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Maintenance as a sustainability tool in high-risk process industries: A review and future directions

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ABSTRACT

The intricate interplay between sustainability and maintenance management within high-risk process industries constitutes a focal point for scientists, engineers, and strategic planners. Recognizing maintenance management as a pivotal component of comprehensive development strategies, this study delves into the challenges posed and opportunities presented by these critical sectors. Leveraging cross-sectoral scientific data from diverse applications and databases, this research aims to discern novel developmental patterns and multifaceted sustainability aspects embedded within high-risk industrial contexts. Drawing upon an extensive literature review, the study identifies three fundamental pillars (environmental, economic, and social) that underpin emerging trends in maintenance development. These pillars serve as guiding principles, directing research endeavours towards maintenance strategies conducive to both improvement and sustainability objectives.

This article meticulously examines the nexus between maintenance capacity and the realization of sustainability goals. By exploring nuanced sustainability considerations in the realm of maintenance development possibilities, the research illuminates the vital role of maintenance in ensuring the sustainability of high-risk process industries. This study underscores maintenance management as an indispensable component within the framework of a sustainable organization. This study aims to provide a decision-making framework for stakeholders in the process industries to design sustainable maintenance strategies.

1. Introduction

Throughout the annals of history, the imperative to sustain and support complex technological systems has been an enduring challenge for humanity. In this context, the realm of plant maintenance has risen to prominence as a discipline of paramount importance, resonating profoundly within the process industries (Mi et al., 2021; Li et al., 2022). This paper unravels the intricate significance of maintenance, particularly within high-risk process industries, often referred to as "Seveso establishments" in European regulations, where its primary mission revolves around upholding and enhancing process safety and reliability objectives, entailing rigorous risk management practices. Maintenance strategies, aligned with the French Association for Standardization's (AFNOR) standard NFX-60-010 definition as "*a set of actions enabling the maintenance or restoration of an asset to a specified state capable of providing a specific service*" are oriented toward fostering fewer failures, reduced costs, heightened manufacturing equipment availability, superior service quality for customers, and the overarching goal of enhancing safety (Ochella et al., 2022; Mohammadi and He, 2022).

The impacts of maintenance extend broadly across key domains, including production capacity, which wanes in the presence of machinery failures, direct and indirect production costs, incorporating labour expenditures, repair teams, preventive maintenance inspections, and the provisioning of spare parts. Furthermore, the quality of products and services is intricately linked to maintenance, as inadequately maintained equipment manifests frequent failures, which, in turn, compromise service quality to customers. And for safety, both in terms of employee well-being and process safety, emerges as a critical concern, given that operational equipment is susceptible to untimely failures, potentially culminating in incidents or accidents. Lastly, the pivotal facet of customer satisfaction hinges upon the uninterrupted flow of equipment, as equipment failures disrupt production schedules, thereby affecting product quality and delivery timelines (Schmitt et al., 2016; Hadef et al., 2020; Martínez-Galán Fernández et al., 2022).

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The objectives and benefits of maintenance, as expounded upon, coalesce into a trinity of facets: cost, environment, and society. This trifold construct underscores the diverse objectives that maintenance strategies aim to optimize, often focusing on one or more of these dimensions. The heightened complexity of high-risk process industries necessitates the adoption of sustainable maintenance strategies, rooted in the tenets of sustainable development. Yet, it is crucial to acknowledge that integrating these principles into high-risk industry management presents a particular challenge, as highlighted by (Hallaji et al., 2021; Ghaleb and Taghipour, 2022; Jimenez et al., 2020).

In the contemporary landscape, human progress propels advancements in technology, industrialization, and resource utilization (Vrignat et al., 2022). Simultaneously, the concept of sustainable development has arisen as an imperative to parallel this trajectory of growth. As articulated by the World Council for Environmental Development (1987), sustainable development is founded upon the principle of "*meeting the needs of the present generation without compromising the capacity of future generations to meet their own needs*". Consequently, the high-risk process industries sector shifts its goal from mere production to the pursuit of safe manufacturing practices, ensuring the sustained viability of facilities.

In a parallel pursuit, high-risk process industries are invested in the pursuit of sustainability to achieve multifaceted objectives. These objectives encompass bolstering competitive advantage, assiduously safeguarding and promoting the high-risk process industries brand image, ensuring long-term success, and enhancing operational efficiency through the reduction of costs and waste. This endeavour also encompasses the adept management of regulatory constraints and opportunities (Holgado et al., 2020). The ethos of sustainability empowers high-risk industry managers to curtail risks, bolster energy efficiency, minimize waste, and kindle innovation in the development of environmentally friendly products and services (Kennedy et al., 2007; Vrignat et al., 2022). Indeed, the clarion call for sustainability resonates ever more resoundingly among the scientific and engineering communities, who increasingly prioritize the harmonization of industrial activities with environmental preservation goals, including addressing air pollution, transportation issues, habitat preservation, and combating global warming (Liyanage et al., 2009; Franciosi et al., 2018; Hefaidh et al., 2019).

Sustainable development is based on three main aspects. First, the economic component involves changing patterns of production and consumption, ensuring that economic growth is not achieved at the expense of the environment and society. Second, social (human) aspect, sustainable development aims to improve working conditions, train workers and create diversity. Finally, the environmental aspect (widely recognized) focuses on avoiding activities that are harmful to the environment, in order to safeguard ecosystems, biodiversity, as well as flora and fauna.

In this context, the study of the literature carried out by (Karki and Porras, 2021) aims to investigate the concepts (maintenance services, sustainability impact and digitalization) independently and in relation to each other. Indeed, this study was carried out to understand the relationship between maintenance and sustainability, and to describe the role of digitalization in achieving these goals. In addition, (Franciosi et al., 2022) identified the role of Digital twing in terms of maintenance and production activities to improve industrial sustainability. And as results obtained, a quantification of the dimensions was carried out (economic, environmental and social respectively, with sub-criteria for each dimension. Notwithstanding the salience of maintenance within the high-risk process industries, limited studies have explored the symbiotic relationship between maintenance techniques and their potential to augment sustainability objectives.

Thus, the primary objective of this paper is to dissect the intricate interplay among pivotal performance elements associated with asset enhancement. Specifically, this research endeavours to elucidate the contributions and ramifications of maintenance practices in securing the sustainability objectives of high-risk process industries. The second objectif to discuss and analyze the current challenges as well as the future prospects of sustainable maintenance. This research study linking maintenance optimization strategies and facility sustainability aims to provide a decision-making framework for stakeholders in the process industries to design sustainable maintenance strategies.

2. Methodology

The literature review presented in this article employs a organized approach to consolidate existing data, enabling researchers to grasp the current state of a particular area of maintenance research. In pursuit of this objective, the study is framed by the methodology outlined in this section, which serves to delineate the research problem statement, establish the objectives to be attained, and outline the structure to be followed to achieve the defined goals.

2.1. Research questions

Maintenance function holds substantial influence, whether positive or negative, on economic, environmental, and social dimensions. Therefore, decision-making processes related to optimizing maintenance strategies should be grounded in these aspects. Consequently, these parameters are subject to optimization. Notably, these aspects align with the same criteria utilized to evaluate the attainment of sustainability objectives within this context. This leads us to the research questions raised in this review, which form the basis of the study's problematics.

RQ1. what are the contributions of maintenance practices to ensure the sustainability objectives of high-risk process industries?

RQ2. By reviewing the correlation between maintenance and sustenaibility. What challenges and future prospects can be discussed and analyzed regarding sustainable maintenance?

The response to this inquiry is derived from an examination of the interplay between these two concepts. In other words, it involves discussing how maintenance serves as a tool for sustainability in manufacturing industries by attaining economic, environmental, and social objectives. These criteria form the basis for assessing the effectiveness and impact of maintenance practices in promoting overall sustainability in these industrial contexts. Indeed, the maintenance management is widely recognized as a crucial tool in assisting high-risk process industries in meeting the economic, environmental, and social challenges associated with sustainable production (Karuppiah et al., 2021; Hami et al., 2020; Saihi et al., 2022). Indeed, adopting a maintenance vision focused on profitability enables achievements across the three pillars of sustainability by implementing concepts such as "lean maintenance," "green maintenance," and "maintenance-centered circular manufacturing" (Cagno et al., 2021; Josef Peter et al., 2022). By incorporating the concepts of maintenance and sustainability into high-risk process industries strategies, it becomes possible to streamline and optimize target systems while contributing to the safety and resilience of the industrial ecosystem through the RAMS (Reliability, Availability, Maintainability, and Safety) approach. This approach encompasses all the performance and sustainability-related requirements, ensuring a comprehensive perspective (Zhang and van Luttervelt, 2011; Zhao and Yu, 2011). When exploring the connection between maintenance and sustainability, it's crucial to delve into the discussion and analysis of both the existing challenges and the potential future prospects of sustainable maintenance.

2.2. The purpose of this article review

This study aims to establish and examine forthcoming trends in maintenance development, with a specific focus on identifying sustainability dimensions within these trends. Additionally, it seeks to model the relationship between maintenance and sustainability and underscore the significance of maintenance as a tool for realizing high-risk process industries sustainability objectives. To achieve this objective, the study conducts a comprehensive analysis of various scientific articles from diverse databases to extract future development trends and explore the sustainability dimensions embedded within these trends.

2.3. Selection of publication

This synthesis research collected papers for review from various databases such as Google Scholar, Scopus, and Web of Science. As a result, the following keywords have been used to search for database articles: « maintenance » AND « optimization » OR « approaches», « maintenance » AND « sustainability » OR « modeling», « maintenance » AND « management » OR « optimization».

The search was performed based on all possible combinations between the terms mentioned above. The articles used in this review (400 articles) are carefully examined to extract quality information that is relevant to the title, abstract, and objectives of the study. Furthermore, the list of articles mentioned in the bibliographic reference section is not an exhaustive list of all articles beds and reviewed for the study's conduct.

2.4. Inclusion and exclusion criteria

In this study, journal articles, conference papers, research reports and books were included, while book reviews and commentaries were deliberately excluded from the scope of the research. Likewise, the search was restricted to publications in English, with no explicit time limit for year of publication, but with a particular emphasis on recent studies, particularly for the results and discussion section. To minimize bias, journal ranking and Hirsch index (h-index) of articles were not used as exclusion criteria. This ensures equal consideration of contributions regardless of their ranking or the impact of the journal.

Publications dealing with differences between maintenance policies were excluded from the analysis, thus focusing the study on specific aspects related to sustainable maintenance. And, in the bibliographic research on the social aspects of sustainable maintenance, the study focused on the process industry. This approach was adopted due to the risky nature of this industry, making it particularly relevant for exploring the social aspects of sustainable maintenance. Therefore, other aspects were deliberately excluded from this analysis.

2.5. Structure of the article review

The structure of this review study follows a progression from maintenance development to sustainability (or sustainable maintenance). To facilitate this progression, the second section explores two maintenance philosophies (PM, CM). Building upon this, the third section analyzes research articles conducted to develop approaches for maintenance modeling and optimization. The insights gleaned from this analysis inform the subsequent phase of the research. This study's analysis was conducted in two parts. Firstly, future trends in maintenance development were explored to identify the aspects that these trends seek to optimize, as well as to uncover their underlying sustainability dimensions. Subsequently, the modeling of the relationship between maintenance and sustainability was discussed, highlighting the contribution of maintenance to sustainability and the synergies between these two concepts. In paragraph 4.2, we discuss the challenges and future prospects for sustainable maintenance based on the study of the relationship between maintenance and sustainability that was discussed in the previous paragraph 4.1. Many studies were examined within this context to strengthen our observations and emphasize the crucial role that maintenance performs in managing high-risk process industries sustainability. Lastly, the conclusion serves to capitalize on the findings obtained throughout the study.

3. Maintenance philosophies

The analysis of the various maintenance policies is essentially based on the event that caused the maintenance action; either it is based on a schedule and/or a status of good issue such as sensor information … etc. It is Preventive Maintenance (PM), or is based on the failure occurrence; it is Corrective Maintenance (CM) (Nacchia et al., 2021). All high-risk process industries have adopted both maintenance policies.

The CM is one of the oldest maintenance policies, with the concept of "fixing it in the event of failure" without monitoring (Kothamasu and Huang, 2007). According to AFNOR X60-010 (AFNOR), *this is maintenance performed after a failure (total or partial). This is random in nature, and the tasks associated with this form of maintenance are sustained and not planned.* "The PM defined by NF EN 13306 X 60–319 "*PM is maintenance performed at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or degradation of the functioning of an asset*". This type of maintenance is intended for those elements which cause production stoppages or unforeseeable downtime costs to high-risk process industries.

In this context, maintenance is performed according to specified criteria to reduce the potential, for example, failure or degradation of the services provided. As a part of this maintenance, there are two types distinguished: Systematic Preventive Maintenance (SPM) "carried out at predetermined time intervals or according to a defined number of units of use but without prior checking of the condition of the property" (NF EN 13306:2001). In addition to the Conditional Preventive Maintenance (CPM) « *the CPM based on a monitoring of the functioning of the asset and/or the significant parameters of this functioning integrating the resulting actions*» (NF EN 13306 X 60–319). These two maintenance philosophies are complementary and must be practiced as part of a maintenance policy adapted to the technical and financial challenges of the high-risk process industries (Azadeh and Abdolhossein Zadeh, 2016; Wang et al., 2014).

The PM is the field of optimizing the maintenance of scientific and industrial technical systems which can be difficult. Indeed, it is a task that can be quite challenging. It involves striking the delicate balance between costs, frequency, and scope of maintenance activities. PM objective is to reduce the probability of failures, the consequences criticality, and enhance overall system performance. However, it is important to note that PM actions can also introduce potential failures, thus presenting a paradoxical situation that requires careful planning and consideration (Selvik and Aven, 2011).

Operational research introduced the PM application in the 1950s on the basis of a scientific approach. Which includes specific processes and principles using various analytical techniques such as statistics, mathematical planning, and artificial intelligence, among others? Its key advantage lies in informed decision-making based on rigorous real-world data analysis (Ahmad and Kamaruddin, 2012). Accordingly, several strategies have been developed to model and optimize PM, aiming to achieve the desired objectives. Some of these strategies include.

3.1. Time based maintenance (TBM)

Time-based maintenance (TBM) or periodic maintenance is classified as one of the traditional PM techniques (Yam et al., 2001a; 2001b). This allows regularly checking, detection and improvement of the equipment condition. The decisions made in this regard are based on an analysis of time or aging that is for some equipment, estimated based on usage data or failure time data (Lee et al., 2006). Indeed, the decision is built upon the analysis of probability distribution functions statistically derived from the failure rate and time as predictors of equipment reliability. For example; Time Between Failure (TBF), Time To Repair (TTR), time elapsed since installation … etc. Similarly, the TBM can be divided into two classes.

