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Review

Overall Equipment Effectiveness: Systematic Literature Review and Overview of Different Approaches

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Abstract: Overall equipment effectiveness (OEE) is a key performance indicator used to measure equipment productivity. The purpose of this study is to review and analyze the evolution of OEE, present modifications made over the original model and identify future development areas. This paper presents a systematic literature review; a structured and transparent study is performed by establishing procedures and criteria that must be followed for selecting relevant evidences and addressing research questions effectively. In a general search, 862 articles were obtained; after eliminating duplicates and applying certain inclusion and exclusion criteria, 186 articles were used for this review. This research presents three principal results: (1) The academic interest in this topic has increased over the last five years and the keywords have evolved from being related to maintenance and production, to being related to lean manufacturing and optimization; (2) A list of authors who have developed models based on OEE has been created; and (3) OEE is an emerging topic in areas such as logistics and services. To the best of our knowledge, no comparable review has been published recently. This research serves as a basis for future relevant studies.

Keywords: overall equipment effectiveness; OEE; systematic literature review; model-based

1. Introduction

Currently, various key performance indicators (KPIs) are used to make decisions at different organizational levels. Chan and Chan (2004) [1] considered KPIs as general indicators for identifying performance losses. Bititci et al. (2012) [2] reported that performance measurement has been developed in response to global and business trends. KPIs are used to measure process deviations to ensure that corrective action can be performed [3]; they are typically presented in dashboards and scorecards. Digital transformation has enabled information to be obtained quickly to accommodate the market changes. Martinez (2019) [4] suggested including digitalization as part of the business aspect of the evolution. In the Industry 4.0 framework, the digitalization of the production process in factories and data collection is important for improving business efficiency.

Overall equipment effectiveness (OEE) is a KPI introduced by Nakajima (1988) [5]; this metric was developed as part of the total productive maintenance (TPM) to measure the equipment productivity in a manufacturing system. OEE is a productivity ratio between real manufacturing and what could be ideally manufactured [6]. This indicator is widely accepted as a tool by some companies, e.g., when implementing lean manufacturing [7] or maintenance programs [5] to monitor the actual performance of an equipment. OEE identifies six big losses comprising aspects of availability, performance and quality that reduce the equipment effectiveness. Dunn (2015) [8] defined those three aspects as follows: (i) availability—'Is the machine running or not?'; (ii) performance—'How fast is the machine running?'; and (iii) quality—'How many products satisfied the requirements?'.

Availability measures downtime losses due to breakdowns or setup/adjustments; performance measures speed losses due to minor stoppages and reduced speed; and quality measures defect losses due to process defects or reduced yield [9]. Over time, OEE applications have been modified depending on industry needs; some authors have slightly modified the original formula, whereas others have proposed new formulas.

The insufficiency of OEE as an indicator has resulted in its modification [10]. Many industries have customized it to fit to their particular requirements [11]. Based on the OEE structure, models have been developed for domains such as sustainability [12], line manufacturing [13,14], assets [10], resources [15], transport [16,17] and ports [18].

The objective of this research is to review and analyze the evolution of OEE. Hence, we conducted a systematic review. In this study, the chronology of the main contributions and modifications pertaining to OEE was analyzed to establish future trends.

For a systematic review, we defined the research questions (RQs), selected and searched the database, applied inclusion and exclusion criteria, analyzed the results and answered the following (RQs).

RQ (1) What is the focus of the current research effort in the OEE domain?

RQ (2) What models based on OEE have been developed?

RQ (3) What are the principal contributions in OEE and what are the future trends?

This paper is structured as follows: Section 2 describes the methodology; Section 3 explains the systematic review process developed to obtain the information; Section 4 provides the results; and the final section presents the discussion and conclusions.

2. Materials and Methods

Reports and research results that contribute to science are constantly evolving; hence, an overview of the changes is necessitate. In this study, a systematic review was performed through a rigorous and transparent methodology to organize existing information. The systematic literature review was identified, evaluated and interpreted using existing empirical evidence to answer specific RQs [19]. Some reasons for performing the systematic literature review were as follows: to identify gaps by summarizing existing information to propose new investigation areas and to provide a background for suggesting new research activities [20].

