Pesquisa Operacional (2022) 42(nspe1): e263613 p.1-17
doi: 10.1590/0101-7438.2022.042nspe1.00263613
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Printed version ISSN 0101-7438 / Online version ISSN 1678-5142
www.scielo.br/pope
ARTICLES

A REVIEW ON THE STUDY OF MAINTENANCE EFFECTIVENESS

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Received April 30, 2022 / Accepted July 22, 2022

ABSTRACT. Increasing human dependence on engineering systems has recently made maintenance a higher priority. Thus, it becomes essential to study the many developments in this field, paying attention to some proposed models that do not appear to be effective in real applications. In this paper, we present a literature review on "maintenance effectiveness", here defined as the level to which a maintenance policy fulfills its pre-defined objectives or optimizes general maintenance actions, hence improving the productive activities of an organization. Some insights into the research so far developed – such as the relationship between interest in studying maintenance effectiveness in a sector and the severity of catastrophic failures in that sector – and possible future trends – such as the focus on case studies rather than more theoretical papers – are presented. We also found that there are still gaps in the literature that, if explored, will open new routes in potentially promising directions.

Keywords: maintenance effectiveness, maintenance policies, literature review, effectiveness of maintenance, maintenance performance measurement, maintenance strategy effectiveness

1 INTRODUCTION

Modern societies have always relied for their production processes on using so- called "engineered objects", which can be broadly defined as man-made and man-perfected tools for accomplishing a desired function. It has been long observed, also, that such types of equipment are liable to defects and failure by nature, being prone to degradation over time due to natural wear or adverse operating conditions that are imposed on them (Ben-Daya et al., 2016). Such failures can lead to a wide range of outcomes, from underperformance and financial losses to high magnitude catastrophes that may endanger human lives (Pintelon and Pinjala, 2006; Sinha, 2015). Today, more than ever, organizations face a constant pressure for high performance in their production processes, there having been an exponential increase in the dependence on technical systems. Motivations for this come from the current market scenario, where competitive advantage over

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the full range of operations are key for business growth and even survival. Not only are companies aiming to prevent failures, they are now increasingly concerned with ceaselessly developing and perfecting production processes, which in turn put the subject of maintenance at a higher level of importance than ever seen hitherto.

Maintenance is a costly activity, ranging to over 40% of operating costs (Dunn, 1987). What once was seen as an unnecessary way to incur expenditures and even a "necessary evil" for the production system (Al-Najjar, 2007), usually conducted as a reactive – and in many occasions even improvised – response to operational problems, nowadays has been recognized as one of the major tools for increasing operational performance and for ensuring the production levels needed to achieve an organization's goals. With the overall purpose of controlling the rate at which equipment wears out, extending its lifetime and restoring operational status after failure, maintenance is firmly established as a combination of managerial and technical activities (Ben-Daya et al., 2016), coordinated in accordance with the particular characteristics of each system and the company's strategic goals by establishing processes called "maintenance policies" (Almeida et al., 2015).

Nowadays, maintenance policies are diverse, and are constantly being modelled on the basis of specific demands or phenomena observed in a given industry. Although such programs need to be adapted to each given operational scenario, some main approaches are well consolidated in the literature, with many developments being the subject of research by undertaking case-studies. A main categorization establishes two main classes for maintenance: Corrective Maintenance (CM) and Preventive Maintenance (PM) (Ben-Daya et al., 2016). In the Corrective approach, maintenance actions are carried out after a failure is recognized, the aim being to restore the operational status of a certain piece of equipment or component. Some subclassifications for this class include Immediate and Delayed Maintenance. These differentiate the type of maintenance according to the criticality level of the item to be maintained. Under the Preventive (PM) approach, however, maintenance actions are carried out even before a failure is experienced, usually based on pre-established operating criteria (time, for example) or by monitoring the working conditions of the equipment. This latter gives way to a subclassification called "Condition-based Maintenance" (CBM), which has become increasingly relevant in the context of modern industry with regard to Industry 4.0 and the computerization of maintenance. An important concept regarding the preventive aspect of maintenance is the consideration that, in real systems, usually a failure is preceded by a so called "defective" state, where the equipment still operates but at a non-optimal level. This time between the start of the defective operation and failure is then called delay-time (Christer, 1999), which can be understood in terms of a "window of opportunity" for performing preventive maintenance actions that can detect and deal with defects before a failure manifests itself in the system (Kobbacy and Murthy, 2008).