- **The age-based policy (lifetime)** is a maintenance/replacement policy. Replacement occurs when the elapsed time reaches the statically defined maintenance period, or when a failure occurs before that maintenance period. Therefore, the replacement end time becomes the starting point for the next maintenance period. This maintenance policy may be affected by failures. The main benefit is to maximize the life of the equipment; however it requires more complex maintenance and planning (Jiang and Ji, 2002).
- **Block-based policy** is a regular PM policy that has no affect on failure events. That is, maintenance is performed after a predefined period, even if a failure occurs before that period (Chin et al., 2019).

The TBM approach follows a systematic two-step process. The first step involves analyzing and modeling failure data to gain insights into device failure characteristics. This statistical analysis allows for determining reliability functions based on collected downtime data. The second step entails making informed decisions to establish an optimal maintenance policy that ensures the desired level of system availability and safety while minimizing costs (Pham and Wang, 1996). Within this framework, the data of component failure used to identify the reliability functions by using two approaches. The first approach involves directly analyzing the empirical data to derive survival functions. This is accomplished by studying the actual failure-to-time (FTT) data, allowing for the derivation of empirical survival functions (Hadef et al., 2020; Chin et al., 2019). The second approach includes theoretical distribution research, which provides more refined reliability estimation. This approach utilizes theoretical distributions such as exponential, normal, and Weibull distributions (Faccio et al., 2014). The Weibull model, in particular, is frequently employed as it allows for the study of component lifetimes with variable failure rates, encompassing different life phases of the equipment, including early, useful, and aging phases (Hadef et al., 2023).

Interest in applying TBM as a tool to resolve maintenance issues related to actual industrial practice (replacement and repair-replacement issues) to determine the optimal replacement time to repair and/or replace a component (or a target system) by minimizing/maximizing certain criteria such as: reliability, safety, availability and maintenance cost or unavailability cost. The TBM application has been developed for applications for example.

- Replacement problem: the authors Laggoune et al., (2009) proposed an optimized model for the replacing a hydrogen compressor in a petroleum refinery was proposed. This model is designed for serial multi-component systems malfunctioning randomly with a minimum cost ratio according to a typical life distribution.
- Repair–replacement problem: the authors Sheu et al. (2010) proposed a regular replacement model has been developed based on the cumulative limit of repair costs, and this model has been applied to systems subjected to shocks.

And various studies of this policy are devlopped sach as: (Scarf and Cavalcante, 2010; Laggoune et al., 2010; Wu et al., 2010).

In conclusion, TBM policy offers several advantages, including determining optimal frequencies and time intervals for maintenance operations. It provides cost-based optimization models, enabling the allocation of resources in a cost-effective manner. Additionally, TBM allows for defining availability and/or reliability thresholds, ensuring the desired performance levels of equipment, and maximizing equipment life and production rates. However, TBM has certain limitations that need to be considered. One limitation is the challenge of obtaining accurate and available data for analysis. Data collection can be difficult, and records of failures up to the point of failure are not always accessible. This can hinder the accuracy of the reliability analysis and decision-making process. Another limitation is that TBM assumes constant operating conditions and does not account for variations in environmental impacts. This static approach may not capture the dynamic nature of the system, potentially leading to suboptimal maintenance decisions.

It is important to be aware of these limitations and consider alternative approaches, such as condition-based maintenance, which address some challenges by leveraging real-time data and adaptive maintenance strategies.

3.2. Condition Based Maintenance (CBM)

Condition Based Maintenance [1] (CBM) is classified as a specific PM technique. It is the most discussed maintenance technique in the literature (Humberto et al., 2020; Jordan et al., 2022). Maintenance decisions are based on information gathered by monitoring the operating status of the system (Jardine et al., 2006). CBM's primary objective is to increase availability by eliminating unnecessary uptime and risk of failure by detecting anomalies early (Xiang et al., 2012; Liao et al., 2006). Additionally, the equipment condition must be evaluated in real time to minimize unnecessary maintenance and associated costs (Gupta and Lawsirirat, 2006). CBM is recommended for high availability critical systems.

The proposed implementation methodology consists of a series of nine consecutive steps that enable the comprehensive consideration of CBM from a preventive standpoint. These steps encompass various aspects, including the identification of failure modes to prevent, the selection of relevant physical parameters (or a set of parameters), the careful selection of suitable sensors, the determination of optimal information collection methods, the establishment of appropriate thresholds, the judicious choice of information processing techniques, the definition of procedures to follow after an alarm is triggered, the organization of conditional intervention based on the identified failure indicators, and finally, the assessment of effectiveness through a thorough review of experience feedback.

The primary constraints associated with this approach pertain to the precision and accessibility of the data. The methodology heavily relies on theoretical and static analyses, which may fall short in accounting for real-time variations and complexities. Furthermore, there are concerns regarding the accuracy of the data used. Despite these limitations, the application of this technique in addressing maintenance challenges across diverse domains has been highly regarded. For example, but not limited to, two applications of this policy will be explained; the first application realized by (Wang et al., 2023), the intelligent operation and maintenance of a hydropower plant heavily relies on implementing CBM for its Hydropower Generating Units (HPGUs). A theoretical structure that combines a generalized proportional hazard model with a semi-Markovian decision process was introduced to strike a balance between predictive capabilities and reliability optimization. The efficacy of this method was validated by comparing it to the average time cost model using real-world instances. The outcomes revealed substantial benefits, including the avoidance of an operating cost of $87.2 per day and a reduction in maintenance cycle errors by 15 days. And, the second application, the authors (Cai et al., 2023) proposed a novel methodology that represents the original entirely data-centric strategy, wherein maintenance actions are prompted by a condition threshold determined exclusively from historical condition data and instances of failure. The numerical results obtained by examining a gamma deterioration process, demonstrate that the maintenance threshold derived from the proposed method progressively aligns with the optimal threshold. During the initial operational cycles leading to failure, the established threshold is intentionally elevated, a tactic that facilitates an in-depth exploration of the deterioration process. An encouraging outcome is the rapid convergence observed, particularly in the initial runs-to-failure stages, leading to the instantaneous convergence of the expected cost rate toward its minimum value.

Some researchers are presented with applications of optimization approaches in CBM decision making such as Wang and Zhang 2008a; Niu et al., 2010; Wang and Zhang (2008a, 2008b); Galka and Tabaszewski, 2011; Pecht and Jaai, 2010; Gaperin et al., 2011; Polenghi et al., 2022)

And, in the recent paper, various authors consider the difference between the CBM and the predictive maintenance (Andriy et al., 2022; Archit et al., 2022). Effectively, the CBM is composed of only diagnosis, while predictive maintenance is composed of both diagnosis and prognosis. The predictive maintenance decision-making process relies on two complementary approaches (Archit, et al., 2022).

- *Diagnosis:* the process of finding the source of a fault by giving early instructions to the technician in the entity that behaves abnormally. That is, when the device is in degraded operation rather than a failed state based on a predetermined alarm threshold.
- *Prognosis:* the process of estimating and predicting failure when it may occur to provide additional warning by estimating when the entity will fail. Therefore, it is useful to determine the appropriate time to perform PM.

Monitoring techniques play a pivotal role in this maintenance policy by allowing the early detection and diagnosis of anomalies and defects before they manifest as critical failures (Yaguo et al., 2018). In this regard, a range of monitoring techniques can be employed, as example.

- *Vibration monitoring*: used to identify and analyze equipment features utilizing sensors that deliver real-time (continuous or regular) information about the health of online systems. These sensors can identify system deterioration or damage (Dias et al., 2021).
- *Sound or acoustic monitoring*: Each component is permanently connected to a vibration sensor, which records local movements, and a sound sensor, that listens to the system (online, continuous or regular acoustic monitoring) (Chin et al., 2019).
- *Lubricant monitoring (oil analysis):* The oil quality analysis result (whether the oil is suitable for future use) indicates the deterioration and wear condition of the internal oil-soaked parts. The objective of this technique is to ensure the quality of the oil and its associated components (Chin et al., 2019).

This maintenance strategy proves highly efficient as it adopts a dynamic approach, focusing on continuous monitoring of equipment conditions. The maintenance activities are carried out only when necessary, while optimizing production processes to ensure they operate within predefined performance parameters. Nonetheless, the management of maintenance resources poses significant challenges. Ensuring accurate diagnosis and prognosis encounters limitations, particularly regarding the reliability of long-term results. Moreover, the presence of noise in data, particularly waveform data, may result in incomplete information, further complicating the analysis.

3.3. Risk-Based Maintenance (RBM)

Risk-Based Maintenance (RBM) encompasses the consideration of unforeseeable risks, exploration of various system failures, risk identification, and the establishment of optimal levels of system reliability and availability. It involves the development of a maintenance strategy aimed at mitigating the costs and consequences associated with high-risk failures (Arunraj and Maiti, 2007).

The primary objective of this strategy is to plan maintenance activities based on the risk's occurrence dynamically. This planning process consists of two key steps: risk assessment and maintenance planning (Arunraj and Maiti, 2007). In order to meet tolerable and acceptable risk criteria, components with higher levels of risk are subjected to more rigorous and frequent maintenance actions (Brown et al., 2003; Ochiai et al., 2005). Various researchers across diverse high-risk industries process have put forth RBM maintenance strategies, as showcased of the authors (Leoni et al., 2021), their study offers a comprehensive evaluation of three RBM strategies, focused explicitly on consequence-based analysis, aimed at identifying maintenance priorities for highly critical components. The initial method introduced involves a hierarchical Bayesian network. The second technique entails quantitative risk analysis performed using Safeti software. Lastly, the third methodology relies on Synergi Plant software. The study's crucial contribution lies in aiding asset managers in selecting the optimal methodology aligned with their specific context while emphasizing critical components. The findings underscore that the most fitting approach is depending upon the accessible data, highlighting the nuanced relationship between methodology suitability and data availability. In addition, the study carried out by (De-León-Escobedo, 2023), RBM procedure has been proposed to recommend a sustainable maintenance strategy for steel oil and gas pipelines subject to internal pitting corrosion. The procedure considers the uncertainty and time course of the corrosion depth, which depends on the initial depth and corrosion rate, and includes the calculation of the time-varying probability of failure, or reliability, and its acceptable limit (target) which is calculated according to the significance of the consequences of a pipeline rupture. The results are used to prioritize attention or pipeline segments and allocate funds for pipeline maintenance work based on segment risk exposure conditions.

Minimizing the risk of system failure and its consequences, surrounding safety, economic, and environmental aspects, aids managers in making informed decisions regarding maintenance investments. However, the implementation of this strategy poses certain limitations. It necessitates a highly qualified team capable of quantifying risks associated with different tasks, and it requires substantial initial planning that demands both time and qualified personnel.

3.4. Opportunistic maintenance (OM)

To minimize maintenance costs, the OM strategy was formulated. This strategy, initially introduced by Radner and Jorgenson (1963), aims to determine the most effective maintenance policies for manned aircraft and ballistic missile systems. The primary objective of OM is to reduce capital expenditures by leveraging the end of the operational process for conducting maintenance operations. For instance, in a two-component system, if one component fails, the other component can still be retained simultaneously. This policy can be applied to various complex multi-unit systems.

Also, the OM strategy optimizes maintenance operations for multi-component systems by considering their shared conditions and interdependencies, reducing overall maintenance costs. This approach proves to be more cost-effective compared to maintaining individual components separately (Koochaki et al., 2012). The dependencies in OM can be categorized as performance-related, stochastic (similar failure rates), and resource-related (limited availability of spare parts or repair personnel) (Petchrompo and Parlikad, 2019). The OM policy is specifically applicable to components characterized by a high failure rate (Besnard et al., 2009).

Various researchers have been implementing this maintenance policy as example, the authors (Nilsson et al., 2009), has benn proposed an optimized OM model has been proposed to replace the shaft seals in nuclear power plant water pump systems. This model is both deterministic and practical. Furthermore, the authors (Zhou and Ning, 2021) proposed a maintenance planning model for multi-unit serial systems for meeting the expectations of random production. This study presents a new OM policy based on the MGW (Maintenance, Gravity, and Window) concept and, the results demonstrate the profitability of this policy through numerical examples. Within the OM framework, further research and applications in various process industries such as (Zhou et al., 2011; Kang and Guedes Soares, 2020): … etc.

OM models are formulated within two primary frameworks, as described by Chin et al., 2019. The first framework is TBM, which relies on predefined age thresholds to determine when to apply OM strategies.

The second framework is based on CBM, which employs real-time system state measurements to guide OM decisions (Moghaddam, 2013). The OM proves to be an effective strategy in significantly reducing maintenance costs, enhancing facility availability, and minimizing production downtime. Nevertheless, it is important to note that this approach does not guarantee a fault-free period of system operation, as the precise timing of maintenance actions cannot be predicted with absolute certainty.

3.5. Reliability Centered maintenance (RCM)

In 1980, the introduction of the RCM strategy by the US aviation industry marked a significant milestone (Emovon et al., 2016). RCM serves as a valuable tool employed by reliability, safety, and maintenance engineers. Its primary objective is to assess the necessity of PM for equipment and complex industrial systems. Doing so enables the development of an optimal maintenance plan that ensures the system's essential functions while enhancing its reliability, maintainability, and availability (Cheng et al., 2008).

The RCM process involves a meticulous evaluation of the equipment and resources within a facility, with a strong emphasis on PM practices. This evaluation aims to identify the most suitable PM strategy that aligns with the system's requirements, ultimately enhancing its reliability and cost-effectiveness (Er-Ratby and Mabrouki, 2018). Effectivelly, SAE JA1012 (A Guide to the Reliability-Centered Maintenance (RCM) Standard) amplifies and clarifies each of the key criteria listed in SAE JA1011 (Evaluation Criteria for RCM Processes), and summarizes supplementary issues that must be addressed in order to apply RCM successfully. These standards are essential to certify that a maintenance method based on reliability can be recognized as being compliant with the RCM-N&H. According to the SAE JA1011 document from August 2009, a process must follow seven steps to be recognized as an RCM: (i) determine the operational context, functions and desired performance standards of the asset. (ii) Determine how an asset may not perform its functions (functional failures). (iii) Identify the causes of each functional failure (failure modes). (iv) Describe the effects of each failure. (v) The consequences of a failure must be classified. (vi) Determine what needs to be done to prevent or predict each failure. And finally, (vii) determine whether other methods of handling failures may be more effective.

It has been shown to reduce maintenance efforts by 40%–70% compared to other strategies (Johnston DC, 2002). The RCM is widely adopted across various high-risk process industries including nuclear power plants, aviation, and ships. This section provides some examples of RCM applications: the authors (Song et al., 2023) present a structured approach for RCM analysis, supported by model-based techniques driven, functional modeling and logical reasoning. The objective is to determine crucial maintenance elements by evaluating the consequences of potential failures. The efficacy of this method is demonstrated through the application of Multilevel Flow Modeling (MFM), which has demonstrated its proficiency in identifying system functions requiring maintenance intervention. Also, this research paves the way for automating the RCM process, addressing the high demand for such automation in intricate industrial sectors. Additionally, leveraging Multilevel Flow Modeling as a foundational framework for functional knowledge enhances its adaptability to alterations in design and operation, thereby facilitating the establishment of a dynamic RCM program capable of responding to changes effectively.

