

Industry 4.0 influences on maintenance operation: a bibliometric analysis

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Abstract: In this paper, it is described the Industry 4.0 influences on maintenance operation through a bibliometric analysis. The current trend is the introduction of 4.0 concepts allied with basic maintenance practices. It has been considered as an important tool to improve the machine availability and equipment reliability. New modern techniques are been used to predict and optimize maintenance processes, in fact it is understood as a strategical activity and a profit contributor to ensure productivity and efficiency in manufacturing systems. With the bibliometric analysis, it is possible to analyze the main trends and the 4.0 tools most related to maintenance operation optimization.

Keywords: maintenance, industry 4.0, optimization, bibliometric analysis, maintenance operation.

1. INTRODUCTION

Maintenance operations has been considered as an important element for the management of an organization, besides being recognized as a source for revenue generation for corporations. (MOSTAFA *et al.*, 2015 *apud* REIS; CAMPOS, 2019) Increasingly, efforts have been made to optimize maintenance processes. In view of the association possibility of Industry 4.0 technologies with maintenance, this paper seeks to analyse its definitions, concepts, characteristics, relations and applications, through a literature review and a bibliometric analysis in the period of 2009 to 2019.

1.1 Maintenance role

Increasing competitiveness and the relentless pursuit of greater profit and less wastes has brought greater importance to the maintenance area. Seen as a potential for the best warranty of equipment operation, maintenance has gained attention in fact that it ensures quality and reliability throughout the process.

Historically, the maintenance processes were executed only when strictly necessary, as in the case of equipment breakdown or sporadic stoppages. With studies and technology development, it is clear that the process efficiency and productivity could be improved with maintenance optimization. Nowadays, industrial maintenance is more reactive and preventive, being the predictive strategy applied for some situations. (CACHADA *et al.*, 2018)

According to Sezer *et al.* (2018), the maintenance has been viewed as a long-term strategic view, no longer as only at a narrow operational and technical level representing an inevitable cost.

The current proclivity in industrial business is introduction of Industry 4.0 concepts and tools into manufacturing processes,

including Big Data, Internet of Things and Cloud Computing concepts. Likewise, it can be further used in predictive maintenance of failure prediction. (SPENDLA *et al.*, 2017)

The main goal of maintenance engineering is to provide high-levels of efficiency and reliability in order to support production needs and objectives. New technologies are intended to transform maintenance practices in an added-value through high-ranking of performance targets. (SEZER *et al.*, 2018)

1.2 Maintenance and Industry 4.0

According to Wang (2016), "Industry 4.0 enables intelligent and flexible production control using IT-based intercommunicating and interacting machines, products, services, equipment and tools."

Industry 4.0 aims to make manufacturing processes more productive and connected, including maintenance activities, using various technologies, such as Internet of Things (IoT), augmented reality, Big Data and data analytics and cyber-physical systems. (WANG; ERKOYUNCU; ROY, 2018)

Dang *et al.* (2018) quotes that one of the key challenges in Industry 4.0 concerns predictive maintenance of devices, in order to reduce downtime of plants as well as the cost of systematic maintenance. Besides that, the maintenance 4.0 can be applied as a contribution to life cycle thinking, better asset utilization, services and aftersales, among other areas, for a sustainable manufacturing (JASIULEWICZ-KACZMAREK *et al.*, 2019)

Predictive maintenance (PdM) has been used by industrial manufacturers to maximize machine and equipment availability and deploy maintenance more cost-effectively. (YU *et al.*, 2019)

According to Windelband (2017), it is expected that optimal time for maintenance could be recognized by intelligent

products or plants with the implementation of Industry 4.0. For the same reason, downtime and non-use times of production facilities will be further minimized.

The following sections are some of the 4.0 technologies and its relation with maintenance activities.

1.2.a Machine learning (ML)

According to Strauß *et al.* (2018), Machine Learning is a subset and the most effective way of implementing Artificial Intelligence. It allows computers and systems to identify patterns through collected data to perform different actions such as failure prediction. Trained on historical data through specific models, machine learning strategy focus on predicting part degradation and equipment failures. Because of that, predictive maintenance is one popular application of this tool in production systems.

Machine learning method can be divided in two classes: Supervised and Unsupervised. According to Susto *et al.* (2015) and Mathew *et al.* (2017), the *supervised learning*, where information of the occurrence of failures is present in the modelling dataset, includes their output classes which are used to train the machine, while the *unsupervised learning*, where logistics and/or process information is available without existence of maintenance data, includes information without its output class.

Mathew *et al.* (2017) uses a comparative study of machine learning algorithms to predict the Remaining Useful Lifetime of aircraft's turbo fan engine. Based on supervised machine learning, using turbo fan engine dataset, including a training set and a test set.

Paolanti *et al.* (2018) describes a machine learning architecture for Predictive Maintenance, based on Random Forest approach. The application of machine learning approach to a real data set from machines on the field, the overall cloud architecture for Industry 4.0 and the high level of accuracy on predicting the state of the main spindle rotor are the main paper contributions.

1.2.b Cyber-Physical Systems

A Cyber-Physical System is an integrated system of computing, communications and control. (ZHOU; LIU; ZHOU, 2015)

According to Li and Lau (2019), Cyber-Physical Systems (CPS) are emerging technologies to exchange information with the human being with machinery and software in Industry 4.0. It is normally applied in Total Productive Maintenance (TPM) to predict unstable performance in machinery.

Ferreira *et al.* (2018) describes the implementation process of a pilot for proactive maintenance in Industry 4.0 for a press brake machine, within the aims of the MANTIS project, which objective is to reduce maintenance costs by means of novel monitoring techniques.

Yang and Lin (2019) presents a design, a development and an implementation of a predictive maintenance big data platform

based on the cyber-physical systems under the Industry 4.0 architecture. The developed and implemented system uses generated synthetic data and real-world data collected from a gearbox plant.

1.2.c Internet of Things (IoT)

The IoT is the connection between the network of physical objects, environments and equipment through electronic devices, allowing the collection and information exchange. (ALMEIDA, 2019)

According to Ayad, Terrissa and Zerhouni (2018), "IoT can be defined also as a global, invisible, ambient networked computing environment built through the continued proliferation of smart sensors cameras, software, databases, and massive data centres in a world-spanning information fabric".

With IoT approach, Goundar *et al.* (2015) analyses the vibration and temperature of an induction motor in order to gather specific data to predict motor's bearing failure, which could reduce downtime.

Baldissarelli and Fabro (2019) concludes that maintenance can better coordinate the needs interconnecting with other departments, supported by IoT, being able to offer solutions more beneficial and advantageous by increasing the level of efficiency.

1.2.d Big Data and Data Analytics

"Big Data technology is using new processing modes to gain valuable information quickly from various data types, in order to achieve in-depth understanding, gain insight and make discoveries for accurate decision making." (ZHOU; LIU; ZHOU, 2015). Big Data refers to volume, variety, velocity, veracity and value of available and data search, that require innovative and cost-effective ways of processing information for better insight and decision-making. (BUMBLAUSKAS *et al.*, 2017)

Zhang *et al.* (2017) proposes a new cleaner production method enhanced by a systematic integration of product lifecycle management and big data analytics. The paper concerns on big data-based manufacturing applications specifically in manufacturing and maintenance processes of product lifecycle.

Canizo *et al.* (2017) presents the evolution of a solution for PdM to a Big Data environment. The aim is for predicting failures on wind turbines using a data-driven solution, using a predictive model generator, a monitoring agent and a dashboard where given predictions can be visualized.

1.2.e Augmented Reality (AR)

Commonly, "Augmented reality is understood as a technology that overlays virtual information over the real-world objects to create imagery illusions for user to simulate with." (WANG; ERKOYUNCU; ROY, 2018)

AR can help to reduce time and errors of maintenance tasks. (MASONI *et al.*, 2017)

Scurati *et al.* (2018) quotes that the main advantage of using AR for maintenance instructions is related to the intuitiveness associated to this innovative displaying technique, because information could be displayed directly on the object it refers to. According to Cachada *et al.* (2018), Augmented Reality contributes for a faster and more efficient reaction and recovery of the failure occurrence when compared to paper procedures.

Bordegoni *et al.* (2014) proposed an application combining AR technologies with mobile technology to help machine producers to improve their maintenance services.

Ceruti *et al.* (2019) suggests possible integration of Industry 4.0 technologies with the aeronautical maintenance. According them, AR can support the operators with user-friendly manuals. In this case, a reduction of workload and time required to complete tasks, and an increase in reliability can be expected, consequence of the reduction of errors which are made using Augmented Reality maintenance manuals.

2. METHODOLOGY

This study methodology is divided in two stages. Preliminarily, a literature review was performed to collect material and to have an introduction to the subject that will be covered during the research. The second part refers to the bibliometric analysis, using determined criteria and software (BibExcel®, UCINET® and Microsoft Excel®)

2.1 Literature review

The literature review consisted of a preliminary research on maintenance optimization theme, in Brazilian events (Encontro Nacional de Engenharia de Produção – ENEGEP and the Simpósio de Engenharia de Produção – SIMPEP), in addition to some Brazilian journals and a research in the repository of Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES.

This part of research was important to define the directions of research in the area. For several reasons, the relationship between maintenance and Industry 4.0 has been very relevant. Thus, having defined the scope of the research, it was started a more targeted publications extract.

The research part will be explained in more detail in the next section.

2.2 Bibliometric analysis

The bibliometric analysis was performed by defining search criteria, with data extraction supported by the BibExcel® software and presentation in UCINET® and Microsoft Excel® of the found results. To search data, tools from repositories of scientific publications was used.

According to Araujo (2006), bibliometric analysis is a quantitative and statistical technique for measuring the indices of production and dissemination of scientific knowledge.

Valid research publications should include just journal and event articles, excluding book chapters, editorials and reports. (PERUCCI; CAMPOS, 2017)

Below, is represented the collect process of publications about the relationship between maintenance and Industry 4.0. The Figure 1, referring to the sample of selected articles in the research, disregards the found duplicates in the data bases, consulted at different times. Below, is considered only new findings at each search location, respecting the defined search sequence.

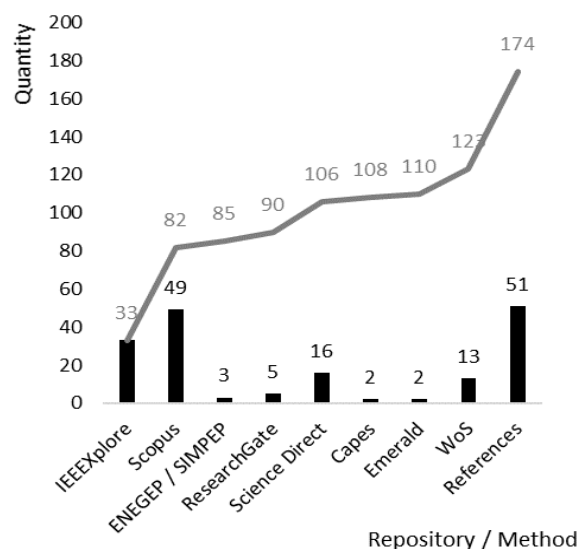


Fig. 1. Research: Accumulated frequency of publications.

Initially, was used repository of scientific publications to collect publications. Scopus has considerably more publications about the relationship between maintenance and Industry 4.0 than the other databases consulted. Later, through the references found in the selected articles, new publications were inserted in the sample, in order to increase and improve the bibliometric analysis scenario.

In total, the final sample consists of 174 publications, which will have their year of publication, authors, filiation country, related university/institute, keywords, the publication means and references, analyzed though the bibliometric analysis process. With the support of UCINET® software, it will be possible analyze the citation relationship between the sample articles.

The results of this bibliometric analysis is described, in details, in the next section.

3. DISCUSSION

The first analysed point of the sample was the publication year. There is a notable growing number of publications from the year 2015, four years after the Industry 4.0 concept first apparition, in Germany. The articles prior to this period refer to the optimization of maintenance processes, already using tools that would be considered as an Industry 4.0 tool.

The vast majority of articles deal with the subject in a generic way, approaching maintenance activities with the Industry 4.0 concept, or associating it with Augmented Reality and

CPS, specifically. Another subject covered in this sample with a certain predominance is the relations between predictive maintenance and Big Data and Internet of Things.

The Figure 2 shows the frequency of publications by years, in the period from 2009 to 2019.

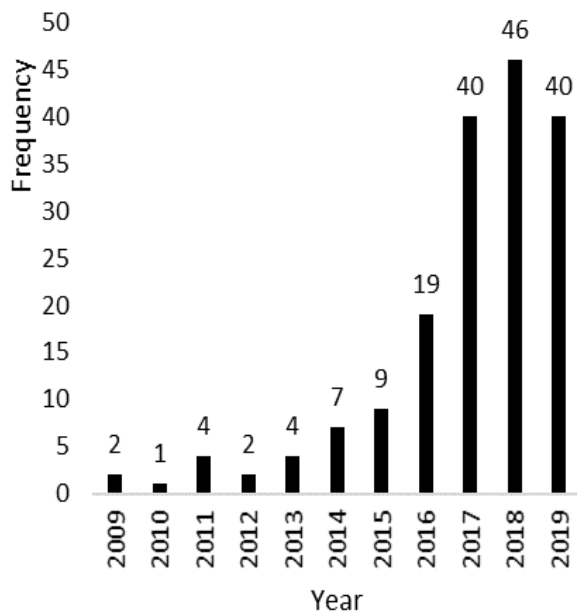


Fig. 2. Publication frequency by year: 2009 to 2019

The 174 selected articles in the sample were written by 596 authors in total. Among them, stand out Luca Fumagalli, from Politecnico de Milano, Italy, with 6 articles in the area. Also notable are Rajkumar Roy, from Cranfield University, UK, with 5 publications, and Erkki Jantunen, from VTT Technical Research Centre of Finland Ltd., and Marco Macchi, from Politecnico di Milano, Italy, both with 4 publications about maintenance processes evolution and optimization.

The Table 1 shows the major countries with publications in the sample of this research.

Table 1. Publications by country (Top 12).

COUNTRY	ARTICLES
Italy	25
Germany	24
UK	18
China	14
Sweden	14
France	13
USA	13
Brazil	9
Portugal	8
Spain	7
Greece	7
Poland	7

Among 43 countries with sample articles, Europe represents the majority of publications about the relations between maintenance and Industry 4.0. In all, 160 of 174 articles in the sample have at least one author from a European country. Italy and Germany are the countries with the largest number of publications, with 25 and 24 select articles, respectively.

The highlights of the list about the affiliation with universities, companies and research and technology institutes of the sample articles is presented in Table 2.

Table 2. Top 5 universities (Articles in the sample)

UNIVERSITY	ARTICLES
Politecnico di Milano	8
Norwegian University of Science and Technology	6
Cranfield University	4
University of Patras	4
Politecnico di Bari	4

The Politecnico di Milano, Italy, is the institute with the largest number (8) of publications in this research sample. Other institutes with good representativeness in the sample are the Norwegian University of Science and Technology, from Norway, Cranfield University, from UK, the Greek University of Patras and the Italian Politecnico di Bari.

Given that only articles published in journals and events should be used in this research methodology, there are publication media with some importance in maintenance area, relating it to Industry 4.0. *The International Journal of Advanced Manufacturing Technology* has 5 publications in this research sample, followed by *Journal of Intelligent Manufacturing*, with 4 articles. *IEEE Transactions on Industrial Informatics*, the *Journal of Quality in Maintenance Engineering*, the *MM Science Journal*, and the *Procedia CIRP* and the *Procedia Manufacturing* also stand out among the others, with 3 publications each.

IFAC conference has the largest number of publications (6) about maintenance and Industry 4.0 relations in the sample. The *CIRP Conference on Manufacturing Systems (CIRP-CMS)* and the *International Conference on Flexible Automation and Intelligent Manufacturing (FAIM)* are represented by 5 articles each. Other events with considerable sample participation are the *IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)*, with 4 articles, and the *International Workshop of Advanced Manufacturing and Automation (IWAMA)*, with 3.

Regarding the keywords, it can be noted a predominance of the terms like 'Industry 4.0' and 'Predictive maintenance', besides a large number of keywords like 'Internet of Things', 'Cyber-physical systems', 'Cloud Computing' and another 4.0 tools, and related terms to remote control and maintenance and data mining and data analysis.

Table 3. Most cited publications in the sample

Publication	Citations in the sample
J. Lee, B. Bagheri and H.-A.A. Kao, 2015, "A cyber-physical systems architecture for industry 4.0-based manufacturing systems"	19
A. Muller, A. Crespo-Marquez and B. Lung, 2008, "On the concept of e-maintenance: review and current research"	15
R.K. Mobley, 2002, "An introduction to predictive maintenance"	15
M. Hermann, T. Pentek and B. Otto, 2015, "Design principles for industrie 4.0 scenarios"	12
H.M. Hashemian and W.C. Bean, 2011, "State-of-the-art predictive maintenance techniques"	10
L. Monostori et al., 2016, "Cyber-physical systems in manufacturing"	10

In the sample, there were more than 4026 publications among the references, in a total of 4726 citations. Table 3 shows the publications with large number of citations among the 4026 works, cited more than 4726 times.

With 19 citations, the article "A cyber-physical systems architecture for industry 4.0-based manufacturing systems", by Lee, Bagheri and Kao, presents an architecture for CPS in Industry 4.0 manufacturing systems, to provide a guideline for industries to implement it to improve the product quality and system reliability. Muller, Crespo-Marquez and Lung (2008) develops a research about the concept e-maintenance, an emerged term in 2000's based on the pursuit of excellence in maintenance processes.

Another very cited publication is the book "An introduction to predictive maintenance", by R.K. Mobley. The book focuses on present strategies and methodologies to develop and implement a maintenance management program, using predictive tools. Hermann, Pentel and Otto (2015), Hashemian and Bean (2011) and Monostori *et al.* (2016) are other articles with more than 10 citations in the sample.

The most cited publications, as can be seen in Table 3, is more related with Industry 4.0 and predictive maintenance concepts, showing the main relationship between maintenance operations with 4.0 environment.

A citation network was created to show the relationship between sample articles, presented below in Figure 3. There are 4 nodes with prominence, due to the large number of connections. The diagram development was supported by the software UCINET® and its tool NetDraw®.

The node I refers to Lee, Kao and Yang (2014), which proposes a systematic framework for self-aware and self-maintained machines, including CPS and decision support system concepts.

The second node (II) shows the connections network around Lee *et al.* (2015), which discusses trends towards CPS industry, allied to maintenance operations and services.

Ni and Jin (2012), center of node III, describes decision support tools for planning effective maintenance operation in an automation-based manufacturing system. Besides that, the article presents real implementations to demonstrate the effectiveness these tools.

Another publication with prominence is Roy *et al.* (2016), represented by node IV, which presents technologies required to offer the maintenance, as component and system level degradation science and Big Data analytics for the continuous maintenance.

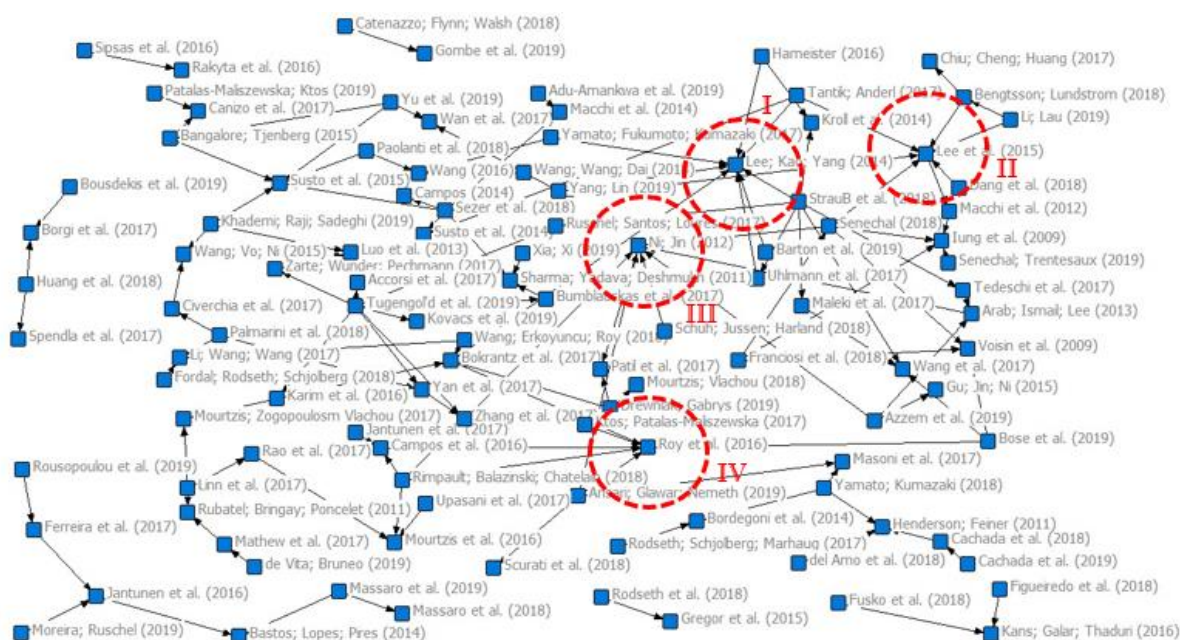


Fig. 3. Citation network

4. CONCLUSION

Considering the current industrial scenario, maintenance has been considered as a strategic point of manufacturing industries. The predictive strategy allied to Industry 4.0 tools has been used in this area to predict failures, reduce equipment downtime and maintenance costs, as shown by the bibliometric analysis developed with recent research publications in maintenance area. Machine Learning, CPS, Big Data and AR has been inserted into the maintenance environment more frequently. To further researches, it's recommended to study more deeply the application of Industry 4.0 technologies on maintenance operations.

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