, and can be used as a potential strategy for the development of sustainable production [134], capable of social, economic and ecological changes [121], [124]. The sustainable perspective on smart companies can be developed primarily by using technologies to react more quickly to change, reduce overproduction and waste, and incorporate smart grids for efficient energy management [134]–[136], which seems to be happening according to our results (Fig. 13, above). In this context, our finding shows the energy issue is considered as one of the main factors to promote sustainable development [137], [138]. The industrial sector is one of the largest consumers of energy [139]–[141] and in order to progress towards sustainable energy production and use it is necessary that the use of renewable energies increase progressively [84], such as solar, wind, and water, among others [142]. Thus, by reducing energy costs due to improved energy efficiency generated by I4.0 technologies, sustainability could be pursued by organizations in order to maximize profitability [50], [55].

A. INDUSTRY 4.0 AND SUSTAINABLE MANUFACTURING

Although several terms have emerged in the literature, including industrial sustainability, clean production, green manufacturing, eco-manufacturing [143] and CE [103], the term SM (Fig. 6, above) is the most appropriate to develop and address the social, environmental and economic aspects of sustainability [103]. SM has strong relationships with I4.0, which has promoting sustainability in organizations as one of its pillars [50], [55]. I4.0 has great potential for the development of sustainability [14], [25] because of its production flexibility and the possibility of using renewable energy sources [2]. Besides, I4.0 technologies can improve resource efficiency or increase productivity through supply chain integration [39], [136], [144], enabling industrial managers to move beyond environmental control and protection initiatives, incorporating intelligent process safety and control, as well as the well-being of employees and the community [28]. Therefore, I4.0 also proves to be a strategy for establishing production focused on significant economic, environmental and social developments [121], [124], [134], [145], which are the pillars of sustainability [2], also known as triple bottom line (TBL) [146]–[148].

However, in order to achieve sustainable manufacturing, several challenges still need to be overcome according to existing research, such as the implementation of life cycle analysis [50], [117], enhancement of maintenance and supply chain management [61], reduction of environmental impacts [76], implementation of I4.0 technology frameworks [63], proper use of circular economy concepts [103], real-time data processing and security [47]. energy resource management [82], maintenance schedule optimization [78], and others. These challenges require an organizational culture focused on innovation and learning, as well as academic knowledge translation into practice to facilitate the implementation of both emerging technologies and sustainable practices. Such expertise could be achieved with the use of new training methods to introducesustainable manufacturing concepts and using I4.0 skills training to improve the understanding of emerging technologies and related concepts [149].

B. INDUSTRY 4.0 AND CIRCULAR ECONOMY

We also suggest future works that integrate the socio-environmental relationship, since this is an aspect that provides means for human survival [150], [151]. In a scenario full of environmental problems, such as pollution, loss of diversity and resource depletion [152], [153], the need to adopt more sustainable socio-technical systems is urgent [154]. Moreover, the concept of CE (Fig. 14, above), despite the low integration with I4.0 technologies, has been providing positive results when used to address sustainability issues [155], which has been treated as the ability to coexist between the environment and the economy, giving opportunities to companies profit without causing risks and damage to the environment. Nowadays, the CE has a restorative aspect, and operates as a cycle that analyzes the multiple phases of the use of materials, and energy [156], making possible the analysis and monitoring of resources [157].

However, the widespread implementation of CE is still difficult to achieve, since barriers regarding cultural, technical, regulatory and marketing aspects still must be overcome [158], [159]. Moreover, another challenge relates to the indicators and assessment tools to measure and monitor CE, which seems to be immature and in early stages of development [160]. In this sense, the exhaustive review of Kristensen and Mosgaard [161] regarding CE indicators highlight that few approaches consider the social sphere of the TBL. In order to move forward for efficient methods of CE, studies regarding closed-loop supply chain models should be extended, because the identifications of metrics can enhance current CE approaches [162].

In this perspective, further studies focused on the CE and I4.0 are also needed in order to develop a course of action capable of support social changes and generate a global transition to a sustainable circular model, remodeling production and consumption models to sustainable approaches [163]. CE has been under discussion, but its integration with I4.0 pillars is beginning to be developed [101], as well as the comparison between innovation policies to deploy I4.0 with a focus on sustainable development [164]. Researchers should devote efforts that link circular economics [100], to pursuit shared economy, dematerialization, the Internet of Things, and production systems, so that new practices and solutions from different schools of thought can be embraced to enable innovation and sustainable systems of production and focus on value and sustainable development.

C. INDUSTRY 4.0 AND BIG DATA

Furthermore, there is a need to develop research related to big data, as our findings (Fig. 6, above) match the bibliometric analysis of I4.0 [24], which shows that big data is one of the biggest challenges. Data generated by the deployment of I4.0 technologies becomes information capable of creating industrial networks that help resource management and can balance the facets of TBL, increasing resilience and reliability. Similarly, the use of big data enables better analysis to develop better corporate culture and behavior, as well as optimizing the supply chain and fostering sustainable consumption [165].