With a multitude of maintenance policies proposed in the academic literature, it becomes a pressing and non-trivial matter to make sure that these programs have a positive effect on the system to which they are applied (Almeida et al., 2015). In this sense, a challenge is thus set on how best to assess the "maintenance effectiveness", which can be defined as the property of a maintenance policy to achieve desired outcomes from the managed technical system, as set by the Maintenance Department and the strategic planning of the organization. It is known that many policies widely researched in the academic field do not appear to be effective in real-case scenarios, ultimately resulting in losses to the maintained system, due to problems such as over-simplified hypotheses and not considering some key aspects under certain operating conditions (Oke and Ighravwe, 2017). Furthermore, the study of maintenance effectiveness manifests itself in many different approaches in the current literature. Far from being a consensual theme, many methodologies for evaluating, optimizing and applying concepts of effectiveness in maintenance are today proposed under very distinct particularities – some of which even disagree with each other.

Regarding the problematic of ensuring the effectiveness of maintenance over the many policies and models proposed in the current literature, as well as the diverging character of multiple methodologies developed for studying such effectiveness, this paper therefore sets out to presenting a systematic literature review on the subject of "Maintenance effectiveness", by covering the main contributions published in reputable databases over recent times (by recent times, we understand the time period currently covered by the databases consulted). A useful review of the major past and current themes in maintenance effectiveness is provided, along with a survey of some relevant bibliometric indicators. Insights into possible future trends are presented, highlighting some gaps in the literature that await being addressed by future studies.

The remainder of this paper is organized as follows: In section 2, a proposal for a systematic literature review is presented and the procedure adopted is specified. Section 3 briefly discusses the major themes in the current and past literature about maintenance effectiveness, focusing on some relevant applications and relationships with other fields of science. Results in the form of bibliometric indicators are presented in section 4, alongside some important findings and observations obtained from the literature search. Finally, section 5 concludes with summarized remarks and a statement of the main contributions provided by this article. Some gaps in the literature are then identified and possible pathways for future relevant research on the subject of Maintenance Effectiveness are suggested.

2 SYSTEMATIC LITERATURE REVIEW

Conducting a review of the literature is the base foundation for scientific writing (Ferenhof and Fernandes, 2016), the main purpose of which is generally defined as to recognize aspects of interpretative unity and diversity regarding a specific theme of study (Echer, 2001). Among many possible variations in how to conduct such a review, for this paper we opted to undertake a Systematic Literature Review (SLR) as a means of identifying, evaluating and interpreting all relevant research made available regarding the topic of maintenance effectiveness (Kitchenham, 2004). As a secondary type study, we specifically aim to survey multiple research papers under the same scope, and thereby to evaluate their methodologies, the context in which they were applied, and finally to compile the relevant papers into a form fit for statistical analysis. With this latter step, we are able to summarize the existing evidence concerning the effectiveness of the current approaches to maintenance problems, while also pointing to relevant gaps in the current literature and hence to provide appropriate guidance on promising discussions for future research activities (Carvalho et al., 2019; Kitchenham, 2004).

In order to conduct an SLR, and so as to guarantee the completeness of the search to be addressed and avoid any possible bias factors, the Systematic Search Flow (SSF) method is adopted (Ferenhof and Fernandes, 2016), using the implementation structure for the main four steps (Search Protocol, Analysis, Synthesis and Writing) as developed by Silvestro and Gleize (2020). Figure 1 shows the details regarding the procedure adopted for the literature review:

