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Abstract

Purpose – The purpose of this review paper is to provide comprehensive information about preventive maintenance (PM) planning and methods used in industry to achieve an effective maintenance system.

Design/Methodology/Approach – The literature review is organized in a way that provides a general overview of the research conducted concerning PM. This paper discusses the literature that has been reviewed in terms of four main topics, which are the holistic view of maintenance policies, PM planning, PM planning concepts and PM planning based on developing optimal planning when executing PM actions.

Findings – PM policy is one of the original proactive techniques that has been used since research into maintenance systems began. A review of methods presented in this paper shows that most research has analysed effectiveness using artificial intelligence (AI), simulation, mathematical formulation, matrix formation, critical analysis and multicriteria methodology. While, in practice, PM activities tend to be planned based on cost, time or failure, research trends on planning and methods for PM show that there have been variations of approaches used over the years from the early '90s to the present day.

Practical implications – Research about PM is known to have been conducted extensively and the majority of companies have applied the policy in their production line processes. However, most of the analyses and methods suggested in the published literature were based on mathematical computation rather than on solutions derived from real problems experienced by industries. Normally, this would lead to problems in understanding by practitioners. Therefore, this paper presents research on PM planning and suggests methods for application in real industrial situations that are practical, simple and effective.

Originality/Value – The originality of this paper comes from its detailed analysis of PM planning in terms of its research focus and also the direction for its application. Extensive reviews of the methods adopted in relation to PM planning, such as cost-based, time-based and failure-based planning, have also been provided.

Keywords – Maintenance policy; preventive maintenance; planning, cost-based; time-based; failure-based

Article classification – Literature review

1. Introduction

In general, maintenance is defined as the combination of all technical and administrative actions, including supervision, which ensure that a system is in its required functioning state (Reason, 2000; Swanson, 2001). Maintaining a system is usually related to maintenance actions such as repairing, replacing, overhauling, inspecting, servicing, adjusting, testing, measuring and detecting faults in order to avoid any failure that would lead to interruptions in production operations (Duffuaa et al., 2001; Ismail et al., 2009). Performance measurement for maintenance systems can be based on various factors (Parida et al., 2015).

According to Wikstan and Jonannson (2006), effective maintenance can reduce the consequences of failure and extend the life of a system. Implementation of maintenance refers to maintenance policies, which can be defined as the plans of action used to provide direction and guidelines to carry out further maintenance actions required by a system (Waeyenbergh and Pintelon, 2002). Corrective maintenance (CM) is one of the maintenance policies by which maintenance actions, such as repair or replacement are carried out on a system to restore it to its required functioning after it has failed (Paz and Leigh, 1994). However, this policy leads to high levels of system breakdown and high repair and replacement costs, due to sudden failures that potentially can occur. Another maintenance policy, PM, serves as an alternative to CM. Normally, PM is planned and performed after a specified period of time, or when a specified system has been used, in order to reduce the probability of its failure (Kimura, 1997). Mechefske and Wang (2001) claimed that most systems are maintained whilst a significant amount of their useful life remains whenever PM practices are applied.

In this paper, a review has been carried out based on the challenges faced during PM planning processes in order to secure better rates of improvement for organizations. The review has been structured in a way that provides a general overview of studies related to PM as well as PM planning, followed by an in-depth discussion of PM planning concepts. The three categories of PM planning – cost-, time- and failure-based – have been reviewed thoroughly. Finally, an analysis of trends in published research concerning PM planning has been summarized, before closing with suggestions for potential future research directions.

At the end of this paper, it is hoped that people at all levels in maintenance systems may have benefited from considering this review. Most directly, academicians can use this paper as a guideline for understanding the principles and methods underpinning PM, based on the literature presented. For this research, the reviews of methods and tools also provide practical insights for managers. "Management" refers to the process of leading and directing companies by deploying resources, which involves shouldering the responsibilities for making technical and administrative changes to production and maintenance processes and to top management personnel themselves (Murthy et al., 2002).

The expected outcome from management's point of view can be discussed in terms of two levels of management activity, i.e. at the strategic and tactical levels. At the strategic level, which corresponds to Al-Turki's (2011) work, a business's priority is to address generic PM planning as a key supporting function, where the aspects of planning should meet the requirements of a business. At the tactical level, maintenance priorities should support businesses at the strategic level and at the operational level when maintenance is undertaken, and those priorities should fulfil the requirements of PM planning. This corresponds to Márquez's (2007) idea of how standard process planning refers to the assignment of maintenance resources, such as manpower, spare parts and tools as part of detailed planning and scheduling, to ensure that the execution of maintenance at the operational level is acceptable and practicable. This detailed and structured review of PM should help to ease the planning and scheduling of maintenance systems for practitioners and also for maintenance service providers.

2. Overview of maintenance policies

Nowadays, the efficiencies and effectiveness of the whole of a manufacturing operation are dependent on the sustainable performance of systems or equipment, which can lead to valuable improvements in terms of quality, cost and time (Nakajima, 1986; Khan and Darrab, 2010). In order to produce better product quality at a minimal cost, the availability and reliability of the production line, widely known as "the system", plays a central role in sustaining a competitive edge over other manufacturing organizations (Muchiri et al., 2011). The word “system” in engineering terms is translated as, “the assemblage of machines which consists of mechanical or electrical devices that transmits energy to assist in the performance of human tasks”. “System” usually refers to the machines by which equipment, such as tools, as well as materials, people and information, are utilized to produce value-added physical and informational products. Hence, systems are considered to be an inevitable part of production, which require constant attention and maintenance to achieve the desired operating conditions (Ahmed et al., 2005).

Unfortunately, a system is always subject to deterioration in the course of continuous operations. The function of a system will change over time as the importance of maintenance to the system increases due to technical developments, the changing of laws and regulations and variances in operational environments (Söderholm et al., 2007). Moreover, the complexity of a system is a crucial component of the critical requirements of safety and costs throughout its life cycle (Liyange and Kumar, 2003; Foley, 2005). Hence, maintaining a system is extremely important as it requires a proper and effective maintenance policy to ensure that there is a capability for the system to perform its required functions. Table 1 illustrates threetypes of maintenance policies that are normally adopted by industries. The policies come with many features that suit different situations and implementation stages. The basic objectives of maintenance policies are to reduce unplanned system breakdowns and to increase available operational time.

Table 1: Maintenance policies (Source: Parajapathi et al., 2012)

Features	**Maintenance policies**			
	Corrective Maintenance (CM)	**Preventive Maintenance (PM)**	**Predictive Maintenance (PdM)**	
Maintenance approach	Reactive	Proactive	Proactive	
Maintenance category	Fixing after failure	Time-based maintenance (periodic)	Diagnostic-based maintenance (condition monitoring)	Prognostic-based maintenance (reliability-centred)
Downtime	Highest	Less	Close to minimum	Least
Good for failures	Random age-based	Age-based	Prevents to occur (near-optimal)	Prevents to occur
Expensive (manpower)	Maximum	Little less	Moderate	Minimum
Initial	None	Slightly higher	Expensive	Most

deployment cost				expensive
Computational cost	Least	Little higher	Higher	Highest
Schedule required	Not applicable	Based on the standard useful life of component or history of failures	Based on current conditions	Based on forecast of remaining equipment life
Action	Inspect, repair or replace after failure	Inspect, repair or replace at predetermined intervals, forecasted by design and updated through experience	Inspect, repair or replace based on need. Continuous collection of condition-monitoring data	Forecasting of remaining equipment life based on actual stress loading
Prediction type	None	None	On and off system, near-real-time trend analysis	On and off system, real-time trend analysis

Preventive maintenance (PM) was introduced in the 1950s, after the recognition of the need to prevent failure (Murthy et al., 2002). As an alternative to corrective maintenance (CM), PM has been adopted for emerging technologies since such systems are generally more complex than those based on the use of hand tools. The basic principle of a PM system is that it involves predetermined maintenance tasks that are derived from machine or equipment functionalities and component lifetimes. Accordingly, tasks are planned to change components before they fail and are scheduled during machine stoppages or shutdowns. Meanwhile, predictive maintenance (PdM) is an advancement on PM and commonly involves condition-monitoring systems. In PdM, repetitive or high-risk failures are studied using historical data detailing occurrences of a machine's operational failures and then maintenance is conducted during its operation, based on the condition of the monitored component. In summary, PM and PdM are both proactive maintenance approaches and have similar objectives, but PM is conducted when a machine is stopped, while PdM is undertaken while a machine continues in operation.