Similarly, another application was presented, this is the study proposed by (Patil et al., 2022), the RCM methodology represents a synthesis various maintenance strategies, offering the potential to streamline maintenance expenses and guarantee system availability. This approach focusing on its application to the steam boiler system within the textile industry. As indicated by the study findings, the proficient utilization of RCM technique results in a significant enhancement in both the reliability and availability of the boiler system, with an increase of 28.15 percent and 0.16 percent, respectively. Furthermore, implementing these structured maintenance programs leads to substantial annual savings, with up to a 20.32 percent reduction in maintenance costs.

Several tasks have been successfully completed under the RCM policy in process industries including: (Lu et al., 2021; Zakikhani et al., 2020; Yavuz et al., 2019; Piasson et al., 2016).

Implementing the RCM strategy requires a considerable amount of time due to its meticulous nature. Each failure mode is meticulously examined individually within the RCM approach, which may result in the potential oversight of significant combined effects. However, the RCM strategy aims to uphold the inherent levels of safety and reliability of the equipment while effectively allocating resources based on demand. By doing so, it strives to enhance overall reliability, contributing to cost reduction efforts.

Finally, summaries of the methods have been presented in Fig. 1.

These methods can be applied individually or in combination, depending on the specific needs and characteristics of the assets and systems. The selection of the most suitable optimization method depends on factors such as asset criticality, complexity, available data, resources, and organizational objectives. Based on these maintenance optimization approaches presented in this section, future guidance obtained from the approaches' analysis has been presented in the following section.

Through a thorough exploration of diverse maintenance policies, it becomes evident that there is not a singular "best" approach; rather, these policies need to be harmoniously employed based on contextual requirements. The synergy between these policies proves essential. In practice, a combination of strategies is adopted. Scheduled systematic maintenance interventions are organized alongside corrective maintenance actions. Opportunistic maintenance interventions are leveraged during planned maintenance or shutdowns, maximizing efficiency. For equipment of critical significance, continuous degradation monitoring is undertaken, paving the way for condition-based, risk-focused, and reliability-driven maintenance strategies. The amalgamation of these maintenance policies has resulted in an improved maintenance management system across various dimensions – encompassing costs, timelines, and societal benefits. This holistic approach allows for a comprehensive and effective management of maintenance operations.

4. Results and discussion

Through this part of the study, the answers to the research questions posed by section 2 were analyzed and discussed based on the description of maintenance policies mentioned in section 3 and through the analysis of various scientific articles published in this context. For this, we devote section 4.1 to answer the first research question, and section 4.2 to answer the second question.

4.1. Future research directions for maintenance in the context of sustainability

Based on the analysis of the maintenance policies discussed in the previous section, researchers applied this framework to address real-world challenges faced in high-risk process industries. Through this process, the future perspectives in the maintenance have been identified. It is important to note that maintenance is not only repair activities, but also an integral part of project management systems. This should be integrated into the comprehensive management system, aligned with the objectives of the high-risk process industries, and become a decision-support tool. The maintenance plays an important role in solving technical problems. The examined section explored the future direction of maintenance by considering three dimensions of sustainability: cost, environmental and social impact. And therefore, the discussion of the contributions of maintenance practices to ensure the sustainability objectives of high-risk process industries in answer to the first research question. To accomplish this, we address this relationship by analyzing

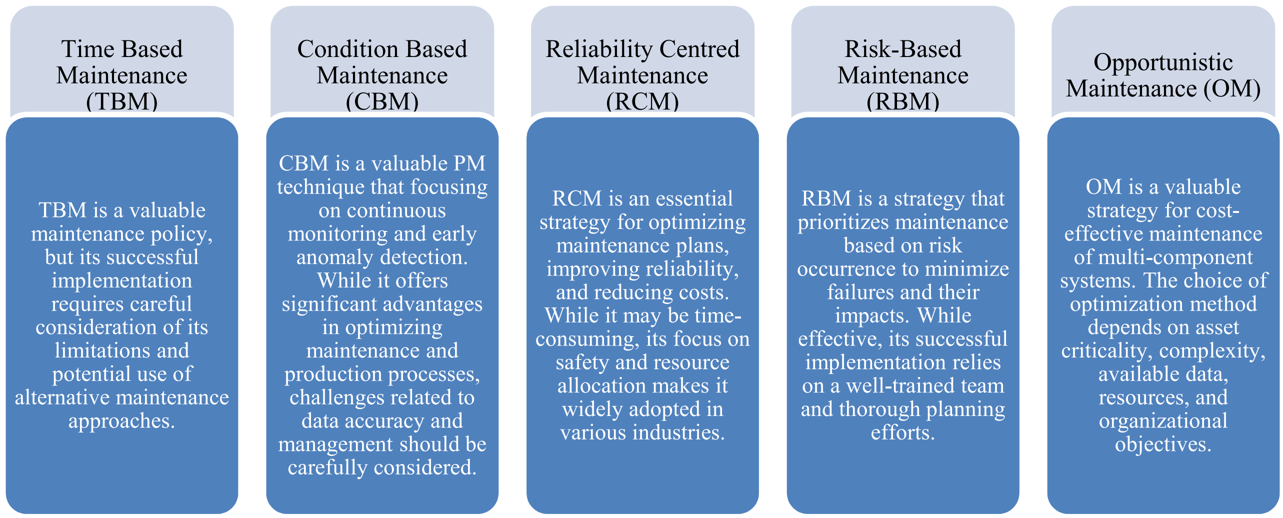

Fig. 1. Preventive maintenance optimization methods.

sustainability aspects and trends in maintenance approaches as criteria for evaluating the performance of these strategies.

4.1.1. *Extract maintenance aspects within the framework of sustainability through maintenance policy trends*

4.1.1.1. Maintenance as a sustainable alternative (environmental aspect). Environmental challenges have indeed become a major concern for engineers. In some cases, maintenance activities can increase waste and environmental burden. For example, the use of flaring as a method of waste disposal in the oil and gas industry (an example of high-risk process industries) can generate significant substantial emissions if a treatment unit malfunctions (Bouabid et al., 2022).

Certainly, selecting the appropriate maintenance strategy can effectively reduce the environmental impact of failures in various entities such as factories, machines, and processes. Conversely, inadequate maintenance practices can lead to environmental releases and energy-related consequences that generate risks to individuals, property, and the environment. The emission of pollutants from malfunctioning equipment, such as filters in a poorly maintained cement plant, exemplifies a substantial environmental hazard and underscores the importance of proper maintenance in preventing such occurrences. A typical example is the Bhopal disaster in India (1984), a cloud of highly toxic gas (40 tons of methyl isocyanate) escaped from a pesticide production process belonging to the American Multinational Group Union Carbide. It caused the death of 16,000 to 30,000 people and 500,000 others were injured. A detailed inspection of this accident reveals major deficiencies in the process safety systems. As the facilities becomes unprofitable due to the poor sales of its products, the Indian subsidiary UCIL decides to reduce operating costs and the budget allocated to maintenance. To this end, a catastrophic accident due to the failure of the MIC cooling unit occurred with serious consequences: gas leakage and environmental contamination continue to seriously affect the basic human rights of the surrounding population (Eckerman, 2019).

In this context, it is crucial to consider technologies that can effectively reduce pollution (water, soil, and air) and enhance product efficiency. Consequently, when performing maintenance, it is recommended to carefully weigh the trade-offs between investments and their environmental impact (Ishizaka and Labib, 2014). The effective maintenance in response to environmental risks highlights the close relationship between maintenance and sustainability. In fact, the environmental compliance makes it possible to ensure that costs are controlled and worker safety (both workers and the public) is promoted.

As a result, various aspects of sustainability (environmental, cost, and social) can be achieved. Going forward, maintenance has the potential to emerge a viable alternative for promoting sustainability, rather than relying on new technologies and environmental mitigation strategies. These principles are aligned with the concept of the circular economy (CE), which seeks to shift away from the linear economy model by minimizing resource waste and reducing environmental impacts (Franciosi et al., 2020). In line with this perspective, it is important that products including machines and systems comply with performance, safety and especially environmental standards with a view to green maintenance so occurs (Ajukumar and Gandhi, 2013). In this context, Orosz et al. (2018) used the P-graph tool as an extension of basic process design to measure productivity, reliability, and sustainability in process design simultaneously. It should be noted that poor planning can lead to permanent losses during the operation and maintenance phase. It is therefore important to incorporate sustainability considerations into production design to minimize such losses and ensure long-term efficiency.

The authors (Ndhaief et al., 2020) examine examples of joint operations and maintenance programs that incorporate carbon emission limits. The conventional bridge management systems generally prioritize cost and safety when considering sustainability considerations. To overcome this gap, the authors (Xu and Guo, 2022) propose a CBM approach, which aims to reduce total carbon emissions in bridge networks under a limited maintenance budget. This approach utilizes two-stage Markov chain to predict that the bridge degradation processes. Q-learning algorithms are used to identify maintenance strategies for individual bridges, while integer programming is used to optimize budget allocations in the network Integration of carbon emission constraints into maintenance plans. This approach requires providing sustainable improvement in the management of bridges.

A case study (New York State concrete bridges) validates the proposed method by showing the effects of budget levels on maintenance facilities (a 10% decrease in budget level) and total carbon emissions (low 39 tonnes of additional annual carbon emissions). This highlights the importance of maintenance systems that consider investments in new environmental technologies can effectively mitigate environmental impacts and contribute to sustainability goals.

4.1.1.2. Maintenance as a modelling tool for accidents (social aspect). It is essential to emphasize that this study focuses specifically on the aspect of employee safety and accident prevention. This focus arises from the specific context of the process industry. However, it should be noted that there are other sub-criteria that have been studied by other researchers in similar contexts. working condition (Martín et al., 2021; Wang et al., 2020), **such** as labour comfort and workload and labour productivity (Kannan and Arunachalam, 2019; Wang et al., 2020). condition of products received by customers (Barata et al., 2020), and product utilization through the accessibility of complete life cycle information (Kannan and Arunachalam, 2019). And land use for residue disposal is considered by Llamas et al. (2020) as a criterion related to the community, because it can have a negative impact on social well-being. But the employee safety is the most considered criterion of the social dimension (Franciosi et al., 2022).

To perform root cause analysis of incidents and near-miss events can play an important role in finding strategies to improve the maintenance facilities. Indeed, it leads us to identify the cause of faults causes for controlling them by PM interventions. Thus, the analysis of theses events can have a positive impact on process safety, especially in terms of the effectiveness of critical equipment maintenance. This relation has been observed by researchers such as (Rathnayaka et al., 2011; Gnoni and Saleh, 2017), who have highlighted the relationship between near-miss management systems (NMS), risk reduction, and maintenance practices aimed at accident prevention.

Similarly, Okoh and Haugen (2014) found that in 2000–2011; 46% of the 183 major maintenance-related accidents in the United States and Europe (including fires, explosions, and hazardous substance emissions) in chemical and petrochemical facilities involved maintenance issues. The results reveal that maintenance is linked to 80 major accidents (44%), with a downward trend. The most frequent causes, in terms of active accidental process, are the lack of barrier maintenance (50%). Regarding the latent accidental process, the predominant cause is poor design, organization, and resource management (85%). Finally, in terms of work processes, the main cause is poor planning/scheduling/fault diagnosis (69%). These findings highlight the critical role of maintenance to improve safety and prevention of maintenance-related accidents in this industrial sector.

The catastrophic accident at the Skikda gas liquefaction facility (Sonatrach, Algeria) on September 1, 2004, is a terrible example of what can be caused by mechanical leaks caused by corrosion. This incident resulted in significant human casualties, with 27 fatalities and 74 injuries, and significant materials losses estimated at more than $2 billion (Chettouh et al., 2016). Aging equipment has been identified as a contributing factor (Belmazouzi et al., 2020), and incidental investigations revealed that unmaintained equipment, especially in the furnace, was a major cause of the explosion. This highlights the important impact of maintenance control on the process safety.

The selection of appropriate maintenance strategies is crucial in reducing risks to people, property and the environment. Moreover, the adoption of these policies based on key indicators of system failure proves more cost-effective than learning from accidents (Bugalia et al., 2021). Near-miss reporting plays an important role in improving safety practices in systems aimed at achieving high levels of safety. In this context, a balance between safety, productivity and maintenance is required, recognizing that the formation of such compromise is critical to overall operational success. Indeed, it is important to recognize that near misses resulting from process deviations can potentially lead to accidents (Chen et al., 2020; Winkler et al., 2019). Consequently, monitoring and controlling these deviations through appropriate maintenance policies is a critical concern for engineers and scientists. Therefore, maintenance serves a dual purpose regarding safety, as it can help prevent potential severe accidents, but it can be a contributing factor to serious accidents. This recognition positions maintenance as a tool of risk management. The impact of maintenance on process safety is significant. Consequently, a clear correlation between maintenance and safety has been established. Over time, maintenance has become a tool that not only ensures safety, but also performs an important role in ensuring sustainability. The maintenance contributes to the overall sustainability of systems and processes by successfully managing societal elements primarily, while simultaneously taking economic and environmental considerations into account.

4.1.1.3. Maintenance optimization models as cost control tools. In sections 2 and 3 of this study, various maintenance methods have been presented. Among these models, the CBM model stands out as the most accurate due to its ability to capture real-time data reflecting the actual state of equipment. This method has garnered significant interest from researchers, leading to the development of several case studies focused on optimizing this maintenance model. The aim of these studies is to effectively manage maintenance activities, thereby addressing cost-related aspects as well as environmental and societal considerations.

In this section, the study discusses selected issues and optimization tools in the design of the CBM maintenance strategy. This example highlights the practical application and effectiveness of CBM model in achieving maintenance objectives while considering various aspects of sustainability. In fact, it was found that optimization of maintenance strategies especially to use CBM techniques have become a valuable tool for high-risk process industries to manage maintenance costs. Different models have been developed for efficient cost control and maintenance scheduling, such as mixed integer linear programming (MILP) and mixed integer nonlinear programming (MINLP) models. These models aim at the maintenance planning and scheduling complexity successful. In addition, graph theory tools have been used to visualize network design, enabling decision makers to determine optimal and near-optimal solutions. Several studies have focused on the use of these methods. For example, the use of P-Graphs in failure analysis of process systems, the authors (Orosz and Friedler, 2019; Kovacs et al., 2019) carried out a reliability analysis on process systems, while Orosz et al. (2018) investigated the interaction between reliability and sustainability analysis. These assessments contribute to improvements in the efficiency of maintenance policies and procedures, and provide maintenance managers with valuable insights into effectively managing maintenance costs and ensuring their overall sustainability of their operations.