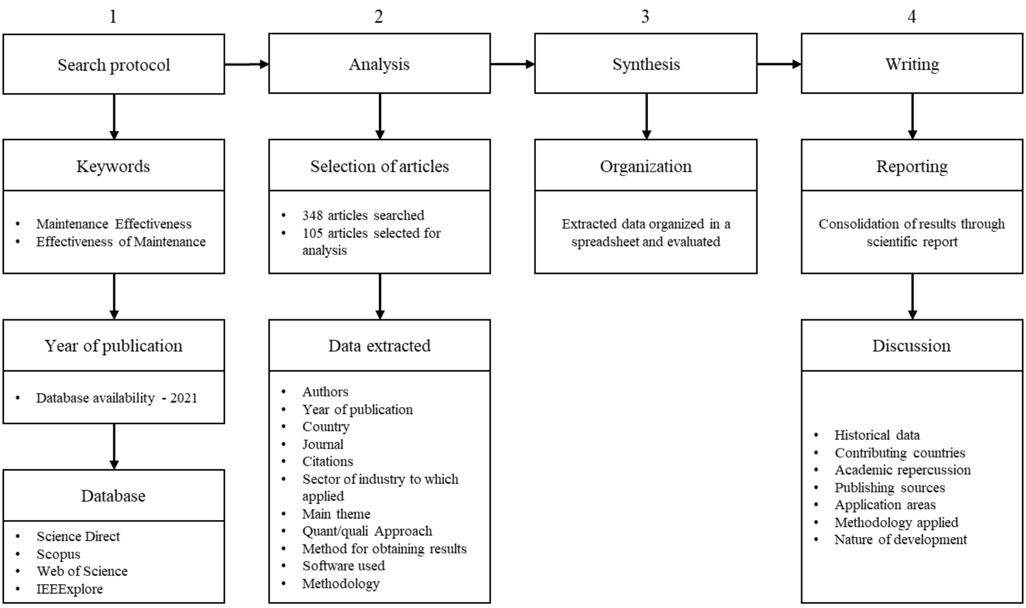

Figure 1 – Stages of Systematic Literature Review (SLR) according to Systematic Search Flow Method (SSF).

For this study, defined keywords were searched in the titles, keywords and abstracts of articles, and the procedure itself was conducted iteratively during the months of March and August (2020) and October (2021). Multiple search sessions were conducted during this period in order to update the review with the latest papers published in the literature. For historical parameters, no thresholds were imposed, so that the articles covered by the review include the full range of those available (in the databases consulted) in the relevant literature on the subject. Databases considered reputable, as well as available for search, account for ScienceDirect, Scopus, Web of Science and IEEExplore. Also relevant are some filters applied in the search engine of each database consulted: Only journal papers with at least an abstract in English were searched, restricted to themes regarding Engineering, Decision, Operational Research, Mechanics, and Industrial and Computer Sciences.

After the search protocol was conducted, a total of 348 articles was obtained, when adding up the results from all databases. Of this total, papers that were not related to maintenance, and those that did not present the approach of effectiveness as having been properly developed, were rejected for further analysis. After some mining and gathering procedures (which included removing duplicates as some studies appeared in more than one database, and considering minor unavailability for download), a final total of 105 articles was selected for data extraction. As for synthesis of the collected data, a spreadsheet was used in order to organize information, as well as to compile statistics and to record a survey of bibliometric indicators. An extensive report of the study and a discussion of the results are presented in the remaining sections of this study.

3 MAJOR THEMES IN MAINTENANCE EFFECTIVENESS

Here we briefly discuss major developments in the recently available literature regarding the theme of Maintenance Effectiveness, and thus describe the main current views on the subject, relations with other fields, some of the main applications and latest methodologies and technologies proposed.

We start by noting that, due to its being applied widely, the term "Maintenance Effectiveness" has been frequently used from distinct points of view, consequently manifesting itself in multiple ways. Generally speaking, the subject is conventionally dealt with under two main approaches: one more aligned with aspects of strategy regarding the Maintenance Function and its interactions within organizations (henceforth called an "organizational view") and the other more focused on evaluating the performance of maintenance actions (henceforth called an "operational view"). Much of the consolidated development under both views is currently described in many books on Maintenance Management and its operations. In this sense, Ben-Daya, Kumar and Murthy (2016) develop both views on the effectiveness of maintenance. With the operational approach more linked to the performance of maintenance policies through studies related to Perfect/Imperfect Maintenance and Minimal Repair, on the organizational side, effective maintenance is associated with observing some internal factors such as good control of maintenance work and a proactive attitude towards maintenance problems. Ben-Daya et al. (2009) understand such differentiation by deeming there to be the "external" and "internal" maintenance effectiveness. Internally, this is linked to the smart use of maintenance resources, while externally it is marked by the performance of business aspects and indicators such as market share and consumer satisfaction. Kobbacy and Murthy (2008) highlight the measurement of maintenance effectiveness as one of the main issues faced by organizations regarding Maintenance Performance Measurement (MPM). Higgins and Mobley (2002) develop the insight of maintenance effectiveness being related to the coordination of activities among many production plants of a single company, and also associate it to key elements of human resources management in order to improve it.