According to Simões et al. (2011), PM is realised from two perspectives, which are known as the managerial and the operational. The managerial perspective refers to the support for decision-making which facilitates the analysis of data (Söderholm et al., 2007). Inputs for the managerial perspective include the determination of PM's objectives, planning to perform maintenance actions, and methods involved in solving any problem that occurs with regard to PM as well as the performance of systems. The managerial perspective is also known as an outer process, as it bases decisions on history and analysis prior to the execution of PM actions. Meanwhile, the operational perspective refers to the execution of maintenance actions in order to sustain the capability of a system to perform its intended functions (Bjorklund et al., 2010). This perspective is an inner process that consists of technical aspects by which PM is carried out based on inputs to the outer process.

Both perspectives that prefigure PM are crucial for ensuring its effectiveness and efficiency. However, the managerial perspective plays the more important role in planning and determining suitable and feasible solutions before carrying out PM so that it meets its objectives. This is because without proper planning, the execution of PM actions could affect the system or other systems that may then require further planning actions (Ab-Samat et al., 2012). Therefore, most attention should be given to planning as the key to connecting the managerial and operational perspectives. With the aid of planning, PM can be directed in a structured and systematic way to monitor and increase the lifetime of a system.

3. PM Planning

In the context of maintenance, planning encompasses activities that are undertaken with the aid of all maintenance resources such as material requirements, labour requirements, time assignments and technical references related to equipment, that are determined and prepared prior to a task's performance (Duffuaa et al., 1999). In other words, without proper planning, inconsistent and unreliable procedures will result, which may lead to interruptions in production. Therefore, proper planning is basically the preparation for performing necessary maintenance tasks on a priority basis by referring to the required resources, information and schedule.

As PM is one of a number of maintenance policies, it is pertinent to that maintenance planning which requires a long-term strategy for executing maintenance actions within a predetermined interval. This ensures that a system continues to fulfil its intended function (Palma et al., 2010). The scope of PM planning covers all the aspects of PM that are to be integrated with planning in order to aid decision-making, in the cases of actions to be taken and the performance of the system to be monitored and improved. PM planning is also a feature of the managerial perspective which requires objectives, planning and methods to be considered prior to the execution of PM on a system (Basri et al., 2014). From the managerial perspective, the process of developing PM planning necessitates the incorporation of both PM policy and planning to ensure that the PM actions are performed in a proven and standardized way. The significance of having proper objectives, planning and methods is to provide a better understanding and proper guidelines to facilitate the process of developing and improving PM planning.

The literature on PM planning concentrates on various aspects in relation to the maintenance environment. In this research, the focus of PM planning has been narrowed down and placed on the concept underlying PM planning, which embraces the objectives behind PM's performance, the state of the systems involved, as well as the methods applied to solve maintenance issues. The PM planning concept will be explained in the next section.

4. PM Planning Concept

In general, the PM planning concept is briefly described as the general idea that covers the elements of PM in a simple and systematic way. The process for determining a PM planning concept is based on an investigation of the characteristics of the conceptual description, specifications and application domains (Young, 2003). Hence, in this research, the literature on the PM planning concept that is reviewed and discussed consists of three facets:

i. the objective(s) or the purpose of performing PM planning;
ii. descriptions of the system's state in terms of its importance and its functions; and
iii. methods that are divided into several classifications which help in determining the best solutions for the issues highlighted.

These facets are important as they provide a guide on how the literature and its substance are reviewed. Each of the facets of PM planning will be explained further in the subsections that follow.

4.1 Purpose(s)

As part of the planning concept, “purpose” is described as the objective or goal intended by performing PM planning. The reason for establishing significant objectives prior to the execution of PM planning is to narrow down and focus the study and to guide the collection of related information. Significantly, PM planning is described as an aid to decision-making to determine any action that is to be taken based on the outcome or objective to be achieved from the planning conducted in relation to the issues experienced in the maintenance environment.

From the aforementioned operational perspective, in which PM consists of technical operations, the execution of PM is frequently associated with a wide range of issues. These issues are regarded as technical problems taking place on the production floor that would affect production processes and the maintenance of quality. Several issues have been highlighted in terms of PM and its related systems, such as system downtime, system deterioration, imperfect PM actions, improper time estimation for PM, insufficient numbers of maintenance personnel and system unavailability (Reason, 2000; Swanson, 2001). Hence, the issues that have been highlighted have drawn the attention of researchers wishing to solve them by establishing objectives to be achieved before conducting any actual problem-solving.

For instance, one of the major issues discussed with regard to the maintenance environment is that of system breakdown, which may lead to other problems such as system or component deterioration, unplanned failures and interruptions in production processes. These might be caused by improper planning before undertaking PM actions and the improper conduct of PM on a system (Percy and Kobbacy, 2000; Liyange and Kumar, 2003). Therefore, most researchers have studied the issue of minimizing system downtime, particularly system reliability and availability, setup times, product quality, spare parts and the complexity of PM actions. Here, PM planning plays an important role by establishing objectives or purposes in order to solve issues regarding system breakdown. Thus, in the extant literature some purposes that are commonly discussed are optimal PM intervals, proper job scheduling and the assignment of PM tasks. The descriptions of these purposes are presented in Table 2.

Table 2: Description of the purpose

Purpose	Description
Optimal PM intervals	The time intervals for PM actions such as replacement, which predetermines when to replace a system or component before they fail.
Proper job scheduling	The job-to-job sequencing of PM actions within the range of a time interval (Cassady and Kutanoglu, 2005).
Assignment of PM tasks	What PM actions to undertake and how to perform them.

Referring to Table 2, the objective is to set out the intentions for studying PM planning as derived from literature reviews, since doing so will guide PM planning reviewers in a highly systematic and organized manner. Besides setting out the purposes behind PM planning, another important element in explaining the PM planning concept is to describe the state of systems, which will be explained further in the subsections that follow.

4.2 The state of systems

Other than defining objectives, the PM planning concept encompasses the description of a system’s state, its function and importance. A system is envisaged as an assembly of interconnected components arranged to carry out a process. From an operational perspective, the system is defined in terms of its state, which refers to its condition with respect to its attributes. The purpose of considering the state of a system is to represent it as operating normally, as operating in breakdown mode or as having failed completely. Thus, the decision-making for PM planning is based on the state of the system, which seeks to base an analysis on the condition of the system with respect to its function. Therefore, most researchers have concentrated their work on solving maintenance problems by paying attention to the state of systems prior to further measurement and analysis. This is where PM planning should consider the system's state to assist with further complex analysis. In the literature, the state of a system is categorized in two ways, i.e. as single-unit and multi-unit systems. A description of the state of systems in PM planning is presented in Table 3 below.