The mathematical model of maintenance planning requires mathematical and programming knowledge for its interpretation, and for this purpose, the Pinch method (a graphical approach based on the thermodynamic background) was used to facilitate the problem formulation and visualization of the results (Klemes et al., 2018). And for maintenance project scheduling, the authors (Chin et al., 2019) proposed a systematic framework that provides easily understandable tools aims to improve the effectiveness and efficiency of maintenance operations, contributing to overall maintenance performance. By carefully managing maintenance aspects, such as optimizing maintenance strategies to control costs, considering environmental and social aspects, a close relation between can be identified between maintenance and sustainability. This highlights the importance of integrating sustainability considerations into maintenance practices as it allows aligning maintenance activities with broader sustainability goals.

4.1.2. Discussion of relationship between maintenance aspects in the context of sustainability

The authors (Karki and Porras, 2021), it is observed that 41% of the research studies conducted from 2000 to 2021 have focused on examining the correlation between maintenance management and sustainability. Indeed, the maintenance serves as a valuable instrument in promoting sustainability by mitigating adverse ompacts and incorporating sustainability considerations to ensure the availability, quality and performance within the confines of available resources. Consequently, scientists and managers leaders have introduced the concept of sustainable maintenance, which aims to ensure regulatory compliance while concurrently minimizing industrial impacts on the economy, society, and the environment. These three criteria are interconnected as depicted in Fig. 2, which is further elucidated in this section.

Inappropriate maintenance practices have significant economic implications, predominantly in terms of costs, downtime, and failures, which ultimately impact the overall performance of high-risk process industries (Zonta et al., 2020). Conversely, implementing efficient and effective maintenance strategies can enhance the condition of

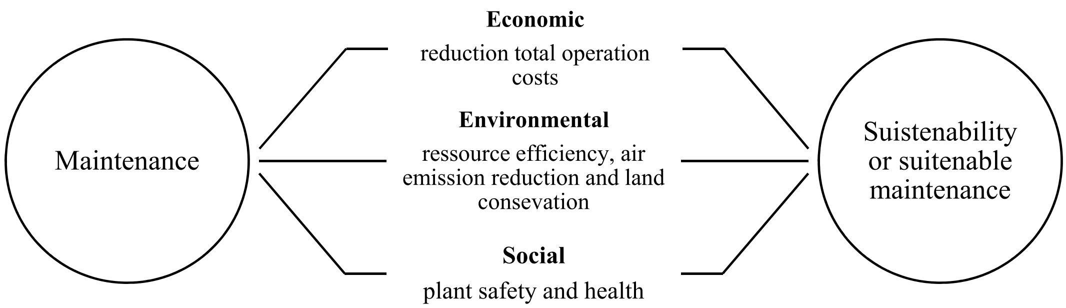

Fig. 2. Suitenable maintenance concept model (Karki and Porras, 2021).

equipment by reducing failure rates and, in turn, minimize operational costs associated with CM and PM expenses, both direct and indirect. Embracing sustainable maintenance practices offers economic benefits by promoting compliance, avoiding unnecessary maintenance activities, and reducing costs linked to penalties, downtime, and failures, thereby enhancing operational efficiency.

Inadequate maintenance pratices is associated with a variety of environmental consequences, such as emissions of hazardous gases, energy inefficiencies, and resource overuse (Xia et al., 2018; Franciosi et al., 2020; Vrignat et al., 2022). In this context, sustainable maintenance practices bring many benefits, such as the ability to reduce emissions, improve air quality, improve waste management, extend asset life and reduce energy costs. Additionally, inappropriate maintenance practices can have social consequences, leading to unsafe working conditions, accidents, and incidents that pose risks to individuals, property and the environment, and as a result to damage the reputation of high-risk process industries (Lovrencic et al., 2017; Franciosi et al., 2019). Embracing sustainable maintenance approaches brings significant social benefits by prioritizing the health and safety of employees and reducing the environmental footprint of the high-risk process industries.

Understanding the interdependence of cost, environmental and social factors is essential to increasing maintenance performance. The literature review in this section suggests that future improvements in maintenance optimization aim to improve these three aspects. These aspects serve as criteria for evaluating the performance and effectiveness of maintenance policies. Optimizing maintenance involves enhancing at least one of these aspects, thereby contributing to the optimization of sustainability. The description of the maintenance development trends highlights the proportional relation between maintenance and sustainability. In fact, improving maintenance practices also improves sustainability, and vice versa.

In this context, the role of high-risk process industries managers is essential to meet the metrics required to effectively implement sustainable maintenance the analysis of these metrics has become a decision support tool the importance of ensuring the long-term sustainability of this facilities. Therefore, optimizing the "Cost-environmental-social" triangle is a key strategy for effective performance management in high-risk process industries. This performance-oriented approach aims to maximize the synergy and interdependence of these aspects, and to create a balance between them, in order to maintain the sustainability. Furthermore, these aspects are evaluated using various criteria that are appropriate to each dimension. Fig. 3 presents the main criteria for quantifying the aforementioned aspects of sustainable maintenance.

Similarly, the authors (Sari et al., 2021) develop a framework for Sustainable Cleaner Maintenance Performance Measurement

Table 1
Coefficient of determination value (Sari et al., 2021).

Endogenous Latent Variable	R Square
Cost-Effectiveness	0.8604
Employee Satisfaction	0.6364
Health and Safety	**0.8238**
Learning and Growth	0.7409
Pollution and Waste	**0.8403**
Productivity	0.8528
Quality	0.8059
Resource Efficiency	0.8595
Stakeholder Satisfaction	0.5391
SCMP	0.9998

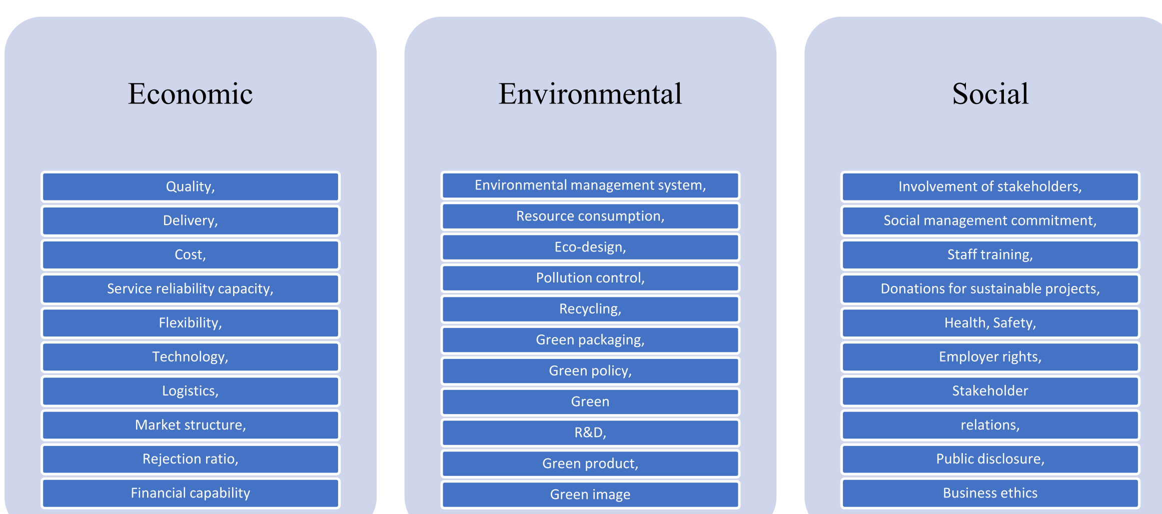

Fig. 3. Widely used criteria in sustainable supplier selection and performance evaluation (Tong et al., 2019; Liu et al., 2019; Zhou et al., 2011; Memari et al., 2019).

Framework (SCMPMF) balanced, integrated and hierarchical. This model consists of new (09) perspectives (see Table 1) associated to 71 indicators. The developed model can assist decision makers in extracting important factors, relevant perspectives, and indicators to measure the SCM's contribution to alignment with corporate objectives.

SCMP have the highest coefficient of determination values for its three factors: economic, environmental and social (Table 1). This study focused on the development of a SCMPMF that identifies the direct relationship between indicators and explores the cause-effect relationships among them. However, it should be noted that the study did not determine the relative weight or importance of each indicator. Thus, it does not provide a definitive ranking of critical indicators for achieving the objectives of the high-risk process industries. Therefore, a fuzzy multi-criteria approach has been developed by (Amrina et al., 2020) to estimate sustainable maintenance performance based on two processes in the cement industry. In the first step, fuzzy multi-criteria method is used to ensure evaluate sustainable maintenance performance and the Key performance indicators (KPIs) were identified and classified into three categories: economic, social, and environmental. In the second step, the relationships between these indicators were modeled using the Interpretive Structural Modeling (ISM) method. This helped to understand the interactions and hierarchy among the indicators. The results of this modeling process are presented in Table 2, which provides insight into the relationship and importance of the identified KPIs.

The results show that occupational health and safety is the most important indicator, followed by the working environment, lighting, and ventilation. The proposed model is part of an ongoing effort to improve the performance of sustainable maintenance.

Similarly, the petrochemical industries as an example of high-risk process industries, it is important to issue appropriate standards and procedures should be used to evaluate the performance of maintenance work and high-risk operations operating in hazardous areas (Tong et al., 2020). The authors propose a number of criteria for evaluating the performance of maintenance providers. To evaluate and classify the providers, the PROMETHEE II method is used, which is considered to be the most accurate and practical method for solving multi-criteria performance evaluation problems in a fuzzy environment. By using this method, the authors aim to effectively assess and rank maintenance providers based on their performance in the identified criteria.

The findings obtained from the proposed evaluation method play an important role in the development of long-term strategic alliance between petrochemical high-risk process industries and suppliers of high-quality maintenance services. This alliance aims to enhance the safety and sustainability of the entire supply chain. Two aspects can be highlighted about future perspectives in this study. FirstLY, there is potential to generalizing the application of this research methodology in other areas to measure and enhance maintenance performance even in those areas. Second, Secondly, the study acknowledges that subjective expert judgments and decision-makers' judgments influenced by the fuzzy PROMETHEE II method are areas that require further investigation. Addressing these issues is important to ensure the accuracy and reliability of the assessment process. Thus, future research efforts should focus on ways to refine the method and reduce conceptual bias to increase the objectivity of the research method.

Table 2
The importance weight of KPIs (Amrina et al., 2020).

Aspects	Indicators	Importance weight	
		Calculated	Normalized
Economic	Maintenance cost	0.083	0.047
	Availability rate	0.072	0.041
	Product quality	0.078	0.045
	Failure rate	0.056	0.032
	Ease of maintenance	0.054	0.031
	Technology applied	0.054	0.031
	Breakdowne rate	0.044	0.025
Social	Working environnment	0.0348	0.199
	Occupational health and safety	0.409	0.234
	Employee involvement	0.050	0.029
	Lighting and ventilation	0.242	0.138
	Training and education	0.070	0.040
Environmental	Emission	0.098	0.056
	Energy consumption	0.087	0.050
	Material consumption	0.063	0.036
	Water usage	0.037	0.021

Furthermore, the authors (Sarbini et al., 2021) conducted a study to explore the practical issues related to building maintenance practices in Malaysia. The following maintenance issues have been identified: planning and management, personnel and management skills, and technical skills. In addition, the study provides recommendations and best practices from the literature for future maintenance strategy development aligned with ISO 41001 guidelines. Finally, a conceptual framework for best practices in building maintenance is proposed. However, this study ignores the principles of sustainability as a characteristic of any maintenance policy (focusing on the environmental dimension).

The authors Ghaleb and Taghipour (2022) highlighted the absence of a method for evaluating the impacts of maintenance on sustainability by considering environmental and socio-economic factors. To address this gap, a multi-criteria decision support method was proposed, called the best-case method. Their methodology involves developing a sustainability dashboard (for sustainability score calculator). This dashboard consists of maintenance indicators related to sustainability, and the data processing techniques used by the Best Worst Method (BWM).

The proposed methodology was validated through case studies, and the results demonstrated its potential as a valuable tool for practitioners and researchers in understanding the impacts of maintenance practices on the Overall Sustainability Score (OSS) of assets. The maintenance techniques are critical in numerous process industries in pursuit of sustainable development.

In summary, well-planned and executed maintenance practices contribute significantly to achieving sustainability goals in high-risk manufacturing industries, by integrating economic, environmental and social aspects into overall operations management. Below you will find a summary Table 3 of the studies that has been carried out by researchers studying one or more aspects (two or three aspects simultaneously) to evaluate maintenance performance in the context of sustainability.

The results analysis confirms that maintenance is a valuable tool for promoting sustainability goals, especially if high-risk process industries are designed in the greater importance of long-term assets. In this case, maintenance played an important role in preventing damage and ensuring the sustainability of the facilities. From the aspects of cost, environment and safety, maintenance contributes to achieving sustainability goals. Equipment life cycles and the need for effective maintenance programs are particularly important in the design of high-risk process industries. This finding highlights the concept of sustainable maintenance, discussed earlier in this literature review.

This section focuses on the modeling of the relation between maintenance and sustainability; in particular by identifying the aspects of sustainability in maintenance optimization models, the second research question posed in Section 2 is addressed in the next section.

4.2. Discussions of the challenges and future prospects of sustenaible maintenance

The industry has ushered in the Fourth Industrial Revolution (Industry 4.0), characterized by global markets and intense competition. To align with this evolution, industrial players are adopting new innovations and maintenance policies, relying on digitization, a data-driven approach, and servitization. Consequently, the implementation of these sustainable maintenance models requires organizational revision at various levels to adapt to this transformation.

The digitalization of maintenance services undoubtedly impacts

Table 3
Maintenance aspects addressed within the framework of sustainability in the process industry context.