In this perspective, big data is commonly used as a predictive approach by using techniques such as regression modeling, neural network, and other algorithms to predict future scenarios based on existing data. Such techniques can be used to improve the aspects of sustainability [166], however, the most scientific efforts related to big data are concentrated on system infrastructure (data collection, security, storage, etc.), and few works deal with the creation of a data-driven organizational culture, which empowers managers and executives to make more assertive decisions based on data instead of instinct [167]. Therefore, the need for studies with a focus to improve big data analytics skills and organizational culture is urgent in order to move towards superior decision-making, which will impact significantly in the sustainability dimension.

D. INDUSTRY 4.0 AND AGRICULTURE

We encourage studies related to improvements in agriculture sector with focus on farm management in order to increase productivity and reduce environmental impacts such as CSA (Fig. 9, above), which promotes more sustainable agricultural production through the reduction of greenhouse gases, and greater adaptation and resilience to climate change [168]. The use of CSA assists in increasing productivity and sustainability in areas of degraded and rain-poor soils and agronomic practices [66], [67], [169]. CSA is also used for adaptation of farming practices to mitigate decline in soil fertility, ecosystem destruction and biodiversity loss, and ensure the protection of natural resources and food security for the population with quality food [69]. In this sense, the CSA context has key technological innovations for the development of sustainable practices, such as information systems (local data-agronomic models), alert systems for extreme events, LCA, irrigation systems and water management optimization tools, combined farming systems and food processing, simulation tools for spatial distribution of land, among others [69], [170].

Despite the benefits of CSA, different barriers still must be overcome regarding the adoption of emerging technologies. The use of technologies as decision support systems can improve the quality level and customer satisfaction, reduce logistical costs and increase logistical visibility, which impacts on the sustainability of agricultural production [170]. Despite the advantages of a robust management system, many problems related to accessibility, scalability, interoperability, uncertainty and dynamic factors still exist [171]. Other difficulties are also mentioned as modest institutional support for farmers, conflicts between technological approaches and traditional methods, little knowledge and skills to deal with technologies, and market uncertainties [170] In this perspective, the knowledge and understanding of CSA practices is still limited, due to a lack of investment in technologies that support the development of CSA, which can make difficult to define priorities among farmers to manage effective practices [172].

Even common and recognized approaches such as payments for environmental services face challenges to promote CSA, since the integration of these practices requires investments from public sources, and must be very well modeled so that it can meet different ecological and socioeconomic conditions, and be considered together with other environmental services, such as food security and agricultural development [173]. These barriers affect different parts of organizations, such as high investments and costs of implementing measures and uncertainty of results. Therefore, we encourage future research to mitigate such challenges and barriers with the use of emerging technologies in order to promote sustainable agriculture.

E. INDUSTRY 4.0 AND PRODUCTIVITY PARADOX

Another significant challenge is related to the productivity paradox, also known as ''Solow Paradox'' [174], which represents the missing evidence of positive effects of information and communication technologies on productivity and may even generate negative results [175]. However, research began to show positive results [176], [177] due to improvements in the application of more advanced econometric approaches and superior quality data, making possible to highlight the neglected effects of technologies in the past (indirect effects of technologies) [178]. Still, such studies pointed out a high degree of sophistication in the use of technologies. These issues can become a challenge to understand how I4.0 can, in fact, improve productivity in companies that present a lack of resources to deal with such technologies. Besides, regarding the impact of I4.0 technologies in sustainability, the exhaustive SLR of Sony and Naik [179] highlighted the integration of I4.0 with sustainability is one of the 10 critical factors of I4.0 implementation in companies. However, the results showed that future works should be conducted to identify the real benefits of I4.0 technologies and what is the effect in the dimensions of sustainability.

The literature evidently reveals the lack of methods to assess and evaluate the implementation and effects of I4.0 in companies [180] as well as in sustainability dimensions. This might occur because the concept seems to be immature, since the literature presents more than 100 different existing implications and meanings of I4.0 [15]. Consequently, industries commonly fail to plan an appropriate implementation of I4.0 technologies and it makes difficulties for decision-makers to integrate I4.0 initiatives with sustainable practices [179]. Therefore, future research must be conducted to develop assessments and evaluation methods in order to understand the real role and impacts of I4.0 technologies on organizational productivity, because studies related to the productivity paradox are not yet sufficiently mature to define general conclusions.