Table 3: Description of the state of systems (Source: Cho and Parlar, 1991)

System's state	Component's state	System configuration
Single system	Single component	No
	Multiple components	Serial or parallel
Multiple systems (multi-systems)	Multiple components	Serial or parallel

Referring to Table 3, a single-unit system consists of either one component or multiple components. By contrast, multiple or multi-unit systems consist of several system units with several components. Furthermore, the elements of each system state are arranged mechanically into two configurations, namely the serial and the parallel. In a serial configuration, the entire system fails if any one of the system's components fails. By contrast, for a parallel configuration, the entire system works as long as not all the systems or components fail. Hence, if any problem occurs in any one system, the other systems or components may also be affected (Cho and Parlar, 1991; Khanlari et al., 2008). Without a proper maintenance system, a maintenance engineer might replace the entirety of a system's equipment on its failure, which would be very costly (Rana, 2014).

By representing a system in terms of its state, PM can be conducted with the aid of methods applied for solving the issues that have caused a system's breakdown. As a system becomes more complicated, more sophisticated PM planning is needed to solve the maintenance issues related to the system's performance. Therefore, suitable methods that can deal with maintenance issues dynamically should be considered as part of the development process for optimal PM planning. Thus, the state of systems has been a focus of the review of the literature concerning PM planning and proper attention has been given to the condition of systems. Besides considering the state of systems, the other important element in explaining the PM planning concept is the methods used, which will be explained in subsequent subsections.

4.3 Methods

Another important element of the PM planning concept is the methods applied to find the best solution for maintenance issues raised in relation to PM planning. The method is the description of any particular procedure followed to determine an optimal PM plan under certain maintenance requirements or constraints. The purpose is to assist with related analysis through an established and systematic procedure, which can facilitate the achievement of certain accurate and efficient results. Thus, the decision-making in PM planning is based on the methods applied, which can be affected by the outcomes or results of analysis. Therefore, most researchers have studied the most suitable and applicable methods for solving maintenance problems, particularly when considering the measurement and analysis steps. In the literature, several methods have been applied by researchers regarding PM planning, which are classified into six categories as shown in Table 4 below.

Table 4: Descriptions of methods applied in PM planning

Methods	Classifications	Descriptions
Fuzzy logic, genetic algorithm (GA), neural network, Markov chain, Bayesian network, heuristic algorithm.	*Artificial intelligence (AI)*	The theory and development of computer systems which are able to perform tasks and to allow systems to perform functions that would normally require human intelligence (Kobbacy, 2008).
SIMAN, Monte Carlo, Witness.	*Simulation*	A computable technique which has the capability to analyze, design and operate complex systems for better understanding without affecting the real system (Alabdulkarim et al., 2013).
Linear programming, non-linear programming, integer linear programming (ILP), dynamic programming, mixed integer linear programming (MILP), Weibull distribution, proportional hazard model (PHM).	*Mathematical formulation*	A mathematical representation for making a decision on the best possible allocation of scarce resources (Rommelfanger, 1996).
Similarity coefficient matrix.	*Matrix formation*	A rectangular array that encompasses numbers, symbols, or other mathematical objects for which operations like addition and multiplication are defined (Romesburg, 2004).
Failure mode and effect analysis (FMEA), failure mode effect and critical analysis (FMECA).	*Critical analysis*	Detailed studies in identifying the failure mechanism and criticality of the failures that occur and that would affect the condition and the lifetime of a system (Zhao, 2003).
PROMETHEE, analytic network process (ANP), analytic hierarchical process (AHP).	*Multi-criteria*	Decision method that uses various alternatives by considering all conflicting criteria and the judgments of a decision-maker (Labib et al., 1998).

Based on the three elements of the PM planning concept, the reviews are structured in a way that represents planning in conjunction with the objectives, the state of systems and the methods applied. Therefore, it is important to have the basics of the planning outlined for maintenance issues and that process is familiarly known as planning-based PM. Planning-based PM is perceived as a fundamental analysis that should be undertaken before any planning is conducted, in accordance with the elements of the PM planning concept.

5. Planning-based PM

Planning-based PM is all about the essential analysis of comprehensive planning for PM. It involves the fundamental maintenance criteria of systems as the basis for an analysis that derives the best PM plan. Planning-based PM is categorized in three ways, i.e. cost-based, time-based and failure-based planning. Details of planning-based PM will be discussed in subsequent subsections.

5.1 Cost-based

Cost-based planning analyzes the capital cost and benefits to organizations of PM, as well as the revenue it helps to generate (Turkcan et al., 2007). It is important to have cost-based planning as a fundamental assessment as it compares the costs of solutions with the economic benefits that would be gained if the solution was put into effect. In the PM planning literature, cost-based planning analysis makes reference to the cost involved when evaluating maintenance factors, such as the costs for repair, replacement, spare parts, tools and manpower. According to Stenstrom et al. (2016), maintenance costs are formulated dependent on the cost of downtime, reliability characteristics and the redundancy of assets. The methods are conducted based on the maintenance factors that affect PM planning's effectiveness.

Kobbacy et al. (1997a) have performed cost-based planning in order to determine the relationship between the PM interval and the operating cost per unit of time, and the component availability of a single-unit system. The authors used the Weibull distribution method to determine the significance of correct failure time and to compare the effect of the distribution, whether exponential, Weibull, normal, log normal or gamma, with PM intervals. Furthermore, Kardon and Fredendall (2002) developed a mathematical formulation using Weibull distribution for three types of system states, i.e. single-unit systems with a single component, single-unit systems with multiple components and multi-unit systems with multiple components, which incorporated the overall probability breakdown and the cost of PM decisions for multi-unit systems in serial configurations. Based on the comparison between all the system states, the outcome of the analysis offered an optimal PM interval based on the minimum total expected costs that eased the decision to perform PM.

Mijailovic (2003) compared Weibull and exponential distributions in probability calculations of maintenance costs throughout the PM planning process. The calculation was applied to a single-unit system and multiple components and took two parameters into account, which were the period between PM scheduling and the availability of components. Based on the comparative costs, an optimal PM interval which minimized the cost per unit of time, or maximized the component availability was selected. In another study, Bartholomew-Biggs et al. (2006) investigated PM scheduling for single systems which reflected the cost of performing PM. The authors used Weibull distribution with hazard rate models to predict the frequency of a system's failure in terms of cost optimization. Based on the complexity of the mathematical formulation in the analysis, an optimal PM interval was determined by calculating the optimum mean cost for performing PM. When set the main objective of minimizing total costs, Nourelfath et al. (2016) developed an optimization model using Weibull distribution and a solution algorithm that integrated quality, production and maintenance parameters for an imperfect process in a multiperiod, multiproduct, capacitated, lot-sizing context. The authors also proved that an increase in PM levels led to reductions in quality control costs when the proposed model was adopted.

Other mathematical formulation methods are dynamic programming, integer programming and mixed integer linear programming (MILP). Vaughan (2005) addressed the inventory of spare parts by grouping identical components that proved to be economical for PM. The author had performed the analysis in a single-unit system of multi components in order to determine the optimal PM interval. Das et al. (2007) proposed a PM planning model for performance improvement in terms of cost-effectiveness on a cellular manufacturing system. By incorporating integer programming, the authors compared the model in two scenarios; with and without considering PM. Two maintenance criteria were considered, namely a system's reliability and resource utilization, to determine the optimum time interval for PM by minimizing the failure repair cost of the system as well as PM costs. Furthermore, the authors grouped the systems according to the optimum PM interval to improve the reliability and utilization of the system. Hence, by comparing the two scenarios, the scenario which considered PM provided a significant improvement in terms of system reliability and total cost reductions, and thus achieved the objective of PM planning.

In their study, Goel et al. (2003) presented a MILP for integrated design, production and PM planning. The authors applied the method in a multi-process plant environment. At the design stage, a reliability allocation model was combined with the existing optimization framework to determine the initial reliability of each unit of the component and its optimal size. Hence, at this stage, the operational availability of the proposed integrated approach was improved. The outcome of PM planning was presented in terms of an optimal schedule for each component within a predetermined time interval based on the analysis of the maintenance costs and component availability.