Authors	Aspects			Methodology
	Economic	Environmental	Social	
•Ahmed et al., 2023		X		A mixed integer nonlinear programming (MINLP) model was developed to study the relationship between production duration, energy consumption, maintenance actions and carbon footprint. Therefore, the level of service and sustainability measures has to integrate maintenance planning and production from an ecological perspective (reducing the carbon footprint).
Sari et al. (2014) Sari et al. (2015)		X		some measures for automotive companies for assessing the direct environmental impact of maintenance are proposed by the authors, they considered maintenance measures for the three dimensions of sustainability, and with different levels of aggregation.
(Hoang et al., 2015, 2016)		X		The authors identified specific environmental indicators (energy efficiency and energy consumption) and emphasized the need to consider these indicators in the maintenance decision-making process.
Amrina and Aridharma (2016)		X		The authors proposed a set of sixteen indicators to measure sustainable maintenance performance for the cement industry.
Sénéchal and Trentesaux (2019)		X		Specific sustainability measures related to maintenance actions were taken into consideration by a decision-making framework based on the assessment of the impact of cyber-physical systems on the environment (energy and pollutant consumption).
Kunic et al. (2021)		X		It seems like there might be a partial mention or reference to a research study by the authors involving the use of Digital Twins (DT) in the control and optimization of a process, contributing to the creation of a carbon-efficient structure
Barata et al. (2020)		X		The authors introduced the concept of “product biographies.” This approach falls under product lifecycle management and is supported by digital twins (DT). These allow companies to guarantee the certified origin of wood, as well as the adoption of good forest management practices.
Kannan and Arunachalam (2019)		X		It is mentioned that Kannan and Arunachalam (2019) demonstrated the potential of digital twins (DT) to reduce carbon emissions and waste generation
Do et al. (2018)		**X**		A condition-based maintenance model was presented to make maintenance decisions in which the energy efficiency indicator represents the state of health of the system.
Yamano et al. (2021)	**X**			A methodology that was proposed by the authors to solve simultaneously, the optimal operation plan of combined cooling, heat and power (CCHP) systems, and the optimal maintenance plan of gas engines. This methodology makes it possible to reduce the annual operating cost
Chen et al. (2018)	**X**			The article explores the innovation of equipment maintenance business model. And the study introduces a scale aimed at quantifying the level of innovation within equipment maintenance business models, providing a structured approach for evaluation and analysis.
Martín et al. (2020)	**X**			The objective of this study is focused on the implementation aspects of new equipment maintenance business models based on digitalization and

(continued on next page)

Table 3 (*continued*)

Authors	Aspects			Methodology
	Economic	Environmental	Social	
				data-driven approaches. Additionally, the study explores stakeholder integration and alignment with Sustainable Development Goals in the context of these innovative business models.
Ighravwe and Oke (2017)	X			The paper proposes a framework designed for the selection of an optimal maintenance strategy in manufacturing systems based on the principle of fuzzy axiomatic design and fuzzy TOPSIS. It integrates the ranking of sustainability factors and the optimization of maintenance consumables.
Jantunen, et al. (2010)	X			The article provides a comprehensive overview of e-Maintenance, highlighting the benefits and challenges that persist in facilitating the full lifecycle of a product through e-Maintenance. The focus is on assessing the scale of transformation and exploring the financial implications associated with adopting Emaintenance practices.
Simões, et al. (2011)	X			This study highlighted key themes related to the evolution of maintenance performance management (efficient use of maintenance resources, support of information systems, and management of human factors). A conceptual framework was proposed in order to trace the different operational and organizational facets linked to the evolution of maintenance performance management.
Shang et al. (2022)	X			The duty cycle was integrated into traditional maintenance policies, and random replacement modeling by user age first and last was carried out to maintain product reliability. And based on the analysis of the parameter values, classic models have been proposed.
Beloglazov et al. (2020)			X	The authors observe that the skills acquired by staff following training using computer simulations and digital twins based on Industry 4.0 technologies allow operators to optimally master the procedures necessary to deal with emergency situations in the minerals industry. This study is part of the overall context of improving security, highlighting the positive impact of the use of advanced technologies to strengthen staff skills and strengthen preparation for emergency scenarios in this sector specific industrial.
Martín et al. (2021)	X			A new maintenance business model has been proposed for equipment exploiting digitalization opportunities, including relationships with internal and external stakeholders. Different perspectives such as organization, innovation, potentially gained social value and sustainability were adopted to discuss the implications of the proposal.
Kaewunruen and Lian (2019)			X	Railway switches (crossings), crucial for changing the direction of trains, require high-quality construction and maintenance to minimize rapid degradation and component failure, which can lead to train derailments. From this perspective, maintenance efficiency and effectiveness can be significantly improved by integrating existing practices through Building Information Modeling (BIM) level 3 for life cycle management of a

(*continued on next page*)

Table 3 (*continued*)

Authors	Aspects			Methodology
	Economic	Environmental	Social	
				railway turnout system.
Lindström et al. (2020)			X	the authors propose a zero-defect manufacturing model (ZDM) using a cost function in which the operation and state of a production process are reflected, and the quality of the output/product and the production process (thus as security aspects) can be considered. through this approach, production processes in the processing industry can be made more intelligent and interoperable. and consequently, improving the sustainability, competitiveness, efficiency and profitability of businesses.
Fu et al. (2023)			X	Identifying and reducing hidden hazards (HD) is of crucial importance to reduce the frequency of accidents during bridge maintenance. With this in mind, a risk prediction model based on the Bayesian network is developed. This model aims to identify hidden hazards that have a significant impact on the risk levels associated with bridge construction. This approach makes it possible to better target safety measures and improve risk management in the context of bridge maintenance operations.
Zaranezhad et al. (2019)			X	This study presents an accident causality model (early prediction model) for the repair and maintenance of accidents related to accidents during the performance of maintenance activities in oil refineries. The proposed model is based on the integration of artificial neural networks, fuzzy systems and metaheuristic algorithms. And as results, the authors show that the neuronal-GA hybrid was the best prediction model.
Okoh and Haugen (2014)			X	The results reveal that maintenance is linked to 80 major accidents (44%), with a downward trend. These results highlight critical aspects that can be targeted to improve safety and prevention of maintenance-related accidents.
Okoh et al. (2014)			X	The authors rely on the study of the impact of maintenance on the occurrence of major accidents using model-based and empirical approaches. These approaches are applied to accident investigation and analysis reports. The authors proposed a classification system for work processes and major maintenance accidents (WAP).
Vinnem et al. (2016)			X	Maintenance of process components on offshore and onshore oil installations is crucial to preventing major accidents. The study focuses on corrective and preventive maintenance of equipment, particularly in relation to the experience of hydrocarbon leaks. The objective is to optimize the preventive maintenance program for this equipment.
Lee et al. (2023)	X	X		An erosion model was developed to measure time-varying effectiveness that can help select maintenance strategies to optimize environmental and economic performance.
Liu et al. (2022)	X	X		Based on the Decision Tree method, an optimal maintenance strategy for the life cycle of bridges under climate change was proposed by the authors in order to minimize environmental impacts, environmental cost,

(*continued on next page*)

Table 3 (*continued*)

Authors	Aspects			Methodology
	Economic	Environmental	Social	
				economic cost and overall cost.
Guan et al. (2022)	X	X		The authors propose a multi-objective optimization framework integrating interactions between pavement condition and traffic dynamics to identify a wide range of optimal solutions for multi-year maintenance planning of the road network. This model helps minimize agency costs, user costs and environmental impacts
Johansson et al. (2019)	X	X		Proposal of a framework that presents the required capabilities and their link to implement maintenance, and to identify the results of the transition to digital maintenance (eMaintenance). Indeed, researchers, particularly in industry 4.0, have begun to examine eMaintenanc in more depth for greater performance in terms of cost reduction in a first link and in terms of the environment in a second link.
Iung and Levrat (2014)	X	X		This article aims to explore the role of maintenance as a contributor to the development of paradigms such as industrial ecology and the circular economy. The article thus explores how maintenance can evolve to align with sustainable objectives and actively participate in the creation of more responsible industrial ecosystems.
Jain, et al. (2014)	X		X	This study aims to identify the most effective strategy for enhancing the competitiveness of small and medium-sized enterprises (SMEs) in the globalized market. It specifically evaluates the implementation practices of Total Productive Maintenance (TPM) in SMEs. Notably, Safety, Health, and Environment constitute one of the eight pillars of TPM. This involves the implementation of measures, such as the use of protective gear or adherence to work standards, to enhance the safety of machine usage.
Mangano and De Marco. (2014)	X		X	The study highlights the importance of the maintenance and the facilities management for logistics operations and operational performance of warehouses. This finding is in line with the trend of investments aimed at maintaining the condition of warehouse construction and service components, thus highlighting their crucial importance in preserving the efficiency and smooth running of logistics operations.

sustainability in various aspects, but precisely understanding this impact is a challenge requiring in-depth research. In fact, this digitalization faces several constraints and challenges, such as the difficulty of creating values that shift technological attention towards strategic thinking. Additionally, limited operational budgets result in operational gaps and technology limitations, thereby leading to constrained digital capabilities, including limited remote monitoring and inability to optimize big data (Karki and Porras, 2021; Franciosi et al., 2022). The potential benefits of digitizing maintenance are significant, but success depends on proactively managing these constraints.

Despite the importance of PM and the increasing implementation of Industry 4.0 technologies, the authors (Giada and Rossella, 2021) mentioned that a limited number of Italian machinery companies today include PM systems in their products. A study was carried out to determine the barriers to consider when implementing a PM and to propose a set of possible countermeasures. And the results show a list of obstacles such as: complexity of big data management, security and privacy issues, low level of technology maturity, lack of technical skills and data literacy, high investments and lack of understanding economic benefits, ineffective internal change management and employee management and resistance to change.

as noted by Karuppiah et al. (2021), there are challenges/barriers to the implementation of Sustainable Predictive Maintenance (SPM). These barriers, depicted in Fig. 4, were identified through a literature survey and expert interactions (Rauch et al., 2019; Obiso et al., 2019; Singh et al., 2016; Emovon et al., 2018; Ajmera and Jain, 2019; Jeswani et al., 2021; Aberilla et al., 2020; Scope et al., 2020).

According to the authors, (Karuppiah et al., 2021). Based on the problem that inefficient maintenance has a significant impact on cost, environment, and social, and thus affects the high-risk process industries sustainability, the purpose of this study is to identify and evaluate the barriers to PSM practices in the Indian context. And for this, the two methods an integrated Interpretive Structural Modeling (ISM) and

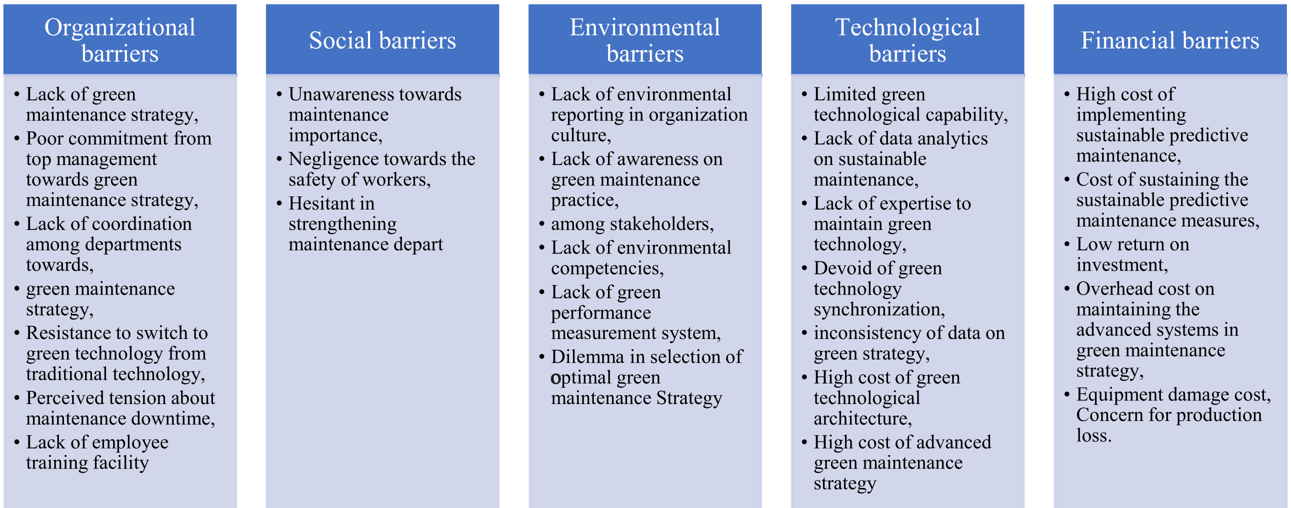

Fig. 4. Barriers to sustainable predictive maintenance (Karuppiah et al., 2021).

Grey-Decision-making trial and evaluation laboratory (DEMATEL) have been used to treat the barriers identified by the review realized for modeling and prioritizing the relationship between the barriers of SPM practices. Finally, a sensitivity analysis was performed to examine the robustness of the result. In addition, the result reveals that among the barriers (of SPM practices) evaluated by this study which are classified in five dimensions of sustainability (organizational, financial, environmental, social, and techno-logical), three most critical barriers have been identified: two technical category barriers: (OB1), poor commitment from top management towards green maintenance strategy and, (TB1), devoid of green technology synchronization. And an organizational category barrier: (TB2) lack of monitoring the green maintenance practices. Understanding the barriers to implementing SPM methods in a manufacturing environment is the study's contribution. Among the limitations of this study that it was carried out in the Indian context, and the method of analysis was carried out using the structural equation modeling (SEM) technique which is primarily confirmatory rather than exploratory.

However, the most important challenge to achieving the synergy between these two concepts (sustainabe and predictive maintenance) is to effectively manage large amounts of data, information and knowledge. In fact, this section illustrates the tremendous progress in the use of intelligent tools to manage the flow of data, information, and knowledge during maintenance practices, ultimately leading to more effective and sustainable maintenance strategies. In this context, Artificial intelligence (AI) approaches such as.

- The Self-Organizing Map (SOM) technique that has been applied to adaptive risk prediction, using quantitative and/or qualitative data to develop maintenance plans (Jaderi et al., 2019). The limitations of this approach are the large amount of historical data used to obtain reliable results on the one hand, and the difficulties of separating the signal from the noise on the other hand. For this end, principal component analysis (PCA) is a promising tool to reduce the dimensionality of the criteria used while largely preserving the accuracy of the information. In addition, the factor weighting priorities used in dynamic risk analysis to aid risk-based decision making in maintenance via AHP/ANP need to be updated dynamically (Bhandari et al., 2016).
- Furthermore, (Daniyan et al., 2020) highlights the importance of integrating AI for predictive maintenance into railway vehicle (railcar) learning factories. This requires training maintenance personnel to continuously monitor and analyze data from the Internet of Things (IoT) and other sources to predict bearing conditions and potential failures.

Among the three approaches discussed in this section, it is important to highlight the role of Industry 4.0 (I4.0) and the aspects of intelligent systems, machine learning (ML), and artificial intelligence developed (AI) methods help to optimiz these three aspects. These advanced technologies and approaches, especially in PM, are widely accepted to better monitor the health of industrial assets and overcome the environmental, cost and social aspects of maintenance. By exploiting the capabilities of I4.0 and AI, maintenance management can better manage the flow of data (acquisition and processing) and the PM can make better decisions on the issue, increasing overall productivity and sustainability.

The use of approaches such as Prognostics and Health Management (PHM) is consistent with the overall objective of achieving maintenance efficiency in I4.0. The PHM represents a higher level of discipline compared to CBM and includes the study of failure mechanisms such as fatigue, wear, and other related processes affecting asset life cycle performance. Its role involves acquisition and processing databases of varying sizes. By integrating sustainable manufacturing principles and maintenance policies, PHM contributes to the advancement of maintenance practices and supports the overarching goals of sustainability. This observation is supported by the findings of a literature review in this section, among the industrial development challenges is to use technology and knowledge bases to predict, diagnose and initiate maintenance (Kumar and Galar, 2018; Zhang and Hu, 2013).