Focusing on an organizational viewpoint, many relevant developments can be observed in the recent literature. Oliveira and Lopes (2019) propose a maturity model to evaluate the current state of maintenance in organizations, leading to customized directions in order to increase its effectiveness to the "world-class" level. In this study, many factors seen as crucial for maintenance management and effectiveness are surveyed as a result of conducting an extensive literature review. Au-Young et al. (2017) point to the evolution of stakeholders' influence over maintenance effectiveness and management, concluding with positive relationships identified among these aspects. Aiming for a deeper analysis over strategy elements, Pintelon and Pinjala (2006) establish a parallel with Hayes and Wheelwright's (1984) Four-stage Framework for Production Strategy in order to provide an innovative Four-staged Model for Maintenance Strategy Effectiveness. The key foundation for such modelling is the premise that maintenance effectiveness can only be obtained by identifying the optimal Maintenance Strategy, which in turn is related with other organizational strategies such as business and production, always with the end-goal of providing competitive advantage in the market. A peculiar methodology is used by Cholasuke et al. (2004) in order to identify key elements for consistently measuring maintenance effectiveness, by conducting a survey regarding the status of maintenance management among United Kingdom organizations and combining this with a literature review.

Switching to an operational approach, the major literature in this scope focuses on the proper performance of maintenance actions being closely related to the measurement of effectiveness, therefore considerably expanding the range of possible applications. Ben-Daya et al. (2009) state that effectiveness, evaluated under criteria such as costs and productivity, works as an indicator for maintenance performance. In another development, Crocker (1999) reports three major areas that, although difficult to measure precisely, are conceived as closely associated to the effectiveness of maintenance: failures induced by maintenance, the effectiveness of inspections and the effectiveness of repairs. The study is supported by a series of examples of real cases from industry, among which we highlight aviation and automobile operations. From some of the popular theories regarding the management of maintenance activities, approaches of Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM) are found to be closely related to the idea of maintenance effectiveness, with the former defined by Ben-Daya (2000) as a way to improve effectiveness in maintenance – encompassing concepts of both efficiency and efficacy – and the latter incorporating effectiveness as an indicator for constant review and improvement of maintenance activities (Blischke and Murthy, 2003). A great effort is observed in order to model maintenance effectiveness as related to equipment and reliability. Samat et al. (2012) propose a four-phase model for performance and reliability of industrial equipment, the results being interpreted in terms of maintenance effectiveness. Sinha (2015) develops the subject of effectiveness in maintenance by linking Maintenance Management (MM) and reliability, this latter being modelled in terms of equipment specification and failure behavior. An actionable program is then developed for improving effectiveness in MM, comprising seven practical steps. Lastly, a seemly promising research field in this scope discusses the relationship between Human Error (HE) and maintenance effectiveness, with major topics on triggering factors for human error, human influence over maintenance actions, operations safety and performance (Reason and Hobbs, 2003; Scarf and Cavalcante, 2012; Taylor, 2000).

Much research in the field of maintenance effectiveness has been developed under the methodology of a case study, with efforts devoted to modelling the main concepts of effectiveness for maintenance programs which are applied in multiple operations across large sectors of industry. We note that, in a considerable number of such studies, the aspects of effectiveness are rather underdeveloped, generally, the only intention being to validate some maintenance model or theory proposed. Other than that, it is noticeable in this kind of literature that there are misconceptions on the usage of terms such as “efficiency”, “performance”, “efficacy” and “effectiveness”, without the due care of precisely defining the concepts involved and therefore militating against the literature being more unified in this matter. Regarding some main applications, we highlight the sector of Nuclear Power Plants (NPPs). In this kind of operation, there has been much development with regard to some aspects of maintenance effectiveness, which manifests itself as a critical analysis in order to optimally identify and correct the effects of equipment degradation. Therefore, using this methodology also contributes to operational safety and the prevention of accidents (Scott et al., 1992; Ashar and Bagchi, 1999; Martorell et al., 1999; Jerng et al., 2011; Contri et al., 2012). Other noteworthy studies focus on cases studies of offshore wind power generation systems (Tuyet and Chou, 2019), High Reliability Organizations (HRO) (Andriulo et al.,2015), fluid pumps (Barberá et al., 2014) and metal equipment (Huyhn et al.,2017).