The methodology used in this study was based on that used in a previous study [20,21], where a series of procedures was defined to execute a systematic process. The procedures adopted in this study were as follows:

1. Definition of RQs
2. Selection of scientific databases
3. General search in selected databases using the search string
4. Define inclusion and exclusion criteria and apply them to articles from general search
5. Data extraction and analysis of selected articles
6. Answer RQs

This methodology is used to develop a structured and transparent study by establishing procedures and criteria that must be followed to select information for review.

2.1. Definition of RQs

First, RQs for guiding the development of this study were formulated. These questions must be answered using the data collected and analyzed in this study. Table 1 presents the RQs and the motivation of each based on the research objectives.

Table 1. Research questions and motivation.

Research Questions	Motivation
RQ1. What is the focus of the current research effort in the OEE domain?	Present a descriptive finding that exhibits interest in the topic and identify trends signified by keywords.
RQ2. What models based on OEE have been developed?	Generate a list of different models that have been developed based on the original OEE, to determine fields of study that have applied the indicator as an effectiveness measure.
RQ3. What are the principal contributions in OEE and what are the future trends?	Summarize main contributions from different authors and establish future trends to propose new research activities.

Based on these three questions, we aim to fulfil the objective of this study: analyze the OEE chronology, main contributions of OEE and model developed based on OEE.

2.2. Search Process

Web of Science (WoS) and Scopus were the two electronic databases used in this study because they contain relevant, updated and high-quality bibliographic information. WoS is a digital platform of Clarivate Analytics, in which Scopus is affiliated with Elsevier; both databases were formed based on thousands of peer-reviewed journals in the fields of science, technology, medicine, social sciences, arts and humanities.

A generalized search for the term 'overall equipment effectiveness' was performed to obtain broad results. The keywords used for this search were 'overall equipment effectiveness' AND 'OEE'. The search string applied in the WoS electronic databases was topic (TS) = ('overall equipment effectiveness' AND 'OEE'). In Scopus, a combined field that searches abstracts, keywords and document titles was used, i.e., TITLE–ABS–KEY ('overall equipment effectiveness' AND 'OEE').

The total number of documents obtained in the general search was 847, i.e., 281 from WoS and 566 from Scopus. Only articles were selected for this study. Compared with proceedings papers, articles are more influential and complete as they contain more information and citations [22]. The results were based on articles obtained after eliminating duplicates and applying the inclusion and exclusion criteria detailed in the following section.

2.3. Selection of Relevant Papers

The selection of relevant articles was standardized as per [20] to avoid information bias. Hence, inclusion (I) and exclusion (E) criteria were defined to ensure that the selected papers were the least subjective.

The I and E criteria were defined as follows:

- I1: The paper is a literature review and/or is related specifically to OEE and its application;
- I2: The study mentions an OEE-based model;
- I3: The study only uses OEE to verify an improvement or change in any process;
- E1: The paper cannot be obtained and/or is not written in English;
- E2: The term "OEE" is only mentioned; no OEE-based model is calculated or applied;
- E3: The paper is not an article, e.g., proceedings papers, magazines, books, editorial material and letters.

This review was adapted from the preferred reporting items for systematic review and meta-analysis (PRISMA) statement [23]. Figure 1 shows a PRISMA flow chart that illustrates the different phases of the systematic literature review.