By combining big data analytics with cloud computing, organizations can better manage the complexity of data flows in maintenance operations by harnessing the power of advanced data processing algorithms and distributed computing capabilities. These techniques enable better data collection, pre-processing, analysis, visualization of data, and supporting decision-making processes and enabling proactive maintenance strategies. And to conclude, this research has been analyzed.

- A monitoring approach based on an adaptive neuro-fuzzy inference system (ANFIS) combined with the Fuzzy C-means (FCM) algorithm has been developed by (Daher et al., 2020), and the results shows that the proposed methodology can accurately determine a remaining useful life (RUL), and the identified indicators used to develop appropriate maintenance programs. For more details on the RUL calculation model see (Okoh et al., 2014).
- The Internet of Things (IoT) has been adopted to manage data flows from sensor networks in order to optimize maintenance. Because

these data related to system state can be historical or real-time (not homogeneous), a more detailed analysis was performed to determine the appropriate data and formal information on the system's state. The authors (Bayoumi and McCaslin, 2017) developed a global methodology adapted to several industries in this framework study. General Machinery, Petroleum and Petrochemicals, and Water Treatment. As well as the study carried out by Elhdad et al. (2013) introduce a methodology based on ontology to enhance maintenance decisions. Effectively, these decisions are based on data gathered during a monitoring process designed to observe the failure behavior of the equipment. Furthermore, the Internet of Things (IoT) technique, in conjunction with Big Data analysis and asset life-cycle planning, has been used as a tool to identify various asset maintenance activities (repair, upgrade, replacement, etc.) and to make the appropriate decision at the right time. The authors (Rojek et al., 2020) present the results of their research on the development of digital twins of technical objects. This process encompasses the acquisition of data and its transformation into knowledge, the use of physical models to simulate tasks and processes, and the exploitation of simulation models to optimize physical tasks and processes. Furthermore, the monitoring of processes and parameters allows continuous improvement of existing processes in the field of intelligent eco-design, planning and monitoring of production processes.

- The current PM trend relies on the creation of a "digital twin" based on asset models (Magargle et al., 2017) used to diagnose anomalies that affect performance and then, the combination of theses digital twins with big data analysis is intended to predict the remaining useful life (RUL) of your assets. These digital twins are progressively improved by recalibration from the operational data collected.
- Du (2018) discusses the application of virtual instrument technology in state monitoring of chemical plants, and provides technical support for energy system automation. ML (Artificial Neural Network (ANN), Support Vector Machine (SVM), Decision Tree (DT), Random Forest (RF) … etc.) offer advantages (reducing maintenance costs, improving operational safety, increased production, the increase in overall profit, etc.) and consequently, the maintenance optimization (Peres et al., 2018; Carvalho et al., 2019; Sezer et al., 2018). Machine learning (ML) techniques have emerged as promising tools for PdM applications for smart (intelligent) manufacturing in I4.0, and we recommend readers to refer to (Çınar et al., 2020) for more information on these techniques.

The examination of the literature review reveals a key finding related to the use of AI tools; big data analytics and cloud computing to enhance sustainable maintenance practices. It focuses on the development of an innovative approach that uses these techniques to process the data, information and knowledge, and; this new approach recognizes the interdependence of cost, environmental and safety aspects of sustainable maintenance. By considering these aspects holistically and using AI tools, big data analytics and cloud computing, organizations can work towards achieving a balance between cost efficiency, environmental impact reduction, and ensuring the safety of assets and personnel.

Overall, the adoption of AI in sustainable maintenance represents a significant advancement in the field, enabling organizations to use data-driven insights and knowledge management techniques to improve their maintenance practices are effective and promote sustainability. A new cognitive approach was therefore considered necessary to not only ensure predictive maintenance but also to actively promote a proactive maintenance approach.

This cognitive approach aims to harness the power of data and knowledge through the use of advanced technology and analytical techniques, ultimately improving maintenance practices and achieving sustainability objectives. The abundance of data and advancements in AI tools, big data analytics and cloud computing have paved the way for a new paradigm in maintenance that is data-driven, information-driven, and knowledge-driven.

By integrating AI tools and taking advantage of on the variety of data and information, the high-risk process industries could optimize maintenance actions, improve asset performance, and contribute to sustainable outcomes, leading to proactive maintenance strategies.

Applying the sustainable predictive maintenance strategy comes with its own set of challenges such as: data quality and availability, integration with existing systems, initial investment costs, complexity of technology, change management, cybersecurity issues, scalability issues, environmental monitoring and regulation, human factors, lack of standardization, unplanned equipment breakdowns and environmental impact assessment.

In order to meet these challenges, a holistic approach is necessary, involving collaboration between different actors of this policy and a commitment to continuous improvement at a high level of the organization. Indeed, overcoming these obstacles is crucial for organizations seeking to successfully implement sustainable predictive maintenance.

5. Conclusion

Sustainability stands as a paramount consideration for high-risk process industries, not merely as a management approach but as an indispensable mandate. It is, in essence, a social responsibility intrinsic to these industries. This imperative demands the integration of sustainability principles across the entire asset lifecycle, encompassing equipment, high-risk processes industries, and related functions. Of particular note is the emergence of the maintenance process as a promising instrument for establishing and assessing sustainability criteria that span economic, social, and environmental dimensions.

The principal objective of this article is to delve into the role of maintenance in advancing sustainability paradigms, a subject elaborated in Sections 4.1 and 4.2. The initial step to response of the first research question entails modelling the interplay between maintenance and sustainability, scrutinizing their intricate interactions. Section 4.1 furnishes an exhaustive analysis of diverse maintenance strategies, informing the delineation of future maintenance directions that espouse economic, social, and environmental considerations, thereby fostering sustainability. In essence, the findings derived from this comprehensive literature review underscore the robust correlation between maintenance and sustainability, with their objectives inherently intertwined. Ergo, the realization of maintenance objectives, spanning economic, social, and environmental dimensions, invariably culminates in the attainment of sustainability objectives.

Addressing the second research question, which challenges and future prospects can be discussed and analyzed regarding sustainable maintenance, this study conducts an exhaustive examination of pertinent studies. The objective is to analyze the profound influence of maintenance on sustainability. The culmination of this analysis underscores that the fulfilment of maintenance objectives bears profound implications for the attainment of sustainability objectives. In Section 4.2, an array of studies is discussed and evaluated, shedding light on the impact of maintenance in ensuring sustainability, and in light of these inquiries, the resounding need to unite these two concepts under the umbrella of "sustainable maintenance" becomes evident.

The core aim is to enhance the economic, environmental, and social performance of high-risk process industries. Thus, sustainable maintenance is driven by the elimination of superfluous practices, cost reduction, and the mitigation of social impacts of actions. It underscores a corporate responsibility to uphold these principles.

Furthermore, the implementation of sustainable maintenance practices in high-risk process industries emerges as a pivotal support element for sustainable manufacturing. Neglecting the integration of sustainability principles in maintenance can have adverse repercussions, spanning reduced production volume, compromised asset performance, diminished equipment availability, diminished final product quality, and potential repercussions on the health and safety of both workers and end-users. It also impacts the surrounding natural environment and social well-being (Savino et al., 2015; Franciosi et al., 2020).

The sustainable maintenance takes center stage in the development of high-process industries, and technology contributes significantly. Elements such as IoT sensors, AI-driven analytics, and cloud-based monitoring have transformed the way businesses approach maintenance. In fact, the technological advancements, particularly in the realm of artificial intelligence, have become indispensable for data management in operational systems. As demonstrated by studies discussed in this review, algorithms utilizing artificial intelligence have showcased their prowess in the context of asset management and maintenance, offering powerful knowledge models conducive to the optimization of sustainable maintenance, particularly for high-risk process industries.

As a limitation of our study, it should be noted that this literature review focuses exclusively on maintenance practices in the high-risk process industry. As a perspective, we propose a systematic review on the challenges associated with implementing smart and sustainable maintenance in the context of Industry 4.0 using artificial intelligence.

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CRediT authorship contribution statement

Djamel Abdelghani Bouabid: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Visualization, Writing – original draft, Writing – review & editing. **Hefaidh Hadef:** Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Fares Innal:** Conceptualization, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

Aberilla, J.M., Gallego-Schmid, A., Stamford, L., Azapagic, A., 2020. An integrated sustainability assessment of synergistic supply of energy and water in remote communities. Sustain. Prod. Consum. 22, 1–21.
Ahmad, R., Kamaruddin, S., 2012. An overview of time-based and condition-based maintenance in industrial application. Comput. Ind. Eng. 63 (1), 135–149.
Ahmed, A., Ahmad, O., Alatwi, A.-A., Omar, G., 2023. Joint maintenance planning and production scheduling optimization model for green environment. J. Qual. Mainten. Eng.
Ajmera, P., Jain, V., 2019. Modelling the barriers of Health 4.0-the fourth healthcare industrial revolution in India by TISM. Oper. Manag. Res. 12, 129–145.
Ajukumar, V.N., Gandhi, O.P., 2013. Evaluation of green maintenance initiatives in design and development ofmechanical systems using an integrated approach. J. Clean. Prod. 51, 34–46.
Amrina, E., Aridharma, D., 2016. Sustainable maintenance performance evaluation model for cement industry. In: Industrial Engineering and Engineering Management (IEEM), *2016 IEEE International Conference on.* IEEE, p. 350e354.
Amrina, E., Kamil, I., Aridharma, D., 2020. Fuzzy multi criteria approach for sustainable maintenance performance evaluation in cement industry. Procedia Manuf. 43, 674–681.
Andriy, A., Lobur, M., Iwaniec, M., 2022. Predictive maintenance – a major field for the application of computer aided systems. Komp`ûternì sistemi proektuvannâ. Teorìâ ì praktika.
Archit, P., Kane, Ashutosh, S., Kore, Advait, N., Khandale, Sarish, S., Nigade, Pranjali, Joshi, 2022. Predictive maintenance using machine learning. arXiv.org.
Arunraj, N.S., Maiti, J., 2007. Risk-based maintenance-Techniques and applications. J. Hazard Mater. 142 (3), 653–661.
Azadeh, A., Abdolhossein Zadeh, S., 2016. An integrated fuzzy analytic hierarchy process and fuzzy multiple-criteria decision-making simulation approach for maintenance policy selection. Simulation 92 (1), 3–18.
Barata, J., Pereira, V., Coelho, M., 2020. Product Biography information system: a lifecycle approach to digital twins. In: IEEE International Conference on Systems, Man, and Cybernetics (SMC). IEEE, pp. 899–904.
Bayoumi, A., McCaslin, R., 2017. Internet of things – a predictive maintenance tool for general machinery, petrochemicals andwater treatment. In: Bahei-El-Din, Y., Hassan, M. (Eds.), Advanced Technologies for Sustainable Systems. Springer International Publishing, Cham, pp. 137–146.
Belmazouzi, Y., Djebabra, M., Hadef, H., 2020. Contribution to the ageing control of onshore oil and gas fields. Petroleum 6 (3), 311–317.
Beloglazov, I.I., Petrov, P.A., Bazhin, V.Y., 2020. The concept of digital twins for tech operator training simulator design for mining and processing industry. Chem. Ind. 18, 19.
Besnard, F., Patriksson, M., Strömberg, A.B., Wojciechowski, A., Bertling, L., 2009. An optimization framework for opportunistic maintenance of offshore wind power system. In: 2009 IEEE Bucharest PowerTech: Innovative Ideas toward the Electrical Grid of the Future, pp. 1–7.
Bhandari, J., Arzaghi, E., Abbassi, R., Garaniya, V., Khan, F., 2016. Dynamic risk-based maintenance for offshore processing facility. Process Saf. Prog. 35, 399–406.
Bouabid, D.-A., Hadef, H., Innal, F., 2022. The Contribution of Maintenance to Minimizing the Environmental Impacts of an Industrial Process: Case Study. The 4th International Conference on Electromechanical Engineering (ICEE2022), Skikda-Algeria.
Bugalia, N., Maemura, Y., Ozawa, K., 2021. A system dynamics model for near-miss reporting in complex systems. Saf. Sci. 142, 105368.
Cagno, E., Neri, A., Negri, M., Bassani, C.A., Lampertico, T., 2021. The role of digital technologies in operationalizing the circular economy transition : a systematic literature review. Appl. Sci. 11 (8), 3328.
Cai, Y., Teunter, R.H., de Jonge, B., 2023. A data-driven approach for condition-based maintenance optimization. Eur. J. Oper. Res.
Carvalho, T.P., Soares, F.A., Vita, R., Francisco, R.D., Basto, J.P., Alcalá, S.G., 2019. A systematic literature review of machine learning methods applied to predictive maintenance. Comput. Ind. Eng. 137, 106024 [CrossRef].
Chen, J., Zhang, R., Wu, D., 2018. Equipment maintenance business model innovation for sustainable competitive advantage in the digitalization context: Connotation, types, and measuring. Sustainability MDPI 10 (11), 1–20. October.
Chen, F., Wang, C., Wang, J., Zhi, Y., Wang, Z., 2020. Risk assessment of chemical process considering dynamic probability of near misses based on Bayesian theory and event tree analysis. J. Loss Prev. Process. Ind. 68, 104280.
Cheng, Z., Jia, X., Gao, P., Wu, S., Wang, J., 2008. A framework for intelligent reliability centered maintenance analysis. Reliab. Eng. Syst. Saf. 93 (6), 806–814.
Chettouh, S., Hamzi, R., Benaroua, K., 2016. Examination of fire and related accidents in Skikda oil refinery for the period 2002–2013. J. Loss Prev. Process. Ind. 41, 186–193.
Chin, H.H., Varbanov, P.S., Klemeš, J.J., Benjamin, M.F.D., Tan, R.R., 2019. Asset maintenance optimisation approaches in the chemical and process industries – a review. Chem. Eng. Res. Des. 164, 162–194.
Çınar, Z.M., Abdussalam Nuhu, A., Zeeshan, Q., Korhan, O., Asmael, M., Safaei, B., 2020. Machine learning in predictive maintenance towards sustainable smart manufacturing in industry 4.0. Sustainability 12 (19), 8211.
Daher, A., Hoblos, G., Khalil, M., Chetouani, Y., 2020. Newprognosis approach for preventive and predictivemaintenance – application to a distillation column. Chem. Eng. Res. Des. 153, 162–174.
Daniyan, I., Mpofu, K., Oyesola, M., Ramatsetse, B., Adeodu, A., 2020. Artificial intelligence for predictive maintenance in the railcar learning factories. Procedia Manuf. 45, 13–18.
De-León-Escobedo, D., 2023. Risk-based maintenance time for oil and gas steel pipelines under corrosion including uncertainty on the corrosion rate and consequence-based target reliability. Int. J. Pres. Ves. Pip. 203, 104927.
Dias, A.L., Turcato, A.C., Sestito, G.S., Brandao, D., Nicoletti, R., 2021. A cloud-based condition monitoring system for fault detection in rotating machines using PROFINET process data. Comput. Ind. 126, 103394.
Do, P., Hoang, A., Iung, B., Vu, H.C., 2018. Energy efficiency for condition-based maintenance decision-making: application to a manufacturing platform. Proc. Inst. Mech. Eng. O J. Risk Reliab. 232 (4), 379e388.
Du, M.Y., 2018. Application of virtual instrument technology incondition-based maintenance of chemical equipment. Chem. Eng. Trans. 71, 1291–1296.
Eckerman, I., 2019. Bhopal gas catastrophe 1984: causes and consequences. In: Encyclopedia of Environmental Health, second ed. Elsevier, pp. 272–287. ISBN 9780444639523.
Elhdad, R., Chilamkurti, N., Torabi, T., 2013. An ontology-basedframework for process monitoring and maintenance inpetroleum plant. J. Loss Prev. Process. Ind. 26, 104–116.
Emovon, I., Norman, R.A., Murphy, A.J., 2016. Elements of maintenance system and tools for implementation within framework of Reliability Centred Maintenance-A review. J. Mech. Eng. Technol. 8 (2), 1–34.
Emovon, I., Norman, R.A., Murphy, A.J., 2018. Hybrid MCDM based methodology for selecting the optimum maintenance strategy for ship machinery systems. J. Intell. Manuf. 29, 519–531.
Er-Ratby, M., Mabrouki, M., 2018. Critical study of the different types of maintenance used in industry. Res. J. Appl. Sci. Eng. Technol. 15 (3), 91–97.
Faccio, M., Persona, A., Sgarbossa, F., Zanin, G., 2014. Industrial maintenance policy development: a quantitative framework. Int. J. Prod. Econ. 147 (PART A), 85–93.