Finally, one last issue to consider regarding the literature on Maintenance Effectiveness is the current trend of constructing, enhancing and applying new tools and technologies so as to optimize maintenance. One of the main developments in this matter is the incorporation of Information and Computation Technologies for the sake of maintenance effectiveness. Attention is drawn to studies in the context of Industry 4.0, where Science Data and Internet of Things are associated to proposing and discussing computational tools for improving maintenance (Bengtsson and Lundström, 2018; Huby et al., 2013; Kans, 2008; Garcia et al., 2006). Some other relevant developments cover aspects of Lean Maintenance and Intelligent Systems (Antosz et al., 2019; Rana e Koroitama, 2018), as well as new analytical modelling applied to the field of maintenance effectiveness (Zhou et al., 2011; Martorell et al., 2017).

4 RESULTS OF LITERATURE REVIEW

In this section, we present bibliometric indicators surveyed through the SLR, as previously detailed, comprising some of the major results from this review. Additionally, important findings and observations are commented on, which provide important insights into the current literature on this subject and indicate possible future trends of research.

4.1 Publication distribution over time

One of the main contributions of the SLR is the historical analysis of relevant research over the years, ranging from the pioneering studies that are still made currently available on reputable search databases to the latest papers published on the subject, most of the latter still not being widely known in the academic field. For the present work, Figure 2 shows the number of articles published each year and by each decade from the 1970s.

It is noteworthy that the literature review indicates that the first two papers on the effectiveness of maintenance – which are still available on reputable databases today – were published in the 1970s. More specifically, the first one concerns an economic evaluation regarding the optimiza-

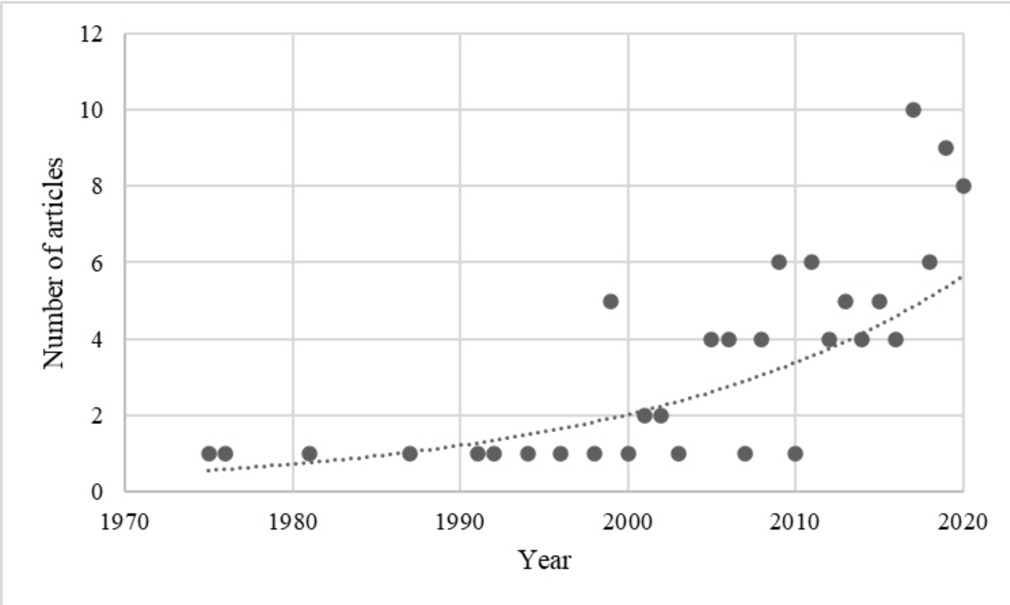

Figure 2 – Number of articles selected by year and number of articles selected by decade.

tion of a maintenance policy for a housing unit, when the effectiveness of maintenance is subject to decreasing returns to scale (Luenberger, 1975) and the second is a literature review over the state of the art of maintenance, which focuses on effectiveness, its related key factors, the reaction of industry to this new approach and some initial insights into assessing this operational aspect (Husband and Basker, 1976). The timeline presented indicates that, historically, the trend has been for publication rates to grow, although some oscillations during this period can be seen. To illustrate, analysis by decade shows an average of 1.1 papers were published per year during the 1990s, while since then there has been a marked increase as shown by an average of 6.5 papers having been published per year during the 2010s and up to 2021.