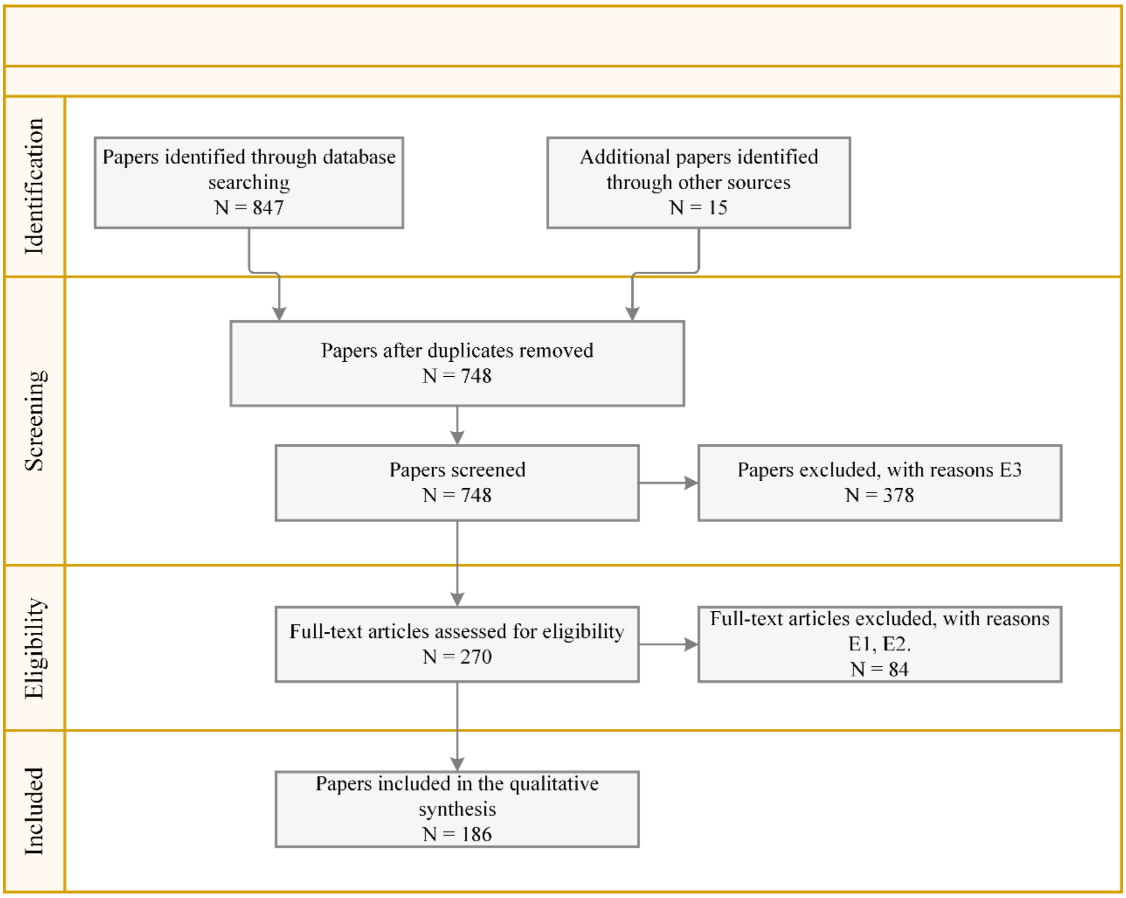


Figure 1. Preferred reporting items for systematic review and meta-analysis (PRISMA) flow chart.

First, a general search was performed using the search string (Section 2.2) in the selected scientific databases. Subsequently, using an Excel spreadsheet, articles were filtered to eliminate duplicates. Finally, the articles were examined, and the I and E criteria were applied to retain the selected articles for answering the RQs.

3. Results

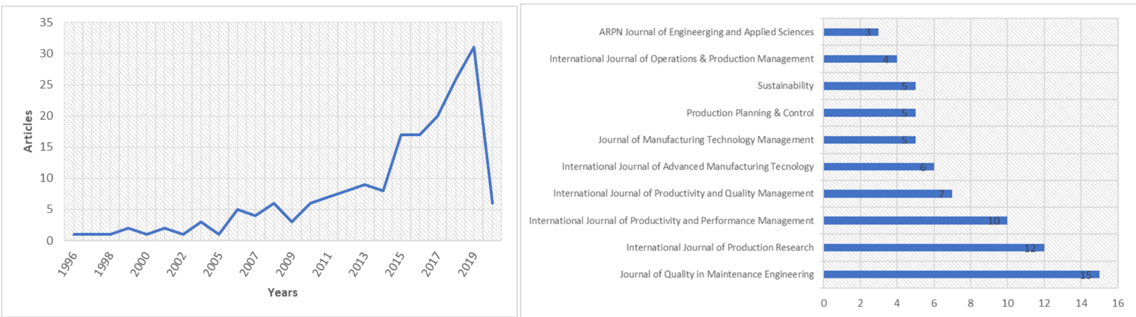
RQ (1). What is the focus of the current research effort in the OEE domain?