Franciosi, C., Iung, B., Miranda, S., Riemma, S., 2018. Maintenance for sustainability in the industry 4.0 context: a scoping literature review. IFAC-PapersOnLine 51 (11), 903–908.
Franciosi, C., Di Pasquale, V., Iannone, R., Miranda, S., 2019. A taxonomy of performance shaping factors for human reliability analysis in industrial maintenance. J. Ind. Eng. Manag. 12 (1), 115–132.
Franciosi, C., Voisin, A., Miranda, S., Iung, B., 2020. Integration of I4.0 technologies with maintenance processes: what are the effects on sustainable manufacturing? IFAC-PapersOnLine 53. Issue 3, Pages 1-6, ISSN 2405-8963.
Franciosi, C., Miranda, S., Veneroso, C.R., Riemma, S., 2022. Improving industrial sustainability by the use of digital twin models in maintenance and production activities. IFAC-PapersOnLine 55 (19), 37–42.
Fu, T., Li, X., Xu, W., Wang, J., Zhang, L., Ye, L., Yu, R., 2023. Risk analysis of bridge maintenance accidents: a two-stage LEC method and Bayesian network approach. International Journal of Transportation Science and Technology.
Galka, T., Tabaszewski, M., 2011. An application of statistical symptoms in machine condition diagnostics. Mech. Syst. Signal Process. 25 (1), 253–265.
Gaperin, M., Juriić, D., Bokoski, P., Viintin, J., 2011. Model-based prognostics of gear health using stochastic dynamical models. Mech. Syst. Signal Process. 25 (2), 537–548.
Ghaleb, M., Taghipour, S., 2022. Assessing the impact of maintenance practices on asset's sustainability. Reliab. Eng. Syst. Saf. 228, 108810.
Giada, C.V., Rossella, P., 2021. Barriers to Predictive Maintenance implementation in the Italian machinery industry. IFAC-PapersOnLine 54 (1), 1266–1271.
Gnoni, M.G., Saleh, J.H., 2017. Near-miss management systems and observability-in-depth: handling safety incidents and accident precursors in light of safety principles. Saf. Sci. 91, 154–167.
Guan, J., Yang, X., You, L., Ding, L., Cheng, X., 2022. Multi-objective optimization for sustainable road network maintenance under traffic equilibrium: incorporating costs and environmental impacts. J. Clean. Prod. 334, 130103.
Gupta, A., Lawsirirat, C., 2006. Strategically optimum maintenance of monitoring-enabled multi-component systems using continuous-time jump deterioration models. J. Qual. Mainten. Eng. 12 (3), 306–329.
Hadef, H., Belkhir, N., González, A.-T., Djebabra, M., Ramadan, M., 2020. Preliminary hazard identification for risk assessment on a complex system for hydrogen production. Int. J. Hydrogen Energy 45 (20), 11855–11865. ISSN 0360-3199.
Hadef, H., Mébarek, D., Belkhir, N., Driss, Z., 2023. Reliability degradation prediction of photovoltaic modules based on dependability methods. Int. J. Qual. Reliab. Manag. 40 (2), 478–495.
Hallaji, S.M., Fang, Y., Winfrey, B.K., 2021. Predictive maintenance of pumps in civil infrastructure : state-of-the-art, challenges and future direction. Autom. ConStruct., 104049
Hami, N., Shafie, S.M., Omar, S., Ibrahim, Y.M., Sabah, A.S., Mohd, R.M., 2020. A review of sustainable maintenance in the manufacturing companies. Int. J. Supply Chain Manag. 9 (3), 935–944.
Hefaidh, H., Djebabra, M., Lila, S., Mouna, T., 2019. Contribution to the evaluation of safety barriers performance, World Journal of Science. Technology and Sustainable Development 16 (1), 56–68.
Hoang, A., Do, P., Iung, B., 2015. Prognostics on energy efficiency performance for maintenance decision-making: application to industrial platform TELMA. In: Prognostics and System Health Management Conference (PHM). IEEE, p. 1e7.
Hoang, A., Do, P., Iung, B., 2016. Investigation on the use of energy efficiency for condition-based maintenance decision-making. IFAC-PapersOnLine 49 (28), 73e78.
Holgado, M., Macchi, M., Evans, S., 2020. Exploring the impacts and contributions of maintenance function for sustainable manufacturing. Int. J. Prod. Res. 58 (23), 7292–7310.
Humberto, N., Teixeira, IsabelLopes, Ana, Cristina, Braga, 2020. Condition-based maintenance implementation: a literature review. Procedia Manuf. 51, 228–235.
Ighravwe, D.E., Oke, S.A., 2017. Ranking maintenance strategies for sustainable mainte nance plan in manufacturing systems using fuzzy axiomatic design principle and fuzzy TOPSIS. J. Manuf. Technol. Manag. 28 (7), 961–992.
Ishizaka, A., Labib, A., 2014. A hybrid and integrated approach toevaluate and prevent disasters. J. Oper. Res. Soc. 65, 1475–1489.
Iung, B., Levrat, E., 2014. Advanced maintenance services for promoting sustainability. Procedia CIRP 22 (1), 15–22.
Jaderi, F., Ibrahim, Z.Z., Nikoo, Mehdi, Nikoo, Mohammad, 2019. Utilizing self-organization systems for modeling and managing risk based on maintenance and repair in petrochemical industries. Soft Comput. 23, 6379–6390.
Jain, A., Bhatti, R., Singh, H., 2014. Total productive maintenance (TPM) implementation practice: a literature review and directions. International Journal of Lean Six Sigma.
Jantunen, E., Emmanouilidis, C., Arnaiz, A., et al., 2010. Economic and technological prospects for e-maintenance. Int J Syst Assur Eng Manag 1, 201–209.
Jardine, A.K.S., Lin, D., Banjevic, D., 2006. A review on machinery diagnostics and prognostics implementing condition-based maintenance. Mech. Syst. Signal Process. 20 (7), 1483–1510.
Jeswani, H.K., Figueroa-Torres, G., Azapagic, A., 2021. The extent of food waste generation in the UK and its environmental impacts. Sustain. Prod. Consum. 26, 532–547.
Jiang, R., Ji, P., 2002. Age replacement policy: a multi-attribute value model. Reliab. Eng. Syst. Saf. 76 (3), 311–318.
Jimenez, J.J.M., Schwartz, S., Vingerhoeds, R., Grabot, B., Salaün, M., 2020. Towards multi-model approaches to predictive maintenance : a systematic literature survey on diagnostics and prognostics. J. Manuf. Syst. 56, 539–557.
Johansson, N., Roth, E., Reim, W., 2019. Smart and sustainable emaintenance: capabilities for digitalization of maintenance. Sustainability 11 (13).
Johnston, D.C., 2002. Measuring RCM implementation. Proceedings of the Annual Reliability and Maintainability Symposium, pp. 511–515.
Jordan, O., Kevin, J., Wilson, Peter, John, Philipson, 2022. A condition-based maintenance policy for continuously monitored multi-component systems with economic and stochastic dependence. Reliab. Eng. Syst. Saf. 222, 108321-108321.
Josef Peter, S., Magdalena, R., Lukas, S., Rupert, J.B., 2022. Implementation of digital technologies for a circular economy and sustainability management in the manufacturing sector. Sustain. Prod. Consum. 2352–5509. ISSN.
Kaewunruen, S., Lian, Q., 2019. Digital twin aided sustainability-based lifecycle management for railway turnout systems. J. Clean. Prod. 228, 1537–1551.
Kang, J., Guedes Soares, C., 2020. An opportunistic maintenance policy for offshore wind farms. Ocean Engineering 216.
Kannan, K., Arunachalam, N., 2019. A digital twin for grinding wheel: an information sharing platform for sustainable grinding process. J. Manuf. Sci. Eng. 141 (2).
Karki, B.R., Porras, J., 2021. Digitalization for sustainable maintenance services: a systematic literature review. Digital Business 1 (2), 100011.
Karuppiah, K., Sankaranarayanan, B., Ali, S.M., 2021. On sustainable predictive maintenance : exploration of key barriers using an integrated approach. Sustain. Prod. Consum. 27, 1537–1553.
Kennedy, G.A.L., Siemieniuch, C.E., Sinclair, M.A., Kirwan, B.A., Gibson, W.H., 2007. Proposal for a sustainable framework process for the generation, validation, and application of human reliability assessment within the engineering design lifecycle. Reliab. Eng. Syst. Saf. 92 (6), 755–770.
Klemes, J.J., Varbanov, P.V., Walmsley, T.G., Jia, X.X., 2018. Newdirections in the implementation of Pinch methodology (PM). Renewable Sustainable Energy Rev. 98, 439–468.
Koochaki, J., Bokhorst, J.A.C., Wortmann, H., Klingenberg, W., 2012. Condition based maintenance in the context of opportunistic maintenance. Int. J. Prod. Res. 50 (23), 6918–6929.
Kothamasu, R., Huang, S.H., 2007. Adaptive Mamdani fuzzy model for condition-based maintenance. Fuzzy Set Syst. 158 (24), 2715–2733.
Kovacs, Z., Orosz, A., Friedler, F., 2019. Synthesis algorithms forthe reliability analysis of processing systems. Cent. Eur. J. Oper. Res. 27, 573–595.
Kumar, U., Galar, D., 2018. Maintenance in the era of industry 4.0: issues and challenges. In: Kapur, P.K., Kumar, U., Verma, A.K. (Eds.), Quality, IT and Business Operations: Modeling and Optimization, *Springer Proceedings in Business and Economics*. Singapore, pp. 231–250.
Kunic, A., Naboni, R., Kramberger, A., Schlette, C., 2021. Design and assembly automation of the Robotic Reversible Timber Beam. Autom. ConStruct. 123, 103531.
Laggoune, R., Chateauneuf, A., Aissani, D., 2010. Impact of few failure data on the opportunistic replacement policy for multi-component systems. Reliab. Eng. Syst. Saf. 95 (2), 108–119.
Lee, J., Ni, J., Djurdjanovic, D., Qiu, H., Liao, H., 2006. Intelligent prognostics tools and e-maintenance. Comput. Ind. 57 (6), 476–489.
Lee, W.-J., Joung, B.-G., Sutherland, J.-H., 2023. Environmental and economic performance of different maintenance strategies for a product subject to efficiency erosion. J. Clean. Prod. 389, 135340.
Leoni, L., De Carlo, F., Paltrinieri, N., Sgarbossa, F., BahooToroody, A., 2021. On risk-based maintenance: a comprehensive review of three approaches to track the impact of consequence modelling for predicting maintenance actions. J. Loss Prev. Process. Ind. 72, 104555.
Li, J., Yin, G., Wang, X., Yan, W., 2022. Automated decision making in highway pavement preventive maintenance based on deep learning. Autom. ConStruct. 135, 104111.
Liao, H., Elsayed, E.A., Chan, L.Y., 2006. Maintenance of continuously monitored degrading systems. Eur. J. Oper. Res. 175 (2), 821–835.
Lindström, J., Kyösti, P., Birk, W., Lejon, E., 2020. An initial model for zero defect manufacturing. Appl. Sci. 10 (13), 4570.
Liu, H.C., Quan, M.Y., Li, Z., Wang, Z.L., 2019. A new integrated MCDM model for sustainable supplier selection under interval-valued intuitionistic uncertain linguistic environment. Inf. Sci. 486, 254–270.
Liu, Y., Pang, B., Wang, Y., Shi, C., Zhang, B., Guo, X., Zhou, S., Wang, J., 2022. Life-cycle maintenance strategy of bridges considering reliability, environment, cost and failure probability CO2 emission reduction: a bridge study with climate scenarios. J. Clean. Prod. 379 (Part 1), 134740.
Liyanage, J.P., Badurdeen, F., Ratnayake, R.M., 2009. Industrial asset maintenance and sustainability performance : economical, environmental, and societal implications. In: Handbook of Maintenance Management and Engineering. Springer, London, pp. 665–693.
Llamas, A.A., Bartie, N.J., Heibeck, M., Stelter, M., Reuter, M.A., 2020. Simulation-based exergy analysis of large circular economy systems: zinc production coupled to CdTe photovoltaic module life cycle. Journal of Sustainable Metallurgy 6 (1), 34–67.
Lovrencic, V., Brezavscek, A., Pantos, M., Gomiscek, B., 2017. Contribution of live working to the quality, safety, effectiveness and efficiency of the maintenance processes. Teh. Vjesn. 24 (5), 1619–1626.
Lu, X.Q., Yan, H.F., Su, Z.L., Zhang, M.X., Yang, X.H., Ling, H.F., 2021. Metaheuristics for homogeneous and heterogeneous machine utilization planning under reliability-centered maintenance. Comput. Ind. Eng. 151, 106934.
Magargle, R., Johnson, L., Mandloi, P., Davoudabadi, P., Kesarkar, O., Krishnaswamy, S., Batteh, J., Pitchaikani, A., 2017. Asimulation-based digital twin for model-driven healthmonitoring and predictive maintenance of an automotivebraking system. In: *The 12th International Modelica Conference*. Prague, Czech Republic, pp. 35–46. May.
Mangano, G., De Marco, A., 2014. The role of maintenance and facility management in logistics: a literature review. Facilities 32 (5/6), 241–255.

Martín, G.M., Pacios Álvarez, A., Ordieres-Meré, J., Villalba-Díez, J., Morales-Alonso, G., 2020. New business models from prescriptive maintenance strategies aligned with sustainable development goals. Sustainability 13 (1), 216.