Two main jumps in the number of published papers are evident from the timeline. The first, during the 2000s, reflects that the relevance of maintenance effectiveness increased considerably during a period when the most diverse areas of industry began to make more complete and wider use of computer technologies and the internet. This reminds us that this was one of the main phases of the Third Industrial Revolution. Based on this insight, there was a similar trend of higher visibility for maintenance effectiveness during the 2010s, with the same expectation for the upcoming decade, this time related to the Fourth Industrial Revolution and the rise of Industry 4.0. In this new breakthrough, a wider and more extensive use of sensors for gathering operational data, allied with technologies such as the Internet of Things (IoT), Big Data and cyber-physical systems for compiling and processing information, are seen as “triggers” for a new application of the maintenance effectiveness approach. This time, this approach is seen to play a role at a higher level of importance – never seen before – in increasing organizational performance and achieving competitive advantage for companies. Therefore, this analysis concludes that, when a major breakthrough in the field of industry-applied technology is achieved – as observed for computational and data science improvements during the 2000s and 2010s - , the academic field tends to find a way of “taking advantage” of such technical development in favor of maintenance effectiveness, thereby increasing its research relevance, which can ultimately be identified in a timeline that shows a steeper increase in the number of papers published during a certain period of time.

4.2 Publication distribution among journals

The present SLR contemplates papers published in journals, found by conducting searches in reputable databases, as a way to assure the quality and content. Imposing this condition also proved to mitigate the frequent lack of commonality between studies regarding the nomenclature and methodology on the subject. After analyzing in what journals the studies had been published, we identified that the variation in the number of papers published by these journals was great. Out of a total of 67 journals, 50 have published a single paper related to the effectiveness of maintenance operations. The main journals publishing papers on this subject in the academic field and the number of such papers published are shown in Table 1.

Table 1 – Number of articles by journal.

Journal	N	%
Reliability Engineering and System Safety	12	11.4
Journal of Quality in Maintenance Engineering	8	7.6
Maintenance and Reliability	4	3.8
Computer-Aided Civil and Infrastructure Engineering	3	2.9
IEEE Transactions on Reliability	3	2.9
Journal of Transportation Engineering	3	2.9

We point out that the main journals here identified relate to the field of reliability and safety, highlighting the relation between maintenance effectiveness and such aspects. Effectiveness also seems to be positively associated with terms of maintenance quality, as represented by the large number of publications in a related journal. Applications regarding transportation and civil infrastructure also appear to recognize the effectiveness factor as having an important role in maintenance operations.

4.3 Citation Analysis

The SLR surveyed citations for the 99 analyzed papers by gathering data from the same databases used when searching for the relevant literature (Scopus, ScienceDirect, Web of Science, and IEEExplore). A total of 2328 citations were counted, which gives an average of 22.17 citations per article. When the date of publication of the paper is considered, an annual average of 2.77

citations per paper is obtained. Table 2 highlights the top four cited articles, which are those that surpass the 100-citation mark.

Table 2 – Summary of top 4 cited articles.

Title	Publication Year	Citations
Age-dependent reliability model considering effects of maintenance and working conditions (Martorell et al., 1999).	1999	252
SIMAP: Intelligent System for Predictive Maintenance: Application to the health condition monitoring of a windturbine gearbox (Garcia et al., 2006)	2006	246
Maintenance performance measurement (MPM): issues and challenges (Parida and Kumar, 2006)	2006	188
Linear and nonlinear preventive maintenance models (Wu & Zuo, 2010)	2010	137

