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Energy efficiency in the context of Industry 4.0

Vinicius Wittig Vianna[1], Wanderley Cardoso Celeste[2], Rodrigo Randow de Freitas[3]

[1]Energy Master's Program, UFES/CEUNES, BRAZIL
[2,3]Department of Computing and Electronics, UFES/CEUNES, BRAZIL

***Abstract*— *The aim of this paper is to identify, through a bibliometric analysis, how and which technologies, in the context of industry 4.0, are explicitly capable of promoting energy efficiency. The research was conducted on the Web of Science platform, using an algorithm with keywords of interest to the theme. As a result, a total of 67 articles were reached. Studies have been identified involving energy efficiency in the fields of industrial internet of things, wireless sensor networks, energy harvesting, cloud manufacturing, big data, artificial intelligence, additive manufacturing, and interdisciplinary research.*
***Keywords*— Advanced manufacturing, Cloud manufacturing, Energy, Smart factory.**

I. INTRODUCTION

In the last decades, the industrial scenario has noticed significant changes where, as new concepts and technologies develop, a trend in the manufacturing transformation can be noticed.

For Wang et al. (2016), technologies such as cloud computing, industrial internet of things, wireless sensor networks and processing large amounts of data have been causing profound changes in industrial processes.

Still, according to the authors, manufacturing processes, which were once manual, today have robust embedded control systems and this is a trend that indicates a new behavior of manufacturing industries, characterized by the implementation of smart manufacturing technologies that understand the context of the 4th industrial revolution, called Industry 4.0.

Liao et al. (2017) describe, through a comprehensive bibliographic review, and in a well-structured manner, the main technologically disruptive events that characterize the four industrial revolutions. Directly, the authors cite that the first three revolutions extended for approximately two centuries, whose main manufacturing impacts were, in order, the introduction of water and steam-based equipment, introduction of electricity-based production technologies, use of electronics and information technology (IT) to support the automation of industrial processes.

Plausible, therefore, to interpret that the set of processes that characterize the fourth industrial revolution comprises a natural way, where the automation of the manufacture becomes more efficient, as it has technologically strategic apparatuses, in the sense to digitize the manufacturing processes and connect faster, and more fully, to human management. Although Liao et al. (2017) demonstrate that the proposal to make intelligent, digital, and interconnected manufacturing systems attractive, it is necessary to look in detail at how the major categories of enabling technologies work and how they are able to make it real.

Parallel to this, Dornfeld (2014) discusses that as energy demand increases significantly, there is a tendency in the industrial context to employ efforts, making manufacturing processes more sustainable. The author also mentions that the sustainability factor is no longer utopia, and is becoming, besides the environmental magnitude, a factor of commercial strategy, through the economy of resources, operational guarantee, product quality and global competitiveness.

Considering the above, and the effects of Industry 4.0 in the context of energy efficiency, the use of the proposed bibliometric analysis is justified here. Despite being widely studied and disseminated in both the academic and casual environments, it remains, to some extent, what are the most relevant impacts of smart manufacturing in terms of energy efficiency. Additionally, it is necessary to highlight which types of enabling technologies from Industry 4.0 influence externally (causing energy efficiency through the provision of improved controls and assertive data for manufacturing management) and internally (causing energy efficiency through the intelligent use of power supply or the efficient use of sensors, transmitting or receiving devices and other equipment).

Therefore, the present work aims to develop the correlation of scientific publications that address energy efficiency in the context of Industry 4.0, by searching for articles in the Web of Science database.

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In order, to establish the concepts discussed here, we sought literature that provides the appropriate theoretical basis. IEL (2017) states that enabling technologies for Industry 4.0 can be classified into large clusters, which, due to suitability for this research, cite the internet of things; sensors and actuators; cloud computing; big data analysis; artificial intelligence and additive manufacturing. It should be noted that, in addition to these, other complementary technologies can help, in parallel, the feasibility of digitization of manufacturing, in its various facets.

Gubbi et al. (2013), Stankovic (2014) and Wan et al. (2016), address an important strategic communication link between man and machine, in the context of industry 4.0, the internet of things. The aforementioned research, as well as several works in the academy, propose that the term characterizes the connection among equipments, especially the machines, to the internet, through sensor instruments, responsible for collecting parameters of the chosen process and sending them to further treatment and use.

Wireless sensors, electronic equipment capable of collecting data of interest, send the information to cloud servers to be processed and made available to the end user, who can, among other resources, use them as an automatic response control, increment predictive maintenance analytics, or for more assertive decision making. Lin et al. (2016) mention that in conventional factories, it is common to apply wired monitoring systems (such as fieldbus or HART systems), however, they have high costs and do not represent an optimal solution in terms of flexibility in the layout of production lines. Thus, the authors propose the use of wireless sensor networks (WSN) as the most practical and inexpensive way to feed data into an industrial process management system.