Martín, G., Pacios Álvarez, A., Ordieres-Meré, J., Villalba Díez, J., Morales-Alonso, G., 2021. New business models from prescriptive maintenance strategies aligned with sustainable development goals. Sustainability 13 (1), 216.

Martínez-Galán Fernández, P., Guillén López, A.J., Márquez, A.C., Gomez Fernández, J. F., Marcos, J.A., 2022. Dynamic Risk Assessment for CBM-based adaptation of maintenance planning. Reliab. Eng. Syst. Saf. 223 (C).

Memari, A., Dargi, A., Jokar, M.R.A., Ahmad, R., Rahim, A.R.A., 2019. Sustainable supplier selection: a multi-criteria intuitionistic fuzzy TOPSIS method. J. Manuf. Syst. 50, 9–24.

Mi, S., Feng, Y., Zheng, H., Wang, Y., Gao, Y., Tan, J., 2021. Prediction maintenance integrated decision-making approach supported by digital twin-driven cooperative awareness and interconnection framework. J. Manuf. Syst. 58, 329–345.

Moghaddam, K.S., 2013. Multi-objective preventive maintenance and replacement scheduling in a manufacturing system using goal programming. Int. J. Prod. Econ. 146 (2), 704–716.

Mohammadi, R., He, Q., 2022. A deep reinforcement learning approach for rail renewal and maintenance planning. Reliab. Eng. Syst. Saf., 108615

Nacchia, M., Fruggiero, F., Lambiase, A., Bruton, K., 2021. A systematic Mapping of the advancing Use of machine learning techniques for predictive maintenance in the manufacturing sector. Appl. Sci. 11, 2546.

Ndhaief, N., Nidhal, R., Hajji, A., Bistorin, O., 2020. Environmental issue in an integrated production and maintenance control of unreliable manufacturing/remanufacturing systems. Int. J. Prod. Res. 58 (14), 4182–4200.

Nilsson, J., Wojciechowski, A., Strömberg, A.B., Patriksson, M., Bertling, L., 2009. An opportunistic maintenance optimization model for shaft seals in feed-water pump systems in nuclear power plants. 2009 *IEEE Bucharest PowerTech: Innovative Ideas Toward the Electrical Grid of the Future*, pp. 1–8.

Niu, G., Yang, B.S., Pecht, M., 2010. Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance. Reliab. Eng. Syst. Saf. 95 (7), 786–796.

Obiso, J.J.A., Himang, C.M., Ocampo, L.A., Bongo, M.F., Caballes, S.A.A., Abellana, D.P. M., Deocaris, C.C., Padua, R. Jr.R.A., 2019. Management of Industry 4.0 - reviewing intrinsic and extrinsic adoption drivers and barriers. Int. J. Technol. Manag. 81, 210.

Ochella, S., Shafiee, M., Dinmohammadi, F., 2022. Artificial intelligence in prognostics and health management of engineering systems. Eng. Appl. Artif. Intell. 108, 104552.

Ochiai, S., Makita, T., Sanjo, T., Sato, K., Katagiri, M., 2005. Quantitative risk evaluations of LNG equipment applying ASME risk-based maintenance concepts. Process Saf. Prog. 24 (3), 187–191.

Okoh, P., Haugen, S., 2014. A study of maintenance-related major accident cases in the 21st century. Process Saf. Environ. Protect. 92 (4), 346–356.

Okoh, C., Roy, R., Mehnen, J., Redding, L., 2014. Overview ofremaining useful life prediction techniques in through-life engineering services. Proc. CIRP 16 158–163.

Orosz, Á., Friedler, F., 2019. Synthesis technology for failure analysis and corrective actions in process systems engineering. Comput. Aided Chem. Eng 1405–1410.

Orosz, A., Friedler, F., Varbanov, P.S., Klemẽs, J.J., 2018. Systems reliability, footprints Sustainability. Chem. Eng. Trans. 1 (63), 121–126.

Patil, S.S., Bewoor, A.K., Kumar, R., Ahmadi, M.H., Sharifpur, M., PraveenKumar, S., 2022. Development of optimized maintenance program for a steam boiler system using Reliability-Centered Maintenance Approach. Sustainability 14 (16), 10073.

Pecht, M., Jaai, R., 2010. A prognostics and health management roadmap for information and electronics-rich systems. Microelectron. Reliab. 50 (3), 317–323.

Peres, R.S., Rocha, A.D., Leitao, P., Barata, J., 2018. IDARTS–Towards intelligent data analysis and real-time supervision for industry 4.0. Comput. Ind. 101, 138–146 [CrossRef].

Petchrompo, S., Parlikad, A.K., 2019. A review of asset management literature on multi-asset systems. Reliab. Eng. Syst. Saf. 181, 181–201.

Pham, H., Wang, H., 1996. Imperfect maintenance. Eur. J. Oper. Res. 94 (3), 425–438.

Piasson, D., Bíscaro, A.A.P., Leão, F.B., Mantovani, R.S., 2016. A new approach for reliability-centered maintenance programs in electric power distribution systems based on a multiobjective genetic algorithm. Elec. Power Syst. Res. 137, 41–45.

Polenghi, A., Cattaneo, L., Macchi, M., Pasanisi, D., Pesenti, V., Borgonovo, A., 2022. Development of an advanced condition-based maintenance system for high-critical industrial fans in a foundry. IFAC-PapersOnLine 55 (2), 48–53.

Radner, R., Jorgenson, D.W., 1963. Opportunistic replacement of a Single part in the presence of several monitored parts. Manag. Sci. 10 (1), 70–84.

Rathnayaka, S., Khan, F., Amyotte, P., 2011. SHIPP methodology:predictive accident modeling approach. Part I : methodology and model description. Process Saf. Environ. Prot. 89, 151–164.

Rauch, E., Dallasega, P., Unterhofer, M., 2019. Requirements and barriers for introducing smart manufacturing in Small and Medium-Sized enterprises. IEEE Eng. Manag. Rev. 47, 87–94.

Rojek, I., Mikołajewski, D., Dostatni, E., 2020. Digital twins in product lifecycle for sustainability in manufacturing and maintenance. Appl. Sci. 11 (1), 31.

Saihi, A., Ben-Daya, M., As' ad, R.A., 2022. Maintenance and sustainability: a systematic review of modeling-based literature. J. Qual. Mainten. Eng.

Sarbini, N.N., Ibrahim, I.S., Abidin, N.I., Yahaya, F.M., Azizan, N.Z.N., 2021. Review on maintenance issues toward building maintenance management best practices. J. Build. Eng. 44, 102985.

Sari, E., Shaharoun, A.B.M., Ma'aram, A.B., 2014. Preliminary framework of sustainable maintenance performance measurement systems for automotive companies. Adv. Mater. Res. 845, 590e595. Trans Tech Publications.

Sari, E., Shaharoun, A.M., Ma'aram, A., Yazid, A.M., 2015. Sustainable maintenance performance measures: a pilot survey in Malaysian automotive companies. Procedia CIRP 26, 443e448.

Sari, E., Ma'aram, A., Shaharoun, A.M., Chofreh, A.G., Goni, F.A., Klemeš, J.J., et al., 2021. Measuring sustainable cleaner maintenance hierarchical contributions of the car manufacturing industry. J. Clean. Prod. 312, 127717.

Savino, M.M., Macchi, M., Mazza, A., 2015. Investigating the impact of social sustainability within maintenance operations: an action research in heavy industry. J. Qual. Mainten. Eng. 21 (3), 310–331.

Scarf, P.A., Cavalcante, C.A.V., 2010. Hybrid block replacement and inspection policies for a multi-component system with heterogeneous component lives. Eur. J. Oper. Res. 206 (2), 384–394.

Schmitt, S., Kynast, K., Schirmacher, P., Herpel, E., 2016. Challenges for quality management in implementation, maintenance, and sustainability of research tissue biobanks. Virchows Arch. 468 (1), 93–99.

Scope, C., Vogel, M., Guenther, E., 2020. Greener, cheaper, or more sustainable: reviewing sustainability assessments of maintenance strategies of concrete structures. Sustain. Prod. Consum. 26, 838–858.

Selvik, J.T., Aven, T., 2011. A framework for reliability and risk centered maintenance. Reliab. Eng. Syst. Saf. 96 (2), 324–331.

Sénéchal, O., Trentesaux, D., 2019. A framework to help decision makers to be environmentally aware during the maintenance of cyber physical systems. Environ. Impact Assess. Rev. 77, 11e22.

Sezer, E., Romero, D., Guedea, F., MacChi, M., Emmanouilidis, C., 2018. An industry 4.0-enabled low cost predictive maintenance approach for SMEs. Proceedings of IEEE International Conference of Engineering, Technology and Innovation (ICE/ITMC). Stuttgart, *German*y, pp. 1–8 [CrossRef].

Shang, L., Liu, B., Cai, Z., Wu, C., 2022. Random maintenance policies for sustaining the reliability of the product through 2D-warranty. Appl. Math. Model. 111, 363–383.

Sheu, S.H., Chang, C.C., Chen, Y.L., Zhang, Z.G., 2010. A periodic replacement model based on cumulative repair-cost limit for a system subjected to shocks. IEEE Trans. Reliab. 59 (2), 374–382.

Simões, J.M., Gomes, C.F., Yasin, M.M., 2011. A literature review of maintenance performance measurement: a conceptual framework and directions for future research. J. Qual. Mainten. Eng. 17 (2), 116–137.

Singh, R.K., Gupta, A., Kumar, A., Khan, T.A., 2016. Ranking of barriers for effective maintenance by using TOPSIS approach. J. Qual. Maint. Eng. 22, 18–34.

Song, M., Zhang, X., Lind, M., 2023. Automatic identification of maintenance significant items in reliability centered maintenance analysis by using functional modeling and reasoning. Comput. Ind. Eng., 109409

Tong, L., Pu, Z., Ma, J., 2019. Maintenance supplier evaluation and selection for safe and sustainable production in the chemical industry: a case study. Sustainability 11 (6), 1533.

Vinnem, J.E., Haugen, S., Okoh, P., 2016. Maintenance of petroleum process plant systems as a source of major accidents? J. Loss Prev. Process. Ind. 40, 348–356.

Vrignat, P., Kratz, F., Avila, M., 2022. Sustainable manufacturing, maintenance policies, prognostics and health management : a literature review. Reliab. Eng. Syst. Saf. 218, 108140.

Wang, W., Zhang, W., 2008a. An asset residual life prediction model based on expert judgments. Eur. J. Oper. Res. 188 (2), 496–505.

Wang, W., Zhang, W., 2008b. Early defect identification: application of statistical process control methods. J. Qual. Mainten. Eng. 14 (3), 225–236.

Wang, Y., Deng, C., Wu, J., Wang, Y., Xiong, Y., 2014. A corrective maintenance scheme for engineering equipment. Eng. Fail. Anal. 36, 269–283.

Wang, Q., Jiao, W., Wang, P., Zhang, Y., 2020. Digital twin for human-robot interactive welding and welder behavior analysis. IEEE/CAA Journal of Automatica Sinica 8 (2), 334–343.

Wang, P., Xu, Z., Chen, D., 2023. An integrated framework for reliability prediction and condition-based maintenance policy for a hydropower generation unit using GPHM and SMDP. Reliab. Eng. Syst. Saf., 109419

Winkler, M., Perlman, Y., Westreich, S., 2019. Reporting near-miss safety events: impacts and decision-making analysis. Saf. Sci. 117, 365–374.

Wu, J., Adam Ng, T.S., Xie, M., Huang, H.Z., 2010. Analysis of maintenance policies for finite life-cycle multi-state systems. Comput. Ind. Eng. 59 (4), 638–646.

Xia, T., Xi, L., Du, S., Xiao, L., Pan, E., 2018. Energyoriented maintenance decision-making for sustainable manufacturing based on energy saving window. J. Manuf. Sci. Eng. 140 (5), 051001.

Xiang, Y., Cassady, C.R., Pohl, E.A., 2012. Optimal maintenance policies for systems subject to a Markovian operating environment. Comput. Ind. Eng. 62 (1), 190–197.

Xu, G., Guo, F., 2022. Sustainability-oriented maintenance management of highway bridge networks based on Q-learning. Sustain. Cities Soc. 81, 103855.

Yaguo, L., Naipeng, Li, Liang, Guo, Ningbo, Li, Tao, Yan, Jing, Lin, 2018. Machinery health prognostics: a systematic review from data acquisition to RUL prediction. Mech. Syst. Signal Process. 104, 799–834.

Yam, R.C.M., Tse, P.W., Li, L., Tu, P., 2001. Intelligent predictive decision support system for condition-based maintenance. Int. J. Adv. Manuf. Technol. 17 (5), 383–391.

Yamano, S., Nakaya, T., Ikegami, T., Nakayama, M., Akisawa, A., 2021. Optimization modeling of mixed gas engine types with different maintenance spans and costs: case study OF CCHP to evaluate optimal gas engine operations and combination of the types. Energy 222, 119823.

Yavuz, O., Doğan, E., Carus, E., Görgülü, A., 2019. Reliability centered maintenance practices in food industry. Procedia Computer Science 158, 227–234.

Zakikhani, K., Nasiri, F., Zayed, T., 2020. Availability-based reliability-centered maintenance planning for gas transmission pipelines. Int. J. Pres. Ves. Pip. 183 (April), 104105.

Zaranezhad, A., Mahabadi, H.A., Dehghani, M.R., 2019. Development of prediction models for repair and maintenance-related accidents at oil refineries using artificial neural network, fuzzy system, genetic algorithm, and ant colony optimization algorithm. Process Saf. Environ. Protect. 131, 331–348.
Zhang, L., Hu, J., 2013. Safety prognostic technology in complex petroleum engineering systems: progress, challenges and emerging trends. Pet. Sci. 10, 486–493.
Zhang, W.J., van Luttervelt, C.A., 2011. Toward a resilient manufacturing system. CIRP Ann. - Manuf. Technol. 60 (1), 469–472, 2011.
Zhao, K., Yu, X., 2011. A case based reasoning approach on supplier selection in petroleum enterprises. Expert Syst. Appl. 38 (6), 6839–6847.
Zhou, X.J., Lu, Z.Q., Xi, L.F., Lee, J., 2011. Opportunistic preventive maintenance optimization for multi-unit series systems with combing multi-preventive maintenance techniques. Journal of Shanghai Jiaotong University (Science) 15 (5), 513–518.
Zhou, X., Ning, X., 2021. Maintenance gravity window based opportunistic maintenance scheduling for multi-unit serial systems with stochastic production waits. Reliab. Eng. Syst. Saf. 215.
Zonta, T., da Costa, C.A., da Rosa Righi, R., de Lima, M.J., da Trindade, E.S., Li, G.P., 2020. Predictive maintenance in the Industry 4.0: a systematic literature review. Comput. Ind. Eng. 150, 106889.