The bibliometrix R-package was used to analyze the 186 articles from the two electronic databases. This packaged, which is written in the R language, provides a set of tools for quantitative studies in bibliometrics and scientometrics [24]. Using this program, the data extracted from WoS and Scopus were consolidated to perform a comprehensive bibliometrics analysis of the current research effort pertaining to OEE. Table 2 shows a general data summary from the 186 articles.

Despite a 24 years timespan, scientific productivity increased only in the later years. The results show that more than 50% of the publications regarding OEE were published in the last five years, indicating that interest in the OEE indicator has increased, i.e., by 9.1% in 2015, 9.1% in 2016, 10.8% in 2017, 14.0% in 2018 and 16.7% in 2019. Thus, far, an increase of 3.2% has been reported for 2020. Figure 2 presents (a) the number of articles per year since 1996 until 9 April 2020, revealing an increasing interest in the subject and (b) the top 10 journals with increasing publications over time.

Table 2. General data summary.

Timespan	1996–2020
Sources (journals)	102
Documents	186
Average citations per document	16.57
Author keywords	554
Keywords plus	434
Authors	450
Authors of single-author documents	25
Authors of multi-author documents	425

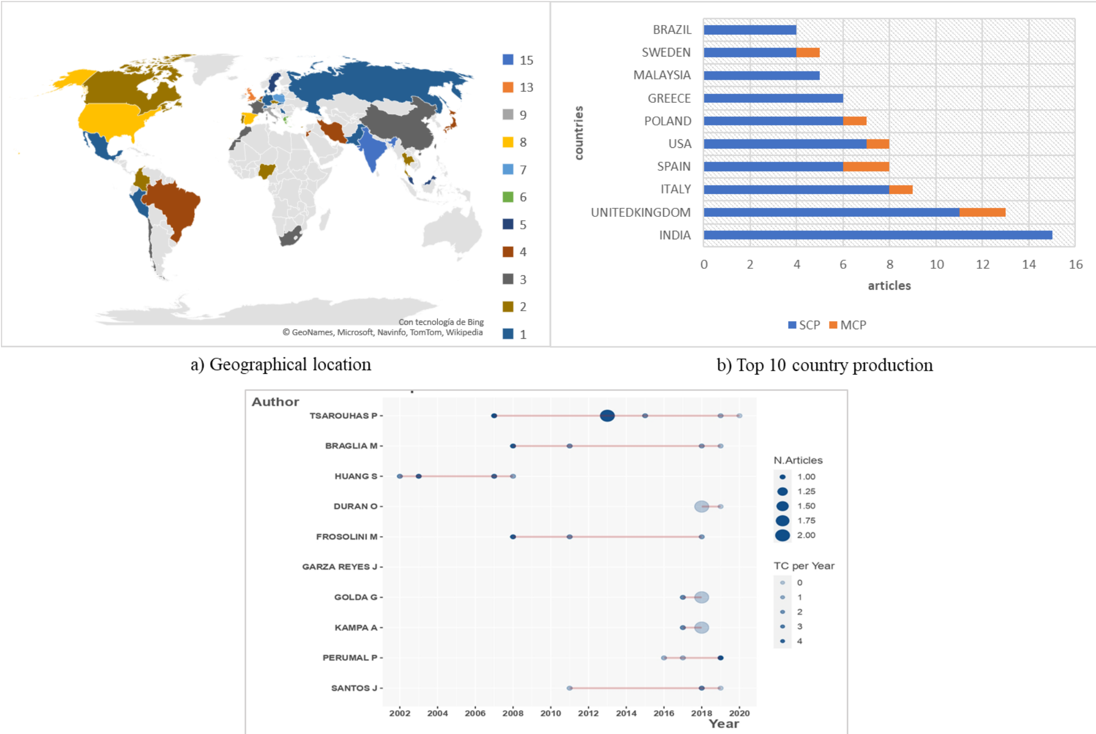


a) Number of articles per year b) Top 10 Journals

Figure 2. Basic data analysis of (**a**) number of articles per year and (**b**) Top 10 journals.

The total number of journals published regarding OEE was 102. Journals pertaining primarily to manufacturing or maintenance issues were not the only ones that focused on the OEE indicator. Evidence shows that an increasing number of journals are focusing on sustainability, business, logistics, mining, etc.