In this particular analysis of the most cited papers, it is interesting to note what the main specific topic targeted by each article is. This reveals latent themes on maintenance effectiveness. This conclusion is drawn based on the understanding that a high number of citations is related to the relevance of a study's main topic, as well as to its importance when developing new research and its criticality for improving the overall maturity of this scientific field. Thus, Martorell et al. (1999) develop an analysis focused on aspects of reliability and human factors, while proposing a model to support the life management of Nuclear Power Plants and life extension programs for them. Garcia et al. (2006) examine an example of applying new technologies in favor of maintenance effectiveness, by implementing an intelligent predictive system for health monitoring and optimization of maintenance planning for wind turbines. Parida and Kumar (2006) discuss the main challenges currently faced by the industry regarding this matter of effectiveness, and propose a new methodology that aligns internal and external factors in order to make an overall quantitative evaluation of maintenance effectiveness. Finally, Wu and Zuo (2010) demonstrate the relevance of new analytical models for studying maintenance effectiveness, by conceiving new generic forms based on the relationships among already consolidated preventive maintenance programs.

4.4 Research method analysis

A different perspective of the SLR accounts for the research method applied in the development of the reviewed papers. Here by "research method" we characterize the main methodology and approach adopted by the respective authors in order to address the specific topic proposed in the article. A survey of this indicator was only possible through our subjective analysis in the examination of the selected literature, and hence might be the target for investigating how to improve such assessments. Overall, the distribution of research methods among the papers considered is as shown in Figure 3.

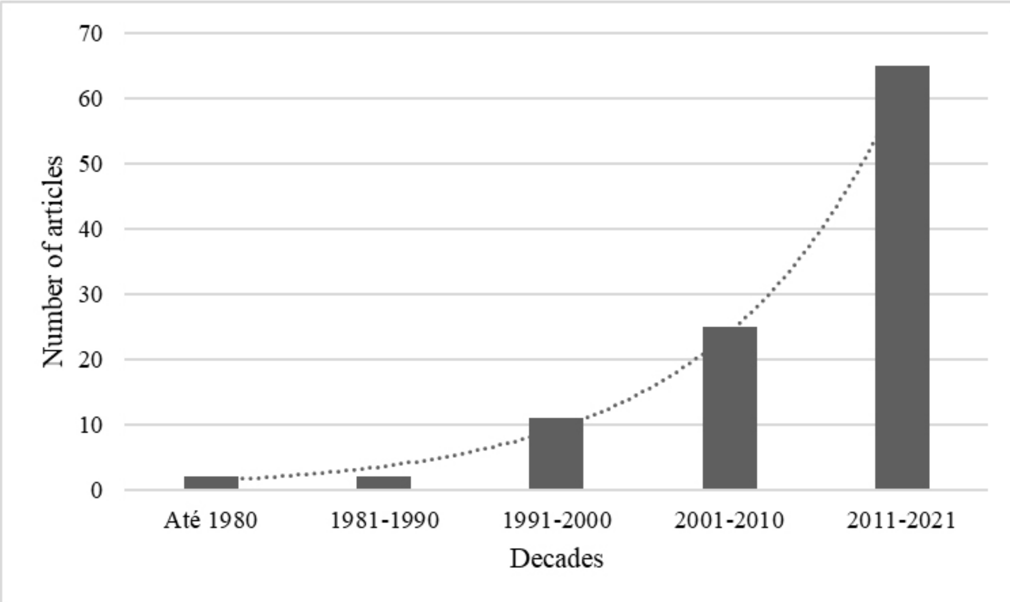

Figure 3 – Analysis of the articles selected by the research method they used.

One important observation regarding this survey is the fact that there is no restraint on the number of research methods applied to a given paper, i.e., there are articles where more than one research method was attributed during our subjective analysis. As to what the categories mean, "Evaluation" stands for measuring maintenance effectiveness, whether this is by proposing a new system for evaluation, by assessing a specific factor or measuring effectiveness in a determined industrial context. "Case study" comprises the main idea of examining a specific industrial scenario in order to study aspects of maintenance effectiveness under such circumstances. "Theoretical Model" represents the development of an innovative algorithm, model or methodology to study maintenance effectiveness, while "Practical Application" involves applying some developed model in a real case scenario, for validation purposes. "Optimization" expresses the aim of improving maintenance effectiveness by proposing a new analytical model or considering a new key-factor for quantitative optimization. Finally, "Literature review" stands for the review of literature regarding methodologies for maintenance effectiveness and "Theoretical Discussion" is the discussion of already established models and theories on this subject.