Meanwhile, Wu and Zuo (2010) investigated the relationship between linear, non-linear and hybrid programming models on a single-unit system. Three maintenance factors were involved in the analysis, which were the failure rate, the system cost and its reliability. The expected cost of the three programming models for the sequential PM were formulated, and necessary conditions for determining the optimal PM policies for both linear and non-linear, as well as hybrid cases, were derived. Integrating quality improvements into PM decision-making, Lu et al. (2016) proposed a joint model for a deteriorating single-machine manufacturing system. In this instance, machine reliability was developed based on a proportional hazard model (PHM) considering the influences of the degradation states of quality-related components on machine reliability. Validated by a case study, the effectiveness of the model was proven when an optimal PM schedule was obtained. Overall production costs had also been minimized due to reductions in loss of quality as well as repair cost savings.

Other than as mathematical formulations, AI techniques had also been applied widely in cost-based planning. Methods that are commonly applied in AI environments are the genetic algorithm (GA), fuzzy rules and the Markov chain. Lapa et al. (2006) built an optimization model for PM planning with respect to a single-unit system with multiple components. Two main criteria had been considered in the developed models which were applicable to unavailable (undergoing maintenance) active operations and components for evaluation procedures. The model was verified through the electrical-mechanical system of a nuclear power plant. The GA was adopted, where the optimal PM that had a high level of reliability with low cost was the search process of the developed model. The result of minimizing total PM costs showed the best schedule job for each component based on the period between the PM schedule and the availability of the system. Bris et al. (2003), on the other hand, proposed a PM planning model in a multi-unit system that was arranged in series and parallel configurations to ensure that the assignment of the properly scheduled PM would be cost-effective. The authors proved that by using the GA in the developmental model, total costs could be optimized by analyzing the system availability and PM intervals.

Mahadevan et al. (2010) used an advanced method that combined GA and a simulated annealing heuristic method to optimize PM planning for a single-unit system with multi components in a process industry. The authors highlighted the objective function for these analyses, which were the PM time for and costs of replacement, the time to repair, downtime, failure and standby, which basically constituted the problem of combining the maintenance actions for the components during the entire design phase. As a result, the outcome for PM planning was the assignment of PM tasks, which was based on the critical components for all systems that provided the minimum cost for the entire design period. Furthermore, Lin and Wang (2012) established an extension from the study by Bris et al. (2003), which presented a hybrid GA to optimize the periodic PM in a case study conducted for a multi-unit system arranged in series and parallel configurations. Development of the hybrid GA concerned the structure of reliability, block diagrams, the maintenance priority of components and a PM schedule. Instead of applying a conventional trial-and-error process, a response surface methodology (RSM) was adopted to determine the crossover and mutation probability in the GA. The outcome from this study was the discovery of the optimal PM interval based on the minimized total PM cost.

In addition, Khanlari et al. (2008) used fuzzy rules to prioritize the systems for performing PM. The objective of the planning was to reduce the total costs for maintenance, and indirectly minimize the system's breakdown. Planning was conducted in a multi-unit system and PM was used to measure the reduced product quality or the lost production capacity. In the developed algorithm, six criteria were identified, which were the sensitivity of operation, the mean time between failures, the mean time to repair, workload, as well as the availability of required parts and the availability of repair personnel. However, due to the limited number of equipment selected in the production plan, a method for maximizing the system reliability was difficult to achieve. In a study of the state of a single-unit system with multiple components, Tosun and Kuruüzum (2009) proposed a model for improving the system's availability and decreasing the repair costs due to system downtime. The authors used a Markov chain in AI to represent the sequence values in the system by focusing on the maximum availability and minimum cost in order to find the optimal inspection period. It was shown that in the numerical examples, system availability was maximized with the minimization of the PM's cost in order to find the optimal PM interval.

Panagiotiduo and Tagaras (2007) also used the Markov chain method to derive the optimal PM interval in terms of cost for a single-unit system. The analysis was conducted by considering the condition of quality (such as in and out of control) and failure rate. Throughout the analysis, the outcome of the cost optimization was the condition of quality before the planning for the system and PM interval, which was based on shift and failure time distribution. Also adopting AI, Fitouchi and Mourelfath (2014) proposed an integrated model for production and general preventive maintenance planning for multi-state systems that was solved by the exhaustive search (ES) method and the simulated annealing (SA) algorithm via numerical experimentation. The integrated model simultaneously gave appropriate instants for preventive maintenance and production planning decisions, which improved the total production and maintenance costs.

For non-AI cost-based planning, simulation techniques also received great attention in the literature. Knapp and Mahajan (1998) optimized a manpower model which aimed to reduce the cost of maintenance resources by optimizing the allocation of the cost of manpower based on workload demand. The optimization model was implemented using a simulation analysis (SIMAN). The model provided statistical information, such as the utilization of workers and the queue lengths of failed systems in each area and for each craft type. Results showed an improvement of the overall performance due to the allocation of workers, worker utilization and queue lengths, which helped with decision-making for PM planning in regard to the workers' assignments.

Matrix formation was also included in the cost-based planning experiments of which one, known as the SCM, was used in a similar matrix structure. Talukder and Knapp (2002) used the group technology (GT) concept of the heuristic method to group the systems into blocks within a multi-unit system in a series configuration in order to make decisions on the block or grouping of the system, which minimized the PM cost. Single linkage clustering (SLINK) is one examples of SCM which was used with heuristic-based calculations to generate groupings of similar systems. The cost of the block PM for each group was calculated using the developed cost model. In the developed block of the PM cost model, the PM interval was measured by reducing the PM cost for individual systems in groups and the time interval was analyzed heuristically using the analysis of variance (ANOVA). The authors stated that the approach generated excellent results for real-size problems, thus it may be able to assist the planning of PM on systems in groups.

By contrast, examinations of multi criteria methods is very limited in the literature as it involves solving complex decision problems. AHP is one method that falls under the multi-criteria umbrella. Labib et al. (1998) used AHP to develop a dynamic and adaptable procedure in a multi-unit system that utilized the existing data and supported decisions for planning purposes accordingly. The methodology consisted of three hierarchical stages such as criteria decision analyses, criteria prioritization and system critical judgments. The outcome of the methodology helped decision-making processes by prioritizing the system's criticality and focusing on specific components for PM operations.

Overall, according to the review, cost-based planning was used aggressively to evaluate the total anticipated cost and effectively weighed the costs and benefits of the proposed method with regards to PM planning. However, there were a number of arguments against cost-based planning as a decision-making tool. The ambiguity and uncertainty involved in quantifying and assigning a monetary value to intangible items could lead to inaccurate analysis. Thus, it may increase risks and cause inefficient decision-making. A summary of the review is presented in Table 5.