F. INDUSTRY 4.0 AND LEAN PRODUCTION

Although I4.0 may have positive effects in companies, the fact of just implementing automation fails if the organizational culture is not prepared in terms of waste management and customer satisfaction (lean thinking). This perspective is aligned with Bill Gates's quote "The first rule of any technology used in a business is that automation applied to an efficient operation will magnify the efficiency. The second is that automation applied to an inefficient operation will magnify the inefficiency" [35]. Although researches [20], [73], [181] have been performed studies applying lean production to develop sustainability in I4.0 environments, we still suggest future researches that integrate concepts of lean production and I4.0, because many companies are struggling to implement both concepts, and studies are showing that lean production and I4.0 support each other in practice in order to achieve a more sustainable production [24], [35], [182], [183]. Therefore, I4.0 can be further exploited for sustainable production, mainly through efficiency improvements, reduced resource consumption and waste generation [165].

G. INDUSTRY 4.0 AND SOCIAL SUSTAINABILITY

The improvements in the economic pillar of sustainability generated by applications of I4.0 technologies can be another paradox regarding the social sphere, as automation means less manual labor. The explicit effect of introducing a new system or machine in the manufacturing process is to substitute the employee who performed a certain job, mainly related to low-skilled jobs [184] consequently increasing unemployment. However, the results of process innovation generate new demand for services and products in other sectors. Therefore, workers will have to be flexible and fast to adapt. In this sense, developing workers by companies will be another big challenge as it will require a highly skilled professional in order to deal with I4.0 technologies [24].

The training of professionals needs to change to a new model focused on the development of interdisciplinary skills and on the increase of capabilities to solve problems and develop abilities to deal with the challenges presented by I4.0 technologies [185]. Such technologies require future workers to handle large amounts of data, manage numerous work activities simultaneously, solve complex and multidisciplinary problems, perform initiatives changes in the organization and be able to perform a cooperative work with robots and dealing with advanced technologies of human-machine interaction [186], [187]. However, these skills are not widely available [188], especially to small and medium-sized companies [189]. Therefore, companies need to improve their competencies and skills through training and innovation [190] by introducing new approaches to knowledge management and skills transfer, such as the use of virtual training [186], [191]; creation of organizational processes centered on the user's view [192]; development of employee skills in technical (hard skills), behavioral (soft skills) and digital (digital skills) areas [193]; human-centered adaptive manufacturing systems for modern companies, where aging workers are increasingly common [194].

This demand for new skills compels universities to improve their education plans, and also encourages organizations to develop training plans for workers [195]. However, difficulties in training the workforce are evident both in universities due to gaps in teaching [196], and in organizations due to the lack of interest of employees due to training programs that often do not meet the real needs of employees due to the lack of sense of belonging and purpose, as well as for the failure of communication between the company and employees [195]. Therefore, there are challenges both in the sphere of education for the development of I4.0 workforce skills as well as in human resources challenges to support manage and develop such skills [197], [198]. Companies will need to be able to develop their human capital according to the new skills required by I4.0 from the implementation of organizational changes and the adoption of new management practices to ensure the efficient use of their intangible assets [199]. Besides, future works must be performed, mainly related to the development of soft skills since will be the last skill to be replaced by automated processes and will be the most prized [200] and the most requested by the I4.0 [201].

Our findings highlighted the lack of theoretical and empirical research on social sustainability mentioned above. This lack can be found in other studies such as [161]. Concern about the social sphere is vital, since environmental externalities are distributed differently in society, disproportionately geographically and between groups, with challenges in different contexts and levels of risk and vulnerability according to urban characteristics, natural disasters and climate change [202]. Therefore, such challenges need to be rethought and new methods developed to plan and improve social issues. Also, we suggest future works to develop solutions to enhance the development of the skills and abilities of workers such as the development of modern digital manufacturing technical support centers to develop relationships not only between universities and manufacturing companies [203], but also including the government efforts because I4.0 will require efforts from the union of industry, universities and governments [2].

VI. CONCLUSION

This BPNA showed the relationship between I4.0 and sustainability, addressing the motor themes and highlighting the main subthemes within each cluster, as well as discussions in the field of research. The growing number of studies that relate I4.0 and sustainability prove the strong relationship between the themes, characterizing sustainability as one of the pillars of intelligent manufacturing. The emergence of clusters such as 'FLOW-CONTROL', 'DECISION-MAKING, FOOD-INDUSTRY', among others highlights the use of I4.0 technologies to promote sustainability. Besides, our results show the scientific efforts are focused to boost both the economic and environmental spheres, and underlines a lack of efforts relating to the social aspects of TBL. Finally, we highlighted the main challenges, perspectives and suggestion for future works. However, its limitations must also be addressed. Although this BPNA was carried out with three different databases, some studies may have been neglected, since the work linked to the most important subthemes with the purpose of reducing the bias of the researchers on the chosen works. Only documents in English were also used, although other documents may present relevant topics and research. This study is the beginning for future research, which should be performed based on the choose of new criteria to identify new gaps, challenges, perspectives and future works. Issues such as circular economy, resource scarcity, lean production, energy problems, food production, process management and modeling, waste reduction, raw material reuse and social aspects should be extended in order to develop the field of study of the relationship between I4.0 and sustainability in order to develop a more sustainable society.

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