Another relevant aspect in the treatment of sensors and automatic actuators concerns their power supply. Since electronic devices require electrical power to operate, cable powering, as well as being a costly and inflexible solution, is not capable of reusing resources that manufacturing processes can offer from power dissipation. In this reasoning, research such as that performed by Newell, Twohig and Duffy (2018) and Sherazi et al. (2018) demonstrate that energy harvesting devices, that is, dissipated energy reuse, have the flexibility to be installed in a wide variety of locations, which could not, due to the need for power via cables, moreover, have a strong call for energy efficiency.

Also, according to Sherazi et al. (2018), the main energy sources capable of feeding sensors through the capture in industrial environment are: photovoltaic energy, from artificial lighting of environments; thermal energy, from heat exchange in equipment; radio frequency energy, from radio signals inside the plant and mechanical energy, from vibration of machines. Additionally, Rubes, Brablc and Hadas (2019) state that the energy collection from vibration is based on mechanical vibration kinetics, which can be converted into electrical energy through a piezoelectric transducer.

Xu (2012) brings another important definition about technology that can digitize manufacturing, making it a more manageable and adaptable process to change: cloud manufacturing. In other words, and based on the National Institute of Standard and Technology - NIST definition for cloud computing, the author discusses that the concept of cloud manufacturing can be interpreted as a natural extension of the concept of cloud computing.

Cloud computing is a model for allowing ubiquitous, convenient, and on-demand network access to a shared set of configurable computing resources (i.e. networks, servers, storage, applications, and services) that can be quickly provisioned and released with minimal management effort or interaction with service providers (NIST, 2011).

Xu (2012) also points out that the typical benefits of adopting cloud manufacturing can be realized in both the technical and economic spheres, as the costs of acquiring and maintaining IT infrastructure can be reduced substantially.

In parallel with cloud manufacturing, data collected on the shop floor needs to be processed into strategic information. This treatment, also known as big data analytics, in terms of manufacturing, is approached by Wang, Wan and Zhang (2016), who broadly describe it through a feedback loop, starting with entering a volume of disarmed information once collected by the wireless sensor network, cloud analysis from specific servers and return information for process control.

Another type of technology that can make manufacturing processes more cognitive is artificial intelligence which, in other words, comprises algorithms and computer systems capable of autonomously making control decisions based on data collected in the most diverse situations. Monostori (2002) approaches the theme through the idea that software acquires cognitive abilities through the acquisition, manipulation and association of data, similar, in limited characteristics, to the natural process of the human mind.

Regarding additive manufacturing, which consists of machinery capable of producing other components by depositing layered material, similar to the term "3D printing", Yoon et al. (2014) mention that the term "three-dimensional printing" was originally used at the Massachusetts Institute of Technology (MIT), published as part of a patent, the contents of which describe manufacturing processes from an inkjet head system, which, was quickly called by the public as 3D printing.

II. MATERIALS AND METHODS

In order to identify relationships between energy efficiency and Industry 4.0, more broadly, we sought to use tags (keywords) that strategically characterize both contexts. In this sense, "energy", "industry 4.0", "smart manufacturing" and "advanced manufacturing" were selected. The database used was the Web of Science - WoS, due to the diversity of contents in the technical areas, robustness in the research and availability of data analysis tools.

The search algorithm used was: "energy" AND ("industry 4.0" OR "smart manufacturing" OR "advanced manufacturing"). In addition, the search timeframe selection field has been enabled for selection of documents in the entire database from its inception to the day the search was performed (1945 to 2019).

Aiming at a better understanding of the methodological step by step used in this study, a flowchart is presented in Figure 1.

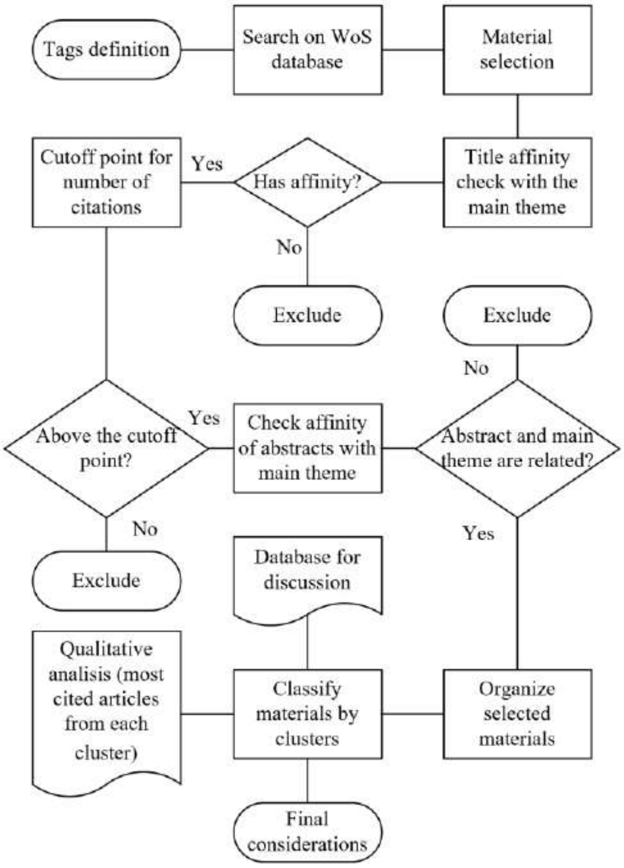

Fig. 1: Selection and analysis flowchart.
Source: Prepared by the authors.

III. RESULTS AND DISCUSSION

From the use of the defined algorithm and initial search conditions, 493 results were obtained. Still at this stage, without the specific refinements, the authors consider it relevant to highlight some behaviors regarding publications. The first of these refers to the ten most active countries in publications of the genre (the research object of this paper is understood). As can be interpreted in figure 2, a considerable number of countries with strong performance in science and technology, including innovation, especially in the northern hemisphere, can be seen.

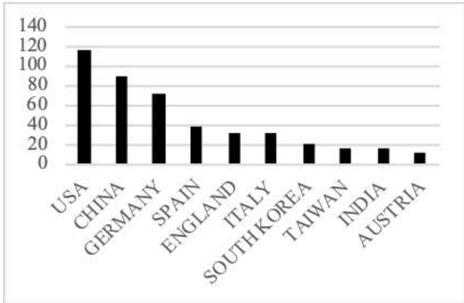

Fig. 2: Publications by country.
Source: Adapted from Web of Science.

From this stage, other refining tools were used, so that the results were restricted in publications in the last 10 years (2009 to 2019) and article type documents. As a result, the tool returned 239 items. Then, the results were sent to a list of marked documents, where, from the affinity analysis of the article titles with the proposal of this work, the first detailed screening was performed. As the screening identified that some articles had no proposals of interest, the number of results decreased to the point of establishing a list of 101 articles with titles that would be candidates for bibliometric analysis.

After this first screening, a more accurate identification and selection of documents from the abstracts was performed. The criterion for persistence in the selection was to analyze whether the abstract makes technology explicit, according to IEL (2017), that causes any impact in terms of industrial energy efficiency. In this screening 67 results were obtained.

At this point other considerations still fit. The first refers again to the ten largest countries active in energy efficiency research in the context of Industry 4.0. Comparing the graphs in figures 2 and 3, it can see a plausible behavior, so that the countries most active in research involving energy or advanced manufacturing are, in their majority, those with the highest representation in research involving energy efficiency in the same context.

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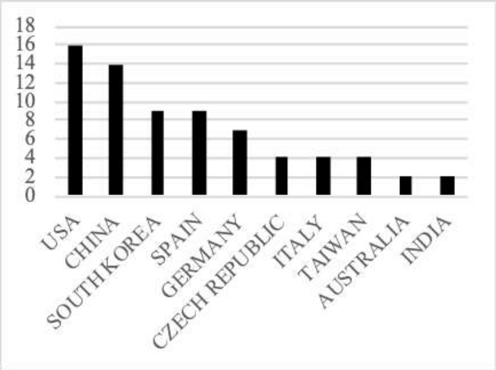

Fig. 3: Publications by country (after abstract trial).
Source: Adapted from Web of Science.

The second consideration refers to the amount of academic papers with similar proposals being published over the years. According to figure 4, an upward line is seen, which demonstrates the emergence of the theme and the commitment to use resources more efficiently, in contrast to the introduction of this work.

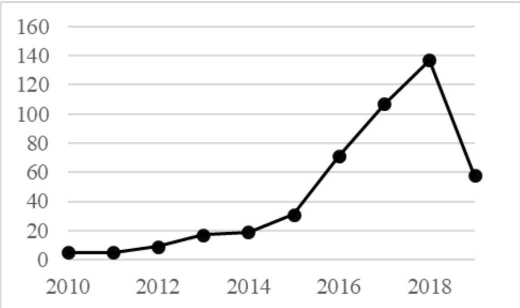

Fig. 4: Publications by year (after abstract trial).
Source: Adapted from Web of Science.

The third consideration refers to the number of publications per knowledge area, according to the Web of Science - WoS database classification criteria. Figure 5 indicates the areas with the most studies, with particular emphasis on engineering, computer science, telecommunications, and systems control automation. This data is relevant because it is consistent with the reality, where the degree of innovation and implementation of Industry 4.0 technologies is highly dependent on research and advances in the above fields.

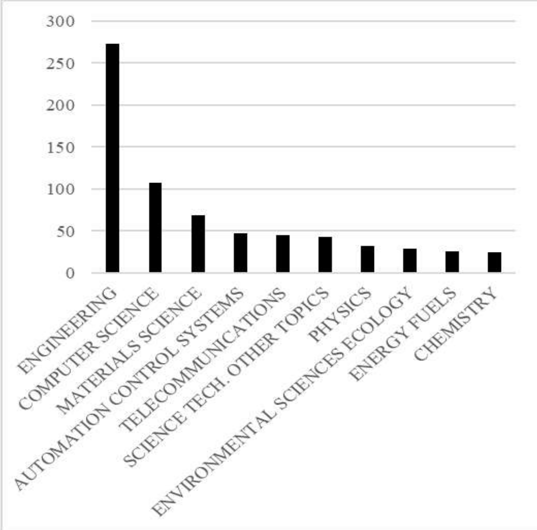

Fig. 5: Publications by knowledge areas (after abstract trial).
Source: Adapted from Web of Science.

By identifying which and how technologies within the context of Industry 4.0 may impact on industrial energy efficiency, the next step was to categorize the results into clusters, that is, into the major enabling groups of industry 4.0 technologies.

At first, it is possible to highlight, globally, some observations from the categorization of screened articles. Figure 6 shows the number of papers identified by the authors in each cluster. The criterion adopted for classification was the analysis of the proposed methodology applied in each work. Articles with methodology involving specific and well-defined technology were classified into one of the following clusters: industrial internet of things (IIoT); wireless sensor networks (WSNs); energy harvesting (EH); cloud manufacturing (CM); big data (BD); programming optimization and artificial intelligence (AI); and additive manufacturing (AM). Those that could not be classified in a specific cluster were counted as miscellaneous.

The figure presents the composition of the identified documents, from the categorization through clusters, highlighting techniques of programming optimization and artificial intelligence.

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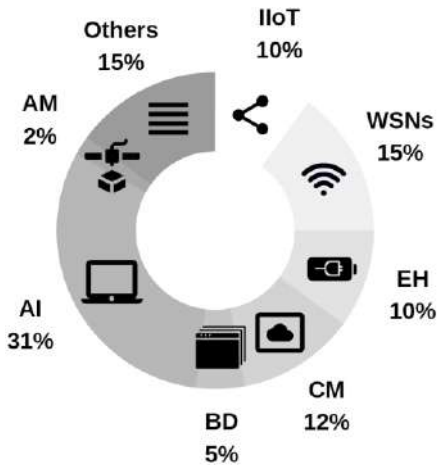

Fig. 6: Filtered publications, categorized by clusters.
Source: Prepared by the author.

Then, will be presented and categorized the articles selected at the end of the screening for abstracts. With this classification, which will follow the order of the technology groups presented in figure 6 and, through a discussion focused on the most cited articles in each of the following tables (based on the points of interest of this research), the authors seek to be able to conclude from how studies, in their respective clusters, tend to converge towards promoting energy efficiency in industrial processes.

Table 1 presents the categorized articles, according to the authors' judgment, in the internet of things cluster. Sisinni et al. (2018) explain that, in most cases, a low throughput is required by transmitting nodes in IIoT applications, demonstrating that companies, when choosing this type of implementation, are concerned with the possibility of providing informational synergy among its assets, both through internet connection and energy and hardware resources, all at a low cost.

The study makes it clear that it is characteristic of hardware for this type of technology to work for years on batteries, which implies the development of increasingly bold designs to improve them, shrinking them and making them more powerful and efficient.

In parallel, the concept of energy reuse is approached, where the power to supply these batteries can be collected through sources from the environment or processes, such as vibrations, radio frequency, thermal and solar.

Finally, in support of achieving energy efficiency, new data transmission technologies are being studied, such as the Low-Power Wide-Area Network (LPWAN), which enables long-distance data communication with power transmission significantly reduced.

Table 1 - Internet of things publications

Title	Journal	Year
Industrial Internet of Things: Challenges, Opportunities, and Directions	IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS	2018
I3Mote: An Open Development Platform for the Intelligent Industrial Internet	SENSORS	2017
Metamodel for integration of Internet of Things, Social Networks, the Cloud and Industry 4.0	JOURNAL OF AMBIENT INTELLIGENCE AND HUMANIZED COMPUTING	2018
Light-Weight Stackelberg Game Theoretic Demand Response Scheme for Massive Smart Manufacturing Systems	IEEE ACCESS	2018
The Energy Industry in the Czech Republic: On the Way to the Internet of Things	ECONOMIES	2018
IoT Heterogeneous Mesh Network Deployment for Human-in-the-Loop Challenges Towards a Social and Sustainable Industry 4.0	IEEE ACCESS	2018
Novel Internet of Things Platform for In-Building Power Quality Submetering	APPLIED SCIENCES-BASEL	2018

Source: Prepared by the author.

Table 2 presents the articles categorized, according to the authors' judgment, in the cluster of wireless sensor networks.

Lin et al. (2016) discuss the concept of wireless sensor networks, composed of components called sensor nodes, which capture the parameters of interest in a particular asset and send them to receiving hardware, which, in turn,

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will process the data and, based on the control criteria, the system will provide commands for production.

Based on this technology, the study takes an approach that proposes, and simulates, a kind of strategy that uses metaheuristic optimization tool (genetic algorithm) which learns and develops a schedule of operation and hibernation of network devices. According to the authors, only active sensor nodes will consume power, while those in hibernation mode, will not. The study reveals a tool capable of contributing to the increase of energy efficiency in industrial operations.

Table 2 - Wireless sensor network publications

Title	Journal	Year
Key Design of Driving Industry 4.0: Joint Energy-Efficient Deployment and Scheduling in Group-Based Industrial Wireless Sensor Networks	IEEE COMMUNICATIONS MAGAZINE	2016
From Sensor Networks to Internet of Things. Bluetooth Low Energy, a Standard for This Evolution	SENSORS	2017
A Methodology for Reliability of WSN Based on Software Defined Network in Adaptive Industrial Environment	IEEE-CAA JOURNAL OF AUTOMATICA SINICA	2018
Energy efficient and QoS-aware routing protocol for wireless sensor network-based smart grid applications in the context of industry 4.0	APPLIED SOFT COMPUTING	2018
MQRP: Mobile sinks-based QoS-aware data gathering protocol for wireless sensor networks-based smart grid applications in the context of industry 4.0-based on internet of things	FUTURE GENERATION COMPUTER SYSTEMS-THE INTERNATIONAL JOURNAL OF ESCIENCE	2018
Deploy&Forget wireless sensor networks for itinerant applications	COMPUTER STANDARDS & INTERFACES	2018
Autonomous micro-platform for multisensors with an advanced power management unit (PMU)	JOURNAL OF SENSORS AND SENSOR SYSTEMS	2018
Wireless sensor network routing method based on improved ant colony algorithm	JOURNAL OF AMBIENT INTELLIGENCE AND HUMANIZED COMPUTING	2019
Data cleansing for energy-saving: a case of Cyber-Physical Machine Tools health monitoring system	INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	2018
An Experimental System for MQTT/CoAP-based IoT Applications in IPv6 over Bluetooth Low Energy	JOURNAL OF UNIVERSAL COMPUTER SCIENCE	2018

Source: Prepared by the author.

Table 3 presents the categorized articles, according to the authors' judgment, in the energy reuse cluster. Following the idea of reusing energy from industrial processes that would eventually be wasted, Sherazi et al. (2019) state that while the more traditional Low-Power

Wide-Area Network (LPWAN) architecture devices provide excellent energy efficiency, they are still powered by the battery, which means frequent maintenance and therefore more time spent and budget costs.

Based on studies that show that the life of a battery is strongly influenced by the amount of cycles (charges and discharges) it undergoes, a modified LoRaWAN (Long Rang Wide Area Network) architecture was proposed, the results of which were optimization of sensing intervals (and related costs), derived from scenarios with energy harvesting and without energy harvesting.

Three sources of energy were considered for energy reuse: photoelectric (from internal artificial light), thermoelectric (from heat dispersion of equipment with this characteristic) and radio frequency (from radio signals within the plant).

It was noticed that the applied methodology was able to adjust the transmission intervals optimally, putting the monitoring devices at rest after each actuation interval, prolonging the operation and reducing costs (long term).

Moreover, the scenario where the sensing devices are powered via energy harvesting demonstrates the significant increase in battery life due to the excess amount of energy supplied and the progressive increase in the sensing interval. Comparing the scenarios with and without energy harvesting, there is a strong reduction in costs (substitutions and labor time) for the first scenario.

Table 3 – Energy harvesting publications

TITLE	JOURNAL	YEAR
Energy Harvesting in LoRaWAN: A Cost Analysis for the Industry 4.0	IEEE COMMUNICATIONS LETTERS	2018
Effect of energy management circuitry on optimum energy harvesting source configuration for small form-factor autonomous sensing applications	JOURNAL OF INDUSTRIAL INFORMATION INTEGRATION	2018
Nonlinear vibration energy harvester: Design and oscillating stability analyses	MECHANICAL SYSTEMS AND SIGNAL PROCESSING	2019
A fully encapsulated piezoelectric-triboelectric hybrid nanogenerator for energy harvesting from biomechanical and environmental sources	EXPRESS POLYMER LETTERS	2019
A 500 Hz-wide kinetic energy harvester: Outperforming macroscopic electrodynamic arrays with piezoelectric arrays	MECHANICAL SYSTEMS AND SIGNAL PROCESSING	2019
Turning the Signal Interference Into Benefits: Towards Indoor Self-Powered Visible Light Communication for IoT Devices in Industrial Radio-Hostile Environments	IEEE ACCESS	2019
Triboelectric effect based instantaneous self-powered wireless sensing with self-determined identity	NANO ENERGY	2018

Source: Prepared by the author.

Table 4 presents the categorized articles, according to the authors' judgment, in the cloud manufacturing cluster. Cheng et al. (2013) emphasize on-demand sharing and allocation of manufacturing resources by introducing the concept of cloud manufacturing, with the goal of minimizing costs and energy consumption.

The study proposes a strategy for scheduling cloud manufacturing services and resources. In this scheduling process, three criteria of importance are considered: energy

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consumption, cost and risk, for three different interested classes: supplier, consumer and operator.

According to the authors, the supplier (person, organization, company or third party) has the necessary resources for the life cycle of a manufacturing process. It registers idle resources on the cloud platform and delivers them to the consumer. The consumer is considered to be the subscriber of the feature available on the platform as per their demands. The operator is responsible for allocating available resources from suppliers, redirected to the demands registered by consumers.

After comparing four resource scheduling models, it was found that the centralized scheduling method has a better ability to optimize manufacturing resources through the risk sharing strategy, which promotes higher efficiency, higher sharing rate, sustainable use of manufacturing resources and hence energy efficiency.

Table 4 – Cloud manufacturing publications

Title	Journal	Year
Energy-aware resource service scheduling based on utility evaluation in cloud manufacturing system	PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART B-JOURNAL OF ENGINEERING MANUFACTURE	2013
Context-Aware Cloud Robotics for Material Handling in Cognitive Industrial Internet of Things	IEEE INTERNET OF THINGS JOURNAL	2018
Fog Computing for Energy-Aware Load Balancing and Scheduling in Smart Factory	IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS	2018
IO-Link Wireless enhanced factory automation communication for Industry 4.0 applications	JOURNAL OF SENSORS AND SENSOR SYSTEMS	2018
Leveraging the Capabilities of Industry 4.0 for Improving Energy Efficiency in Smart Factories	IEEE ACCESS	2019
Multi-objective resource allocation for Edge Cloud based robotic workflow in smart factory	FUTURE GENERATION COMPUTER SYSTEMS-THE INTERNATIONAL JOURNAL OF ESCIENCE	2019
Energy-efficient cyber-physical production network: Architecture and technologies	COMPUTERS & INDUSTRIAL ENGINEERING	2019
Use of Statistical Correlation for Energy Management in Office Premises Adopting Techniques of Industry 4.0	DYNA	2018

Source: Prepared by the author.

Table 5 presents the categorized articles, according to the authors' judgment, in the big data analysis cluster. From a counterpoint to traditional manufacturing platforms, Woo et al. (2018) proposed the implementation of a system for collecting, processing and analyzing large amounts of data, with the aim of making more assertive and collaborative manufacturing processes.

The system is basically comprised of three steps, virtualizing manufacturing processes, real-time data processing, and data-driven decision making for predictive planning. In other words, the system processes and performs data analysis, creating decision-making models based on real-time parameters and history. Also, the application makes use of standardized data interface, which enables the exchange of information and data comparison with other factories that use it.

To illustrate the problem, the authors cite that this is a relevant solution in addressing the limitations of the traditional approach. If it were possible to process all data from a given historical series and cross-reference it with real-time data, it would be possible to create predictive models for resource optimization and energy efficiency.

An example used in the researchers' study was the data analysis modeling approach to an energy forecasting model required by a machining center. According to the authors, it is possible to develop a dynamic predictive model based on the behavior of this resource over its useful life.

That said, it can be concluded that the development of technologies capable of storing, processing and analyzing large masses of data from a manufacturing process history, and cross-referencing it with real-time data, is able to promote industrial energy efficiency through the automatic creation of dynamic forecasting models as a tool to aid decision making.

Table 5 – Big data publications

Title	Journal	Year
Developing a big data analytics platform for manufacturing systems: architecture, method, and implementation	INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY	2018
A big data driven sustainable manufacturing framework for condition-based maintenance prediction	JOURNAL OF COMPUTATIONAL SCIENCE	2018
Sustainable robust layout using Big Data approach: A key towards industry 4.0	JOURNAL OF CLEANER PRODUCTION	2018

Source: Prepared by the author.

Table 6 presents the categorized articles, according to the authors' judgment, in the programming optimization and artificial intelligence cluster. Aiming at a global analysis, Bányai (2018) develops a study based on the idea that in the traditional logistics planning methodology, issues such as energy efficiency and environmental preservation have been neglected through an individualized approach among the various value-chain agents.

Therefore, the author develops a mathematical modeling for the last mile process, that is, the moment when the products leave the distribution center for the final location. The modeling presented aims to establish the ideal tasks and schedules for each order, using a black hole-based heuristic optimization algorithm (BHA), aiming to reduce energy consumption, consequently promoting energy efficiency.

In the case study developed, the author presented a model with two delivery service providers, 17 destinations scheduled on three routes. After methodological execution, the algorithm was able to find the best logistic planning solution for this case, using fuel consumption as a function of the problem.

Table 6 – Programming and artificial intelligence publications

Title	Journal	Year
Real-Time Decision Making in First Mile and Last Mile Logistics: How Smart Scheduling Affects Energy Efficiency of Hyperconnected Supply Chain Solutions	ENERGIES	2018
Smart Manufacturing Approach for Efficient Operation of Industrial Steam-Methane Reformers	INDUSTRIAL & ENGINEERING CHEMISTRY RESEARCH	2015
Multi-dimensional data indexing and range query processing via Voronoi diagram for internet of things	FUTURE GENERATION COMPUTER SYSTEMS-THE INTERNATIONAL JOURNAL OF ESCIENCE	2019
Energy Optimization of Robotic Cells	IEEE TRANSACTIONS ON INDUSTRIAL INFORMATICS	2017
Real-time optimization of an industrial steam-methane reformer under distributed sensing	CONTROL ENGINEERING PRACTICE	2016
Decision rules for energy consumption minimization during material removal process in turning	JOURNAL OF CLEANER PRODUCTION	2017
The cellular approach: smart energy region Wunsiedel. Testbed for smart grid, smart metering and	ELECTRICAL ENGINEERING	2016

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smart home solutions		
Smart manufacturing and energy systems	COMPUTERS & CHEMICAL ENGINEERING	2018
Green Production Planning and Control for the Textile Industry by Using Mathematical Programming and Industry 4.0 Techniques	ENERGIES	2018
Optimizing energy consumption of robotic cells by a Branch & Bound algorithm	COMPUTERS & OPERATIONS RESEARCH	2019
Simulation and Test Bed of a Low-Power Digital Excitation System for Industry 4.0	PROCESSES	2018
Uncertainty reduction in measuring and verification of energy savings by statistical learning in manufacturing environments	INTERNATIONAL JOURNAL OF INTERACTIVE DESIGN AND MANUFACTURING - IJIDEM	2016
Autonomic smart manufacturing	JOURNAL OF DECISION SYSTEMS	2015
Optimization of the energy consumption of industrial robots for automatic code generation	ROBOTICS AND COMPUTER-INTEGRATED MANUFACTURING	2019
Improvement of Temperature Control Performance of Thermoelectric Dehumidifier Used Industry 4.0 by the SF-PI Controller	PROCESSES	2019
Use of On-Demand Cloud Services to Model the Optimization of an Austenitization Furnace	SMART AND SUSTAINABLE MANUFACTURING SYSTEMS	2018
Improvement of Energy Efficiency and Control Performance of Cooling System Fan Applied to Industry 4.0 Data Center	ELECTRONICS	2019
Intelligent Optimization of Hard-Turning Parameters Using Evolutionary Algorithms for Smart Manufacturing	MATERIALS	2019
Energy-efficiency-oriented scheduling in smart manufacturing	JOURNAL OF AMBIENT INTELLIGENCE AND HUMANIZED COMPUTING	2019
Optimal Operating Schedule for Energy Storage System: Focusing on Efficient Energy Management for Microgrid	PROCESSES	2019
X-DNNs: Systematic Cross-Layer Approximations for Energy-Efficient Deep Neural Networks	JOURNAL OF LOW POWER ELECTRONICS	2018

Source: Prepared by the author.

Table 7 presents the categorized article, according to the authors' judgment, in the additive manufacturing cluster.

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Yoon et al. (2014) developed a comparative study of energy consumption in three different manufacturing processes: conventional mechanical conformation (methods of applying external forces to an object to acquire a specific shape), subtractive manufacturing (three-dimensional computed machining for object acquires specific characteristics) and additive manufacturing (three-dimensional computer modeling for an object to assume specific characteristics).

The results obtained by comparing the three case studies developed with the literature data show that, as the number of manufactured parts tends to grow, the specific energy consumption of the additive processes tends to approach a value up to 100 times superior to conventional mechanical forming processes, which is a relatively large difference. Already the subtractive manufacturing processes figured an intermediate position between the other two.

It is therefore noticeable that, in view of the growing demand for sustainable manufacturing, an efficient tool for comparing available manufacturing methods must be implemented, especially in helping decision making involving operational investments and energy efficiency.

Table 7 – Additive manufacturing publications

Title	Journal	Year
A Comparison of Energy Consumption in Bulk Forming, Subtractive, and Additive Processes: Review and Case Study	INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING-GREEN TECHNOLOGY	2014

Source: Prepared by the author.

Table 8 presents the categorized articles, according to the authors' judgment, as diverse, to the detriment of applications of technologies or varied methodologies. Dornfeld (2014) justifies his study, especially in the aspects of environmental preservation. The involvement of sustainable manufacturing technologies at all levels, whether tooling or process, is one of the strategies to promote conscious use of resources.

The author mentions that at the process planning level, for example, in a computerized machining center, planning the tool path can mean a reduction in the manufacturing time for a particular part. In addition, planning focused on minimizing idle times on these devices can mean a considerable increase in energy savings.

On the other hand, the author specifies that it is possible to implement more efficient energy control by detailing the resources consumed and the resources wasted at each stage of a production line, translating crucial strategic information as carbon dioxide equivalent, energy cost, water cost, among others.

Furthermore, it is described by the research, the use of ecological route maps, which specifies, from a baseline (involving current energy expenditures), what improvements should be implemented to maximize energy efficiency objectives.

Finally, considering the tools presented by the author, it is concluded that the technology factor is fundamental to promote an efficient management foundation of energy resources. Industry 4.0 enabling technologies have the potential to assist in automatic control of operations, speeding up processes and avoiding errors; provide more assertive and impactful strategic decision-making information; and reuse underutilized energy resources, promoting increasingly optimized and, especially, sustainable industrial operations.

Table 8 – Other publications

Title	Journal	Year
Moving Towards Green and Sustainable Manufacturing	INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING-GREEN TECHNOLOGY	2014
Impact of advanced manufacturing on sustainability: An overview of the special volume on advanced manufacturing for sustainability and low fossil carbon emissions	JOURNAL OF CLEANER PRODUCTION	2017
A Cost-Effective Redundant Digital Excitation Control System and Test Bed Experiment for Safe Power Supply for Process Industry 4.0	PROCESSES	2018
Smart Manufacturing for the Oil Refining and Petrochemical Industry	ENGINEERING	2017

https://dx.doi.org/10.22161/ijaers.612.1 ISSN: 2349-6495(P) | 2456-1908(O)

Toward Dynamic Energy Management for Green Manufacturing Systems	IEEE COMMUNICATIONS MAGAZINE	2016
Opto-Electronic Sensor Network Powered Over Fiber for Harsh Industrial Applications	IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS	2018
Exploring Organizational Sustainability of Industry 4.0 under the Triple Bottom Line: The Case of a Manufacturing Company	SUSTAINABILITY	2019
Trends in Advanced Manufacturing	INTERNATIONAL JOURNAL OF MULTIPHYSICS	2018
The Role of a Digital Industry 4.0 in a Renewable Energy System	INTERNATIONAL JOURNAL OF ENERGY RESEARCH	2019
Potentials for model-based energy supply forecasts - Energy management in the context of industry 4.0	ATP EDITION	2017

Source: Prepared by the author.

Table 9 provides a compilation of the most cited articles in each of the technology groups selected by the authors, which supported the discussion of this work.

Table 9 – Most cited publications

Title	Year	Citations	Cluster
Industrial Internet of Things: Challenges, Opportunities, and Directions	2018	12	Internet of things
Key Design of Driving Industry 4.0: Joint Energy-Efficient Deployment and Scheduling in Group-Based Industrial Wireless Sensor Networks	2016	25	Wireless sensors network
Energy Harvesting in LoRaWAN: A Cost Analysis for the Industry 4.0	2018	2	Energy harvesting
Energy-aware resource service scheduling based on utility evaluation in cloud manufacturing system	2013	46	Cloud manufacturing
Developing a big data analytics platform for manufacturing systems: architecture, method, and implementation	2018	3	Big data
Real-Time Decision Making in First Mile and Last Mile Logistics: How Smart Scheduling Affects Energy Efficiency of Hyperconnected Supply Chain Solutions	2018	16	Programming/AI
A Comparison of Energy Consumption in Bulk Forming, Subtractive, and Additive Processes: Review and Case Study	2014	98	Additive manufacturing
Moving Towards Green and Sustainable Manufacturing	2014	68	Others

Source: Prepared by the author.

IV. CONCLUSION

The internet of things, once interpreted simply as a network connection, represents a step beyond today's automation architectures because, coupled with wireless sensor networks, cloud computing and collected data analysis, it denotes a more efficient solution, in terms of hardware flexibility and costs saving in installation and maintenance. In addition, digitizing manufacturing processes, through hardware and software, can promote intelligent production management as it provides responsive and fast assertiveness response data, increasing operational availability and predictability, translating into energy efficiency.

Wireless sensor networks, through the energy harvesting from operational processes, characterizes a viable solution as it can reuse energy resources that would be wasted, such as artificial photoelectric light, mechanical vibration, heat and radio frequency signals, promoting energy efficiency and increasing service life by sharing industrial resources.

Despite the breadth of research in the context of Industry 4.0, a relatively small amount explicitly addresses how and which technologies are capable of promoting industrial energy efficiency, leaving the researcher to read thoroughly to address the issue. The report presented was able to demonstrate that there are few researches, compared to innovation studies in the same context. In addition, the growing publication of articles on this subject suggests its global relevance, given that industrial sustainability is pursued as a way of ensuring success, in its various interpretations, for small, medium and large organizations.

As future work, we suggest further research in the database used in this work, as well as in other databases, using a combination of tags involving energy and each of the industry 4.0 enabling clusters, identifying the works that address the theme energy efficiency even if implicitly.

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