Table 5: Summary of cost-based in PM planning

Category	**Method**	**System's state**	**Outcome**	**References**
Mathematical formulation	Weibull, normal and gamma distribution	Single-unit system with single component	Optimal PM interval	*Kobbacy et al. (1997)*
	Dynamic programming	Single-unit system and multi-unit component	Optimal PM interval	*Vaughan (2005)*
	Probability and reliability function	Multi-component system	Cost rate and PM with warranty period	*Darghouth et al. (2016)*
Mathematical formulation	Weibull and exponential distribution	Single-unit system	An optimal PM interval which minimized cost per unit time	*Mijailovic (2003)*
	Weibull and exponential distribution	Single-unit system	An optimal PM interval which minimized cost per unit time	*Mijailovic (2003)*
	Weibull distribution	Single-unit system	Optimal PM interval	*Bartholomew-Biggs et al. (2006)*
	Weibull distribution and	Multi-unit system	Improvement of total cost	*Nourelfath et al. (2016)*

	algorithm			
	Dynamic programming	Single-unit system and multi-unit component	Optimal PM interval	*Vaughan (2005)*
	Integer programming	Multi-unit system	Optimal PM interval in a group of systems	*Das et al. (2007)*
	MILP	Multi-unit system	Proper PM scheduling job	*Goel et al. (2003)*
	Linear, nonlinear, hybrid	Single-unit system	Optimal PM scheduling job	*Wu and Zuo (2010)*
	Proportional hazard model (PHM)	Single-unit system	Optimal PM scheduling job	*Lu et al. (2016)*
Artificial intelligence (AI)	GA	Single-unit system and multi-component	Proper PM scheduling job	*Lapa et al. (2006)*
	Monte Carlo technique/GA	Multi-unit system (series and parallel)	Optimal PM interval	*Bris et al. (2003)*
	GA and simulated annealing	Single-unit system and multi component	Assignment of PM tasks	*Mahadevan et al. (2010)*
	Hybrid GA/RSM as statistical analysis	Multi-unit system (series and parallel)	Optimal PM interval based on minimizing total PM cost	*Lin and Wang (2012)*
	Fuzzy rules	Multi-unit system	Proper PM scheduling job based on minimizing total PM cost	*Khanlari et al. (2008)*
	Markov Chain	Single-unit system	Optimal PM interval	*Tosun and Kurüuzum (2009)*
	Markov Chain	Single-unit system	Optimal PM interval	*Panagiotiduo and Tagaras (2007)*
	ES and SA algorithm	Multi-state system	Improvement of total production and maintenance costs	*Fitouchi and Nourelfath (2014)*

	Multi-objective genetic algorithm (MOGA)	Multi-component system	Optimized machine availability at minimum cost	*Adhikary et al. (2016)*
Simulation	SIMAN simulation	Single-unit system and multi-component	Assignment of PM tasks	*Knapp and Mahajan (1998)*
Matrix formation	Grouping - similarity matrix - ANOVA analysis	Multi-unit system (series)	Optimal PM interval based on group of systems	*Talukder and Knapp (2002)*
Multi-criteria	AHP- multi-criteria evaluation present in the form of a matrix	Multi-unit system	Assignment of PM tasks based on specific components	*Labib et al. (1998)*

5.2 Time-based

Time-based planning involves the measurement of the subject analysis in terms of the allocation and information of a certain period or duration of an operation. The time basis is crucial in planning, as it serves up an analysis which indicates the amount of time spent on projects, usually in reference to periodic processes. In the PM planning literature, the analysis encompasses a wide perspective, which requires a lot of information and data concerning maintenance factors such as the time spent for repair and replacement, the time lost because of failure, the time allocation for gathering spare parts, shift times and time for a system's operation. There are various methods conducted in regard of maintenance factors that would affect the effectiveness of PM planning.

Methods grouped under the mathematical formulation category have received tremendous attention from researchers into time-based PM planning. One of the methods deployed is dynamic programming, which is known as an optimization method that transforms complex problems into sequences of simpler problems. Dekker (1995) developed a framework for an integration of optimization, which consisted of priority setting, planning and combining PM tasks. In the priority setting, the order of PM tasks' execution was determined. The analysis involved a dynamic programming which depended on the rolling horizon presented in the planning and combining of PM tasks. Multiple objective criteria and the uncertainty of the PM interval led to optimal solutions. Hence, a properly scheduled job for PM planning was the outcome of the analysis based on the optimal integration of the combination of PM tasks and planning.

Wilderman et al. (1997) grouped PM actions using a dynamic program with a rolling-horizon approach in order to prepare for a properly scheduled job, and thus they minimized costs. The rolling-horizon approach for grouping PM actions was based on component usage. The approach was founded upon long-term planning, that was to be updated easily by incorporating short-term information that could change over time. However, due to the complexity of practical situations, it was difficult to achieve real optimal solutions. Duffuaa and Al-Sultan (1997) also used dynamic programming to formulate and obtain an implementable solution with regards to PM actions and emergency maintenance. The authors aimed to develop a schedule for job assignment by minimizing delays and maximizing the utilization of resources such as manpower, spare parts and tools through the exploitation of integer and stochastic programming. The solution provided a decision-making tool for assigning manpower, which was reserved for anticipated jobs based on the schedule developed.

In addition, Zhao (2003) applied dynamic programming to determine the optimal PM interval of a critical reliability level for a single-unit system with multiple components, subject to degradation. The parameter adopted to undergo the analysis was the time interval for the PM and its hazard rate. By using dynamic programming for the analysis, criteria such as the hazard rate, reliability, availability and cost were compared with the operational time. The outcome of the analysis could support the decision-making on PM actions based on the value of the acceptable critical reliability level with an optimal time interval in the PM cycle. Van et al. (2011) also presented a study of dynamic programming with the rolling horizon to determine the effectiveness of grouping in PM planning for a multi-component system. The authors took into account the PM durations and the scheduling of maintenance operations occurrences. The authors further developed a methodology for dynamic programming with positive economic dependence, which suggested that the grouping of PM actions was cheaper rather than performing PM on components in isolation. Furthermore, the authors developed a new algorithm by considering some opportunities with limited durations, which led to the reaping of profits from PM actions in the grouping optimization procedure.

Other time-based planning mathematical formulation methods are linear, nonlinear and mixed integer programming. These types of programming involve the computation of the minimization or maximization of the value of an objective function such as time under a set of constraints imposed by the nature of the problem being studied. Yao et al. (2004) developed a MILP model for determining the planning through the assignment of PM tasks according to a group of tools, by using a horizon planning approach in a single-unit system with multi components. The authors also proposed a two-level hierarchical framework, which consisted of PM planning at a higher level and PM scheduling at a lower level. The PM planning captured both the stochastic failure process of the system and the demand pattern, which were modelled for the long term. Meanwhile, PM scheduling was based on a short-term model, which conformed with the PM planning model and delivered an optimal PM schedule. The authors stated that the methodology was feasible and promising, which brought benefits such as the increase of equipment's availability and the ability to generate more profit while eliminating human errors.

Su and Tsai (2010) presented an efficient method of flexible PM planning by determining the period of PM and the sequencing of jobs simultaneously for a multi-unit system in a parallel configuration, that minimized the time taken to complete all jobs, which is known as the "makespan" of a schedule. By using MIP, the authors carried out studies on two systems that were arranged in parallel with three different cases of unavailable periods (*r*, which are $r1 \neq r2;\ r1 = r2 = r$) and no waiting time was allowed for the two unavailable periods. Due to the exponential time complexities, the computational results were quite efficient for large problems. Thus, the decision on the PM planning could be made based on the job scheduling and repair arrangements.

Moghaddam and Usher (2010) developed a non-linear MILP model on a single system in order to determine the optimal PM interval as well as assigned PM actions. Cases that considered PM actions were based on maintaining the system, replacing the system or doing nothing. The method aimed to minimize the total cost subject to constraints on the system's reliability. The developed model could also be used to generate a new PM planning process quickly, even after unexpected failures had occurred in the system; hence, PM scheduling could be updated from time to time. Chen (2010) used ILP to deal with the sequencing and setup time problems in a single-unit system's state. The model was developed to minimize the total setup time, subject to maintenance and due dates. However, the ILP model consumed more computation time and could only be used for small-sized problems when compared to the heuristic approach.