The current effort to spread the topic based on contributor and geographical location is shown in Figure 3. Europe is the continent with the most publications (45%) followed by Asia (26%), America (7%) and Africa (5%), as shown in Figure 3a. Figure 3b presents the top 10 countries in terms of single country publication (SCP) and multiple country publication (MCP). More than 80% of the publications were written by authors belonging to the same country; all the scientific productions in India were based entirely on SCPs, unlike the UK and Spain, who collaborative with other countries. Figure 3c indicate the top 10 most productive authors, including the number of articles (N articles) and total citations per year (TC per year). Greek author Panagiotis Tsarouhas was the first in the top 10, with 83.33% of his publications reporting cases in which OEE was applied to different production industries, e.g., croissant production lines [25], ice cream production lines [26] and production plants of Italian cheese [27] to identify potential opportunities for improving production systems. Braglia and Huang published four articles, whereas the other authors from the top 10 published three articles each. Some of them have developed new models based on OEE, whereas others have applied the indicator in different industries to measure equipment, process or resource effectiveness.



a) Geographical location b) Top 10 country production

c) Top 10 author's production over the time

Figure 3. The effort in terms of (**a**) geographical location (**b**) top 10 country production and (**c**) authors contribution over the time.

Three inclusion criteria were used for the analysis in this study. (a) Criteria I1—include papers that are literature reviews and/or are related specifically to OEE and its application; (b) Criteria I2—studies that mention OEE-based models; (c) Criteria I3—papers that only use the OEE to verify an improvement or change in any process (Table 3). Approximately 20% of the articles contributed scientifically to the modification or new development of models based on the original OEE (Figure 4). Instead of for use in production, the new models were built to measure the effectiveness in areas such as transportation, sustainability, mining, electricity and resources (human and monetary).

Table 3. Overall equipment effectiveness (OEE) application contribution by area.

Application Area	Inclusion Criteria	1996–2000	2001–2005	2006–2010	2011–2015	2016–2020
Productivity in manufacturing processes	I1		[28–30]	[31,32]	[33–39]	[26,40–60]
	I3			[61]	[62–75]	[76–93]
Productivity in maintenance	I1	[94,95]			[27,96–98]	[25,99–110]
	I3	[111,112]	[113]	[114–121]	[122–129]	[130–141]
Oriented to resources productivity	I1			[142]	[143]	[144–149]
	I3					[150–152]
Supply chain productivity	I1				[153]	
	I3				[154,155]	[156]
Other	I1	[9]	[157]	[158,159]	[160–163]	[164–166]
	I3		[167]	[168]	[169]	[170–172]

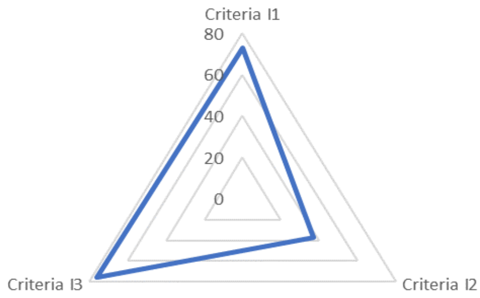


Figure 4. Distribution of inclusion criteria of analysis.

Two types of keywords are shown in Table 2: the author's keywords and keywords plus. The former is provided by the original authors, whereas the latter is extracted from titles of cited references by Clarivate Analytics (WoS). Figure 5 shows the co-occurrence network of the author's keywords; the number of nodes in the network was 40 and was related through association; the clustering algorithm used was Louvain. The network comprised four clusters. The first one comprised nine keywords related to the OEE formulation, availability, performance, quality, downtime, speed loss, etc. The second cluster comprised 12 keywords related to total productive maintenance, optimization, production, maintenance and autonomous maintenance. The third cluster comprised terms such as effectiveness, throughput and performance measurement. The last cluster comprised 13 keywords pertaining to current issues, such as Industry 4.0, simulation, lean manufacturing, six sigma, SMED and DMAIC.

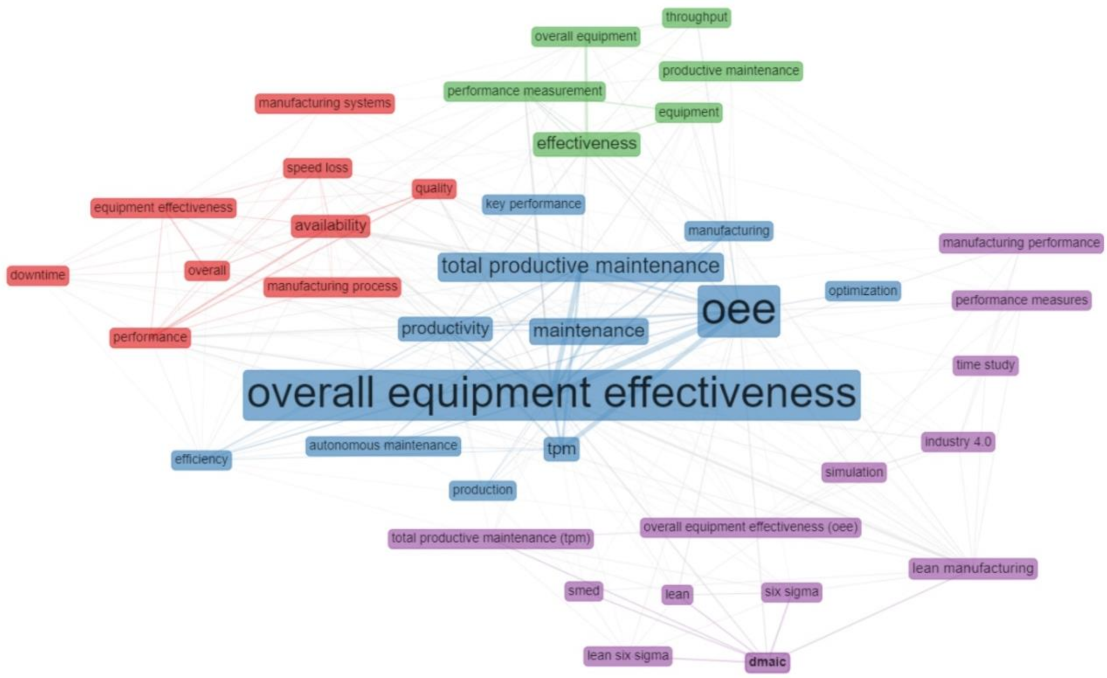


Figure 5. Co-occurrence network.

Initially, studies regarding OEE are associated with total productive maintenance; subsequently, they are associated with the industry, availability and manufacturing process. Currently, they are related with terms such as lean manufacturing, improvement, implementation, reliability, design and optimization. The most cited document obtained from the systematic review considers quality assessments, such as lean tools and six sigma, to improve productivity and financial savings, e.g., in the die-casting unit of a company [115].

RQ (2). What models based on OEE have been developed?

Over time, industries have adapted OEE to their needs. Hence, several authors have developed slight modifications to Nakajima's model whereas others have developed new indicators based on the originally formulated OEE.

A list of models based on OEE, listed by the author and model name, is shown in Table 4. A brief description of each model is provided as well.

Table 4. List of models based on OEE.

Author	Year	Model Name	Brief Description
[173] [174]	2002 2007	Overall throughput effectiveness	Calculates the productivity of a manufacturing system; measures the factory level performance; identifies the bottleneck and hidden capacity.
[175]	2005	Equipment effectiveness	Measures the equipment-dependent states, such as productive state, scheduled downstate and unscheduled downstate.
[13]	2006	Overall line effectiveness	Measures the productivity of a line manufacturing system.
[176]	2006	Total equipment efficiency	To achieve total equipment efficiency, it must include the resource usage efficiency of a machine. This input factor (resource requirements) is known as the overall input efficiency.
[10]	2008	Overall asset effectiveness Overall production effectiveness	Measures losses due to external and internal factors contributing to overall production/asset effectiveness.
[177]	2008	Modified OEE	Includes new factor usability; it classifies unplanned downtime events into equipment-related downtime.
[6]	2008	Overall equipment effectiveness of a manufacturing line	Measures the performances of an automated line in the system.
[16]	2010	OEE for shovel/oee for trucks	OEE is calculated for mining equipment.
[14]	2010	Overall line effectiveness	The performance of the production line in the manufacturing system is measured.
[178]	2010	Overall equipment effectiveness market-based	Monitors production in the steel market; measures equipment effectiveness for a full process cycle.
[179]	2011	Integrated equipment effectiveness	This integration is based on three elements: loading-based, capital-based and market-based elements.
[180]	2012	Overall equipment and quality cost loss	Calculates the losses of equipment, specifically production and quality cost losses, in monetary units.
[181]	2013	Overall resource effectiveness	Includes losses related to resources, e.g., people, machines, materials and methods.
[182]	2015	Machining equipment effectiveness	Calculates the OEE of a high-mix-low-volume manufacturing environment.
[15]	2015	Overall resource effectiveness	Provides information regarding the process performance based on factor material efficiencies, process cost and material cost.
[12]	2015	Overall environmental equipment effectiveness	Identifies losses due to sustainability, based on the calculated environmental impact of the workstation.
[183]	2015	Fuzzy overall equipment effectiveness	Identifies performance fluctuations through LR Fuzzy numbers.

Table 4. *Cont.*

Author	Year	Model Name	Brief Description
[184]	2016	Stochastic shovel effectiveness	Quantifies performance effectiveness of electric and hydraulic shovels.
[185]	2017	OEE of BELT equipment	Bucket-based excavating, loading and transport (BELT) including all equipment comprising a bucket, e.g., draglines, shovels, load-haul-dumps and trucks.
[186]	2017	Strategic equipment effectiveness Operational equipment effectiveness	A global measure of the effectiveness of an integrated electrical system.
[187]	2017	Overall machinery effectiveness	Identifies and ranks decision-making-units in terms of efficiency.
[18]	2017	OEE of port terminal	Identifies the most efficient terminal, addressing either manageable or unmanageable factors.
[188]	2017	Modified OEE	Includes losses associated with human factors and usability (the frequency of setup and changeover process)
[189]	2018	Extended overall equipment effectiveness	Evaluates the entire process considering human resources and equipment Performance. It is applied in medicals activities of operating rooms.
[17]	2018	OEE to transport management	Improves efficiency in road transport by adapting OEE to transport management.
[11]	2018	Modified OEE	Optimizes the effectiveness of urban freight transportation.
[190]	2018	Overall material usage effectiveness	Measures material usage effectiveness and identifies material loss in the manufacturing process.
[191]	2018	Sustainable overall throughputability effectiveness	Includes sustainability criteria and can be used in the system lifecycle.
[7]	2019	Overall task effectiveness	Analyses and evaluates losses related to manual assembly tasks.
[192]	2019	Modified OEE	Improves the effectiveness of scheduling jobs with earliness/tardiness.
[193]	2019	OEE–TCQ	Improves the process approach in maintenance in terms of time, cost and quality.
[194]	2019	Overall effectiveness indicator	Adapted for mining production to examine the effectiveness of the mining machine.
[195]	2019	Standalone OEE	Identifies system bottleneck and excludes effects from upstream and downstream.
[196]	2019	Modified OEE	Calculates the OEE in serial, parallel and combined machine systems in the production line.
[197]	2019	Modified OEE	Includes a term that considers material utilization.
[198]	2019	Overall substation effectiveness	Measures substation performances and indicates the overall maintenance performances.

As presented above, the OEE was modified to solve gaps in various issues, such as sustainability, human factor, transport, manufacturing system, mining, cost, port and resources.

RQ (3). Which are the principal contributions in OEE and what are the future trends?

Initially, OEE was used in production, in particular for TPM, which assists in identifying the overall equipment performance in a manufacturing process [199]. To accommodate industry needs, some researchers began to analyze the productivity of manufacturing line systems [6,13] or factories [174]. Currently, OEE is used with continuous improvement methodologies, such as lean manufacturing to increase productivity by eliminating waste [200]. It is also used as a KPI and data collection tool to measure the effectivity and process capability of new six sigma implementations [61]. Following the methodology of continuous improvement, Braglia et al. (2019) [7] developed a new metric based on OEE, known as overall task effectiveness. This new indicator supports lean and six sigma methodologies to identify, analyze and evaluate losses that occur during manual assembly activities.