Observing the surveyed indicator, we highlight the academic emphasis on the proposal of developing evaluation models for maintenance effectiveness, which is commonly inserted as part of a case study or incorporates some practical application in order to validate the proposed methodology. This phenomenon, therefore, reveals a current trend of the scientific field, which seems to tackle the aspect of effectiveness in maintenance on a more case-oriented mode, instead of proposing general and broad methods for evaluation. Theoretical modelling and optimization also show considerable relevance, which indicates the importance attributed to quantitative-precise approaches usually based on stochastic or numerical formulations. Neither a literature review nor discussion of consolidated methodologies seem to attract much attention, signaling a current *gap* in the understanding and critique of published papers.

4.5 Industrial sector analysis

Lastly, one final indicator for the SLR is related to the operations of the industrial sector aimed by the selected papers. Again, a survey of such an aspect was only made possible by our individual review of the relevant literature, and hence might be the target for investigating how to improve assessments of this nature. It is important to indicate, in this sense, that although some articles did not actually state the sector of industry that they aimed at, in some cases a sector was inferred based on the overall methodology proposed and the parameters adopted. However, in general developments (common in theoretical modelling, for example) no sector could be attributed as the target of the paper. Given the subjective nature of this analysis, only some broad conclusions can be drafted, with no numeric values sufficiently consistent for the purpose of this review.

An overall analysis of the sectors aimed at by selected articles showed a tendency of favoring Nuclear Power Plants (NPP) related operations when studying maintenance effectiveness. This seems reasonable from the reliability point of view, given the catastrophic severity of systems malfunction due to lack of maintenance quality in this sector. Other than that, the sector related to transportation and road structures also showed that the academic community pays significant attention to it, usually by tackling the long-term effectiveness of improvements measured against the costs incurred. In a broader perspective, the prioritization of the manufacturing industry and mechanical systems is consolidated in the literature.

5 CONCLUSIONS

This study explored a systematic literature review on the subject of maintenance effectiveness, focusing on the problem of ensuring effectiveness when using any of the many models currently present in the scientific literature, as well as the diverging character of multiple methodologies proposed for analyzing this issue. After developing the stages of a Systematic Literature Review according to the Systematic Search Flow Method, we discussed the current major themes in maintenance effectiveness, and also considered the relationships with other fields and some of the main applications. Bibliometric indicators were surveyed, and a statistical analysis of 99 papers published in 65 journals linked to reputable databases was presented.

From the historical data, it was possible to observe the increasing relevance of the maintenance effectiveness field of research over the years. A considerable jump in the number of published papers during the 2000s matches with a period that may be related to a wider and more thorough use of computer technologies and the internet in production systems. The distribution of papers among the many journals shows evidence of academic production being scattered. Latent themes on maintenance effectiveness seems to attract more attention from the scientific community, as is shown by the analysis of citations. Lastly, two subjective indicators were surveyed regarding the research methodology conducted and the industrial sector aimed at by the papers reviewed. Such analysis clarifies the trend towards developing case studies combined with procedures for evaluating maintenance effectiveness, mostly applied to the manufacturing industry and mechanical systems.

Some insights can be obtained from the SLR. A new jump in the production of articles regarding maintenance effectiveness is expected over the next years, this time driven by the rise of Industry 4.0 and Information Technologies applied to maintenance in production systems. Other than that, it is recognized there is a need to propose generalized methodologies for assessing maintenance effectiveness in various sectors of industry that can be combined with multiple case-scenario methodologies already established in literature. Further discussion and review of current models for maintenance effectiveness evaluation also seems to be a relevant direction for future research, with special focus on dealing with the apparent disagreement in guiding principles, definitions and metrics to define an effective maintenance program, as proposed among different approaches in literature. Therefore, overcoming this problem will contribute to the unification of the theme of maintenance effectiveness. Finally, it is a fact that maintenance effectiveness is required with more focus in areas where failures have more severe consequences. This is because there is an obvious link between the need to prevent failures and the efficiency of maintenance. Consequently, as regulations and protective legislation become more restrictive, more attention is expected to be paid to the effectiveness of maintenance.

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How to cite

COSTA LQM & CAVALCANTE CAV. 2022. A review on the study of maintenance effectiveness. *Pesquisa Operacional*, **42** (nspe1): e263613. doi: 10.1590/0101-7438.2022.042nspe1.00263613.