Other methods such as the proportional hazard model (PHM) and Weibull distribution have also received attention for determining an optimal PM interval in the analysis of time-based PM planning. Kobbacy et al. (1997b) also used PHM for the state of a single system with multiple components to find the optimal PM interval. During the planning, the authors performed analysis by considering factors such as duration to perform PM and time to experience failure when determining an expected cost within a time horizon. The result of the optimal PM interval was presented by selecting a longer time (in days) with the lowest availability of the system compared to other time in the cycle number. Caldeira and Guedes (2007) furthermore, presented a Weibull hazard function to calculate the optimum frequency to perform PM in a single-unit system with multiple components that arranged in a series configuration. The calculation involves the interval time between PM actions for each component, depending on factors such as failure rate, repair and replacement time for each component in the system, thereby minimizing the PM cost. Thus, costs for breakdown were minimized and the PM actions could be planned and assigned within the predetermined interval.

Aside from mathematical formulation, AI has also been adopted for time-based PM planning. Referring to the literature on PM planning, AI methods that have been applied are fuzzy rules, GA, and Bayesian and heuristic Tabu searching. For example, Hennequin et al. (2009) used fuzzy logic for a single repairable system that had undergone PM by accounting for the impact of imperfections due to human factors. The authors used three membership functions for comparisons such as technicians' experiences, intervention times and the ages of systems, which aimed to minimize the expected cost rate per unit of time and maximize the availability of the system. The results of the cost and availability functions of optimal PM were presented by comparing the optimal ages of PM actions through simulation methods to build more accurate planning models for PM which considered human factors.

Tsai et al. (2001) incorporated a grouping method for mechanical components in a single system with PM actions. The authors optimized the mechanical components based on the failure rate and reliability to formulate an age-reduction model with the integration of GA. In the complex numerical calculation concerning PM scheduling using GA, an optimal combination of PM actions maximized the effects of systems in terms of their costs and lives, thereby reducing the calculation time. Van et al. (2012) optimized both GA and MULTIFIT algorithms based on the rolling horizon for grouping PM actions with the availability constraint of having a limited number of maintenance personnel. The availability constraint refers to the PM interval which indirectly affects a component's useful life. Time-based planning was conducted in a single-unit system with multiple components. Similarly to Van et al. (2011), the authors applied a grouping of PM actions in four steps, namely individual optimization, tentative planning, grouping optimization as well as updates and decisions. However, their study differed in the sense that it used the MULTIFIT algorithm with the aid of the GA to determine the minimum PM duration of each group with a minimum number of maintenance personnel.

Lin and Huang (2010) used an AI model based on Bayesian methodology for a single-unit system with multiple components that usually deteriorated with age. When making decisions for PM planning, the authors determined an optimal non-periodic PM, which minimized the total cost per unit of time. The model had to overcome difficulties in performing analyses due to numerous uncertainties and the scarcity of data. Results of the analysis were based on the impacts of the intensity parameters function and the effect of time for PM actions that led to the attention to the critical factors for decision-making in PM planning. Raza and Turki (2007) compared the effectiveness of two meta-heuristics such as

Tabu searching and simulated annealing in relation to PM planning by focusing on scheduling and job processing for a single-unit system's state. Both algorithms were performed in a numerical experimentation with large-scale problems, which provided a more robust solution for minimizing total completion time. In the study, the characteristics of an optimal schedule assisted in a more directed planning for PM considering the possibility of system failure.

With their main aims being to improve system availability and system throughput simultaneously, Wang and Liu (2015) investigated multi-objective parallel machine scheduling problems with two kinds of resources; machines and moulds, and with flexible preventive maintenance activities on resources. A multi-objective integrated optimization method with version 2 of the non-dominated sorting genetic algorithm (NSGA-II) was adopted, that integrated production scheduling and PM planning on machines and moulds simultaneously. Results showed that that the integrated method outperformed periodic PM planning in terms of multi-objective metrics.

Applications of simulations for time-based PM planning is the approach least covered by the literature. However, that approach is very useful for obtaining significant result from real-world systems' operation and behaviour. The information obtained can be applied in PM planning to improve system performance. Abogrean and Latif (2012a) presented a new approach using Witness simulation for combating issues related to maintenance in a cement industry. The issue they highlighted was the system breakdown due to deterioration caused by age and usage that had led to the interruption of production. The authors developed a simulation model and demonstrated it on a single-unit system by focusing on the spare parts and maintenance personnel, with reference to the time-effective aspects of the situation. Thus, better planning for PM could be implemented in the actual operation based on the result of a simulation by improving the stock control system and ensuring efficient communication and teamwork throughout the facility.

Also adopting simulation, Assid et al. (2015) proposed an effective joint production, setup and maintenance control policy for inflexible and unreliable single machines that produced two part types. The control policy was evaluated using a combined continuous/discrete event simulation model; the hedging corridor policy (HCP) and the block replacement policy (BRP). Aiming to maximize machine availability and to reduce the risk of shortages, it integrated the concept of opportunistic maintenance by taking advantage of the machine stoppages for setup operation to carry out preventive actions.

Overall, time-based planning has been used widely to evaluate the total anticipated time for PM and its impacts in decision-making with regard to PM planning. It has been quickly and easily applied from the planning perspective, but the value of time assigned for projects can be varied and inconsistent. Thus it affects measurement and analysis, especially in the real, practical world. The literature concerning time-based PM planning is summarized in Table 6.

Table 6: Summary of time-based PM planning

Category	**Method**	**System's state**	**Outcome**	**References**
Mathematical formulation	Dynamic program (combined activities)	Single-unit system and single component	Proper PM scheduling job for grouping of PM tasks and PM planning	*Dekker (1995)*
	Dynamic programming with rolling-	Single-unit system and single	Proper PM scheduling job for a group of	*Wilderman et al. (1997)*

	horizon grouping maintenance activities	component	PM actions	
	Dynamic programming	Multi-unit system	Proper assigning of manpower to perform PM	*Duffuaa and Al-Sultan (1997)*
	Dynamic programming	Single-unit system	Optimal PM interval	*Zhao (2003)*
	Dynamic grouping with positive economic dependence	Single-unit system and multiple components	Proper PM scheduling job based on grouping of PM actions	*Van et al. (2012)*
	MILP (group tools)	Single-unit system and multiple components	Proper PM scheduling job based on a group of tools	*Yao et al. (2004)*
	MILP	Multi-unit system (parallel)	Proper PM scheduling job and repairs arrangement	*Su and Tsai (2010)*
	Non-linear MILP-cost	Single-unit system	Optimal PM interval and assignment of PM tasks	*Moghaddam and Usher (2010)*
	ILP	Single-unit system	Optimal PM interval based on minimized total setup time	*Chen (2010)*
	Proportional hazard method (PHM)	Single-unit system	Optimal PM interval	*Kobbacy et al. (1997b)*
	Weibull distribution	Single-unit system and multiple components	Assignment of PM tasks	*Caldeira and Guedes (2007)*
	Genetic algorithm	Multi-component	Optimal PM interval	*Mabrouk et al. (2016)*
Artificial intelligence (AI)	Fuzzy logic	Single-unit system	Proper scheduling job based on human factors	*Hennequin et al. (2009)*
	GA	Single-unit system and multiple components	Optimal PM interval based on grouping of components	*Tsai et al. (2001)*
	MULTIFIT algorithm with GA (grouping)	Single-unit system and multiple	Optimal PM interval based on grouping PM	*Van et al. (2012)*

		components	actions	
	Bayesian	Single-unit system and multiple components	Assignment of PM tasks	*Lin and Huang (2010)*
	Tabu search/simulated annealing	Single-unit system	Proper PM scheduling job based on minimization of total completion time	*Raza and Turki (2007)*
	NGSA-II	Multi-unit (parallel)	Optimal production scheduling and PM	*Wang and Liu (2015)*
Simulation	Witness simulation	Single-unit system	Assignment of stock control system prior to performing PM	*Abogrean and Latif (2012)*
	HCP & BRP	Single-unit system	Reduction of risk of shortage	*Assid et al. (2015)*

5.3 Failure-based

Another basic analysis for deriving the best PM planning, failure-based planning, involves analysis that takes into account information about system or component deterioration. Literature on failure-based PM planning has been reviewed and involved a detailed definition of failures that occur with systems or components before further analysis is carried out. There are several failure-based planning methods that would affect PM's overall effectiveness. In failure-based planning, in order to anticipate the characteristics of a failure mechanism, critical analyses involving the objectives of analysis and evaluations of failure issues are carried out and extensively quantified. This should ensure that PM is conducted properly, thus reducing failure. Methods of critical analysis commonly used are tree diagrams, failure mode and effect analysis (FMEA) and failure mode effect and critical analysis (FMECA).