Sustainability is an aspect that has been investigated by several companies in recent years [201], which shows that concerns regarding the environment have been growing. Hence, it has become increasingly important to include this variable as a criterion in business decision-making. Ghafoorpoor Yazdi et al. (2018) [150] created a design in a study based on OEE and its relationship with sustainability in Industry 4.0. Meanwhile, other authors incorporated the concept of sustainability in OEE, e.g., Domingo et al. (2015) [12] developed the overall environmental equipment effectiveness to identify and measure losses due to sustainability. Likewise, Durán et al. (2018) [191] designed the Sustainable Overall throughput effectiveness indicator to measure the operating performance and factory level sustainability.

The OEE has been adapted for the transport sector. To the best of our knowledge, it first occurred in the mining industry [16] and was used to identify possible losses in the availability, performance and quality of equipment such as shovels and trucks. In recent years, the efficiency framework in the port terminal [18] that considers manageable and unmanageable variables has been studied to create indicators based on OEE. Additionally, the OEE has been adapted to road transportation [17] based on distance, load capacity, route time, stops and services. Furthermore, it has been used to evaluate the effectiveness of urban freight transportation [11] as well as optimize availability, performance and quality metrics.

Accordingly, some authors have established interesting frameworks that can be developed in future studies. Some of them proposed future studies based on the frameworks that they have developed thus far, whereas others developed innovations in new areas. Abdelbar et al. (2019) [193] used a new OEE formula to identify and implement process improvements. Braglia et al. (2018) [190] extended the proposed methodology, including the analysis of material losses based on the finished product. Ghafoorpoor Yazdi et al. (2018) [150] proposed re-performing experiments for long time periods and as a case study in the manufacturing industry. Dadashnejad and Valmohammadi, (2019) [76] applied the same value stream mapping technique that is used to identify improvements in other factories.

By contrast, other authors proposed different areas in which OEE is applicable. In the study by García-Arca et al. (2018) [17] where OEE was adapted to transport management, they assume that the same methodology is applicable to the service sector and other logistics processes, such as goods reception or performing selection in a warehouse. Sharma et al. (2018) [137] and Supriyanto and Mokh (2018) [59] reported that their studies can be replicated in the service sector as well as in other industries, such as pharmaceutical, electrical/electronic, textile and transportation (rail and air travel).

4. Discussion and Conclusions

Companies use measurement systems to identify areas on which to focus to enhance performance and productivity. It is assumed that all parameters that can be measured, can be improved. Through this systematic study—and with the formulation and development of the proposed RQs—the state of the art, evolution, and future trends of OEE indicators were better understood.

The OEE started as a component of TPM and was used to increase productivity and reduce time, speed and quality losses. Dal et al. (2000) [29] reported that the indicator involves aspects other than monitoring and controlling because it provides performance data to make decisions by combining techniques, systematic method and process improvement. The practical and academic interest indicated over time was demonstrated in this study review and in the answer to the RQs. According to the answer to the first question, academic interest increased in the last five years and that the indicator is used beyond production maintenance. This study illustrates the evolution of keywords related to OEE beginning from terms relevant to maintenance and production to concepts related to six sigma, lean manufacturing, sustainability, etc. The second question resulted in a compilation of models developed based on OEE; the results presented a framework of areas or sectors where the indicator was applied. The models have evolved for the analysis of complete production lines, material handling, transportation, ports and sustainability. The answers to the final question were the principal contributions of some authors and future trends that are expected to be followed.

In conclusion, the results indicated that OEE is an emerging topic that can be used as input information for decision-making in business. Industry 4.0, which is based on cyber-physical systems and information digitalization, facilitates the accumulation and transformation of real-time process information into decisions to reduce uncertainty in the results. After analyzing the approaches of the OEE indicator it can be noted that it is adaptable to different domains by measuring the effectiveness not only of production equipment but also the effectiveness of material, economic and human resources. This will require an in-depth study of the process to determine the losses, variables and factors to be included in other OEE approaches. Future studies regarding OEE can be transferred to the logistics sector and may be included in the formulation of environmental variables, such as carbon footprint generated during a specific process. In supply chains, OEE can be used to measure the productivity of cargo movement equipment in a warehouse. Meanwhile, in the service sector, OEE can be used to measure client satisfaction in terms of the availability, performance and quality of the services received. Additionally, an OEE-based model can be incorporated into a balanced scorecard to visualize the overall productivity of a business. All these measures provide a general perspective of the business and achieve the main objectives of production, i.e., increasing productivity and reducing waste.

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