Ab-Samat et al. (2012) carried out a case study on planning for PM with the aid of tree diagrams. The authors outlined the problems faced by the company in their case study which included the insufficiency in numbers of maintenance staff available to perform PM and the systems breakdowns that led to inefficient PM planning. Based on the data of prior failures and system breakdowns, a root cause analysis of the issues involved in the ineffective PM was presented as an affinity diagram. Then, a PM planning model was developed and the analysis was presented in the form of a tree diagram that enabled possible solutions to be generated. The proposed solution that was validated at the company studied provided for the maintenance staff to perform PM by focusing on the critical systems instead of the non-critical systems which improved their PM processes.

In another study, Ahmad et al. (2011) conducted a case study on a single-unit system with a single component in a processing industry. The authors developed a PM model that consisted of three general steps which were problem identification, evaluation of the current system condition and maintenance decision. FMECA was used in the model developed to identify possible external factors that contributed to the component failure. Once the external factors and failure modes were identified, the critical component was evaluated using a PHM before determining the PM interval in the current system state by means of an age replacement model. Thus, the replacement of components based on the PM interval for the current system state implied a reasonable decision to improve system reliability.

Cicek et al. (2010) also proposed a failure analysis methodology for PM planning, where the evaluation was conducted using a reliability model, which permitted the use of flexible intervals between maintenance interventions. The authors focused on the failures and accidents to achieve the best possible safety levels at the lowest possible cost. A case study was conducted on the state of a single unit with multiple components in a fuel oil system in the marine engine industry. Evaluation of the failures using FMEA analysis was structured based on feedback, brainstorming and expert judgment resulting in PM planning that increased the reliability of the system. Therefore, PM tasks can be assigned properly based on the priority of critical components.

Khan and Haddara (2003) presented a new, critical-based maintenance methodology for decision-making in PM planning by integrating the issue of reliability with safety as well as with environmental issues. The critical-based method involved risk and failure analyses that were intended to inform decisions about the required level of system design features, and to evaluate the system's safety and risk. The authors validated their developed methodology in a study of multi-unit system states for heating, ventilation and air-conditioning (HVAC) units. The methodology comprised of three main modules; estimation, evaluation and planning. In the estimation module, the consequences as well as the probability of failure were identified. The evaluation module consisted of aversion and acceptance analyses which reduced incidences of failure amongst components prior to designing the PM planning. This was done to reduce the level of risk resulting from system failure in the final module of PM planning. Based on the results obtained from the analyses, the PM interval time for the system was determined.

Almomani et al. (2012) presented a matrix formation known as SCM to group similar maintenance requirements together by focusing on the system failure types involved before the formation of virtual cells. The authors studied multi-unit systems in the mining industry. The major focus of the study was to group procedures by using SLINK; an example of SCM, to determine which systems could be paired by reference to their failure types. During the grouping process, duplicated systems and systems with variations of failure types were considered as seed systems in order to construct a matrix table of initial system failures. The results were presented in the form of a dendrogram that represented the similarity between systems before they were virtually grouped. The author stated that the grouped systems in the virtual cells indicated that creating a standard process plan with optimized inventory spare parts was an economical tool to use, especially during the phases of PM execution.

Al-Mishari and Sulaiman (2008) designed an optimal PM schedule based on failures that corresponded to the faster degradation of a system. The study was conducted on a single-unit system with multiple components. The authors focused on the impact of the failed accumulator on the degradation rate of a mechanical seal. In order to form an equation model using a load-sharing method, two parameters were taken into account to facilitate the analysis, namely the failure and repair rates. The parameters were modelled using the equation for systems affected by two components and they were presented in matrix form. With the aid of regression analysis, an optimal plan for PM on the components was presented by simulating different frequencies for each component in terms of the PM schedules.

Overall, according to the review of failure-based planning, prior to any further evaluations of failure, thorough assessments and analyses are crucial for defining the criticality of failure. This is because failure evaluation may have an impact on decision-making that pertains to PM planning. However, it is difficult to evaluate failure as the subject matter of any analysis due to the difficulty of gathering information on the time lost and the costs paid due to failures. Having said that, even though determining the root causes of failure mechanisms is time-consuming, it would affect further analysis if a failure's cause was not properly determined, especially in real-world scenarios. The literature concerning failure-based PM planning is summarized in Table 7.

Table 7: Summary of failure-based in PM planning

Category	Method	System's state	Outcome	References
Critical analysis	Tree diagram analysis	Multi-unit system	Assignment of PM tasks based on the criticality of systems	*Ab-Samat et al. (2012)*
	FMECA, PHM and age replacement model	Single-unit system and single component	Optimal PM interval based on critical components	*Ahmad et al. (2011)*
	FMEA	Single-unit system and multiple components	Assignment of PM tasks based on the priority of critical systems	*Cicek et al. (2010)*
	Critical-based analysis - probabilistic failure - consequence	Multi-unit system	Optimal PM interval	*Khan and Haddara (2003)*
Matrix formation	Similarity coefficient matrix	Multi-unit system	Assignment of PM tasks in groups of systems	*Almonani et al. (2012)*
	Load-sharing and regression analysis	Single-unit system and multiple components	Proper PM scheduling job based on failure components	*Al-Mishari and Sulaiman (2008)*

6. Literature assertions

PM is one of the maintenance actions that is normally applied in industry to ensure that systems get to perform their intended functions for a long time. Effective PM has proven to have a positive impact on organizations' operations and profits. According to the survey above, each of the literatures concerning PM planning was studied by discussing the elements underpinning the PM planning concept, namely the objectives, the states of systems and the methods applied. Gaps in the available literature and the justifications for these have been stated in the literature findings. They can be discussed further from three perspectives: the trends in the PM planning used, analyses of PM planning elements; and remarks for the direction of future research. Each of these perspectives will be briefly discussed in the subsections that follow.

6.1 Trend of PM planning

PM planning has been reviewed in terms of cost-based, time-based and failure-based planning addressing the objectives of PM, the states of systems and the methods applied. Reviews of each of the planning categories has been depicted in the forms of trend charts to present the planning-based outcomes by year. The trends have been charted based on the research published, which are summarized for each review. Thus, two elements have been selected to represent PM planning, namely the planning-based terms and the methods applied. The planning-based trends in PM planning have been charted based on the objectives of PM planning by year, whereas the trends for methods in PM planning have been charted out based on the classification of methods by year. Hence, the trends in PM planning and in the methods applied are depicted by year as shown in Figures 1 and 2 below respectively.

Referring to Figure 1, the planning-based literature was reviewed from 1995 to early 2016. From the observation of all planning-based studies, most researchers tended to optimize PM planning by calculating costs and time, theoretically to achieve their planning objectives. Even though the maintenance factors of cost and time can ease the calculation of the PM planning's objectives and direct investigators towards them, both cost and time are required to create reliable data and information before further measurement and analysis can be conducted. By contrast, failure-based planning received less attention and, thus, was scarcely found in the literature. From the review of failure-based planning, most of the literature denotes failure as an integer number which represents the availability of the failure of the system or component. Some researchers have interpreted failure in terms of the cost and time required to determine the complex calculation. However, without a proper definition, the failure that occurs may leave an impact on the data processing and analysis, both theoretically and practically. This is because the information about failure obtained in the form of data acquisition from the performance of the system is an aid for planning future actions and making decisions in relation to PM and taking improvement actions (Duarte et al., 2013).

The planning-based trends in PM planning reflect the changes in research concerning PM planning over time. The charts can be used to show the achievement of objectives in the research about PM planning and the planning-based studies that have received major attention from PM planning researchers. Similar trend can also be depicted in terms of the PM methods applied.

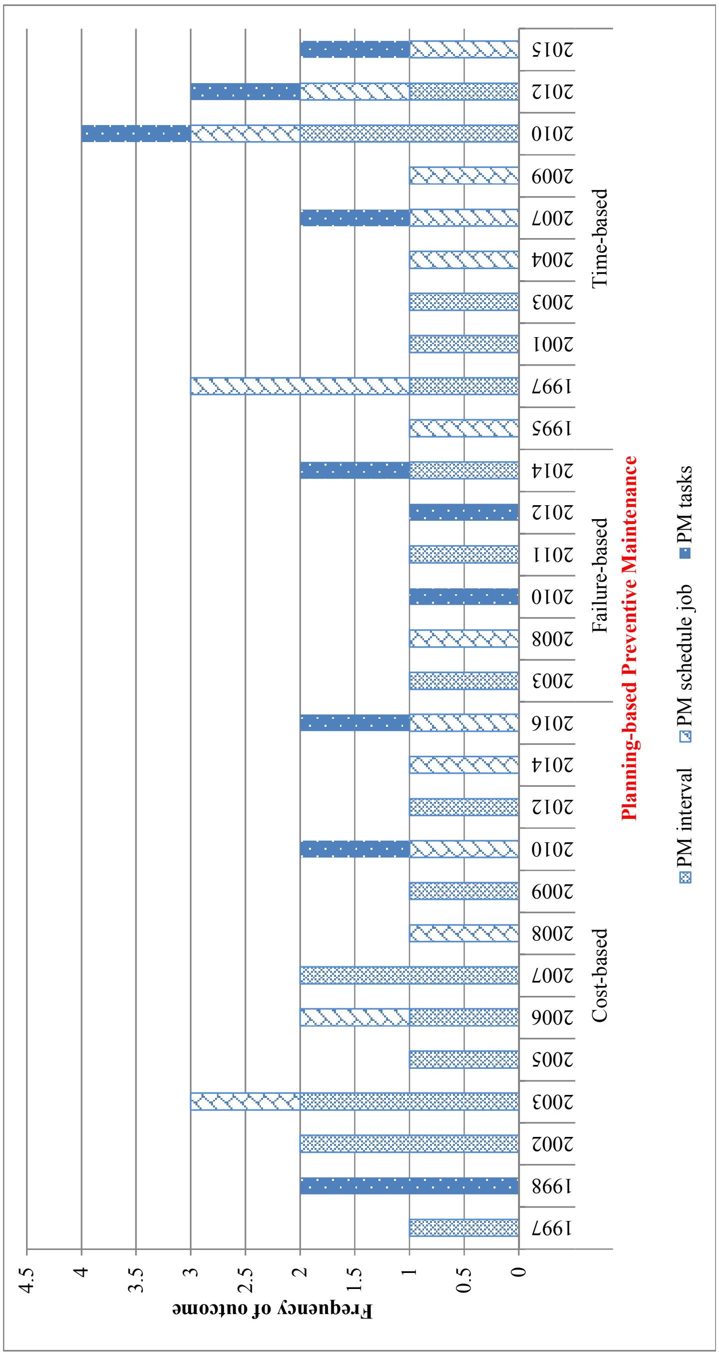

Figure 1: Trends in planning-based PM from 1997 to 2016

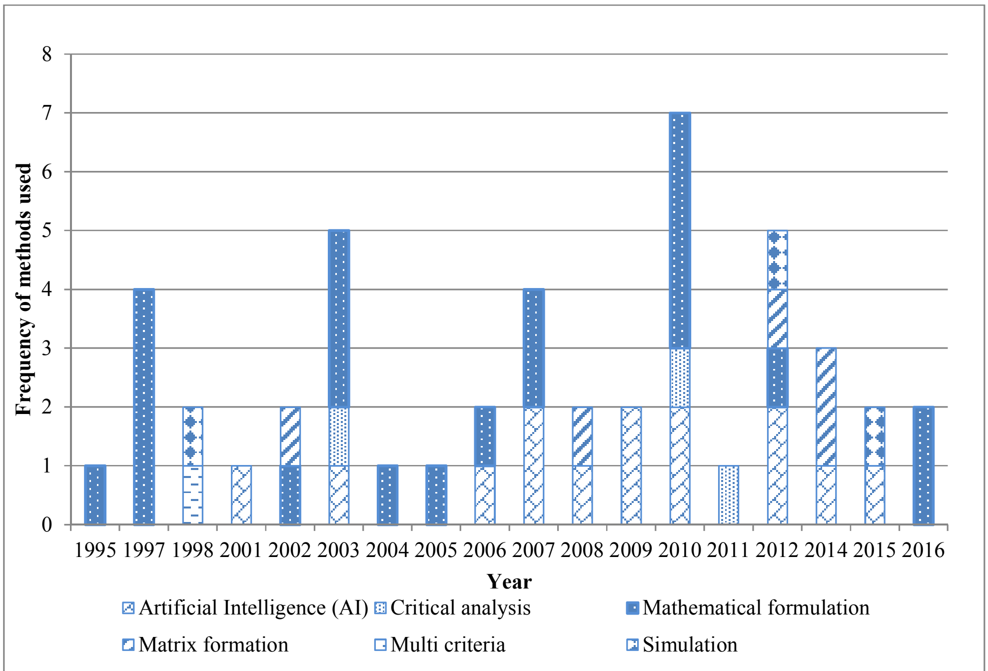

Figure 2: Trends in methods applied in PM planning from 1997 to 2016

Figure 2 shows the frequency with which different methods have been used in PM planning according to the extant literature for the years from 1995 to early 2016. It can be seen that AI and mathematical formulation have received a tremendous amount of attention from researchers setting out to achieve PM planning objectives. Compared to other methods, AI and mathematical formulation require complex calculations in providing great results theoretically speaking, but causing difficulties in terms of real industrial practice. For example, implementing AI requires the use of experts and software for analysis. This can lead to expensive and unreliable systems being implemented due to the fact that relevant parties have to invest in software and training to utilize it properly.

Meanwhile, mathematical formulation is dependent on data, and data problems in the real world will affect the real operational status of a process. For example, unrecorded data might be a major issue when locating documentation, or the required data might be too specific or too uncertain. Furthermore, numerical examples from mathematical formulations are created for application in the development of PM planning approaches. However, the values used in the approach adopted will affect real-world conditions qualitatively, so their practicability and the reliability of their final outcomes may be viewed with some suspicion. According to Wang and Hwang (2004), some practical problems regarding maintenance policies and planning cannot be fitted to mathematical models due to the simplified assumption made during mathematical modelling development. Hence, this would lead to unrealistic and inapplicable results, which might affect actual process operations. These are the reason why both AI and mathematical formulation get minimal interest and take-up in most industries.

Similarly, simulation is also less preferred by industries as it requires the acquisition of related simulation software that requires special training to run it. Even though simulation is very useful for describing maintenance issues, it still cannot replicate reality fully. This is because the accuracy of data would be a major issue among practitioners as it has to reflect real-world problems. Hence, this will affect decision-making for future recommended actions. Besides that, multi-criteria categorization is very complex because it involves making quantitative comparisons across multiple alternatives (Norgard, 2003). Multiple alternatives are usually evaluated based on their strengths and weaknesses by considering all conflicting criteria and decision-makers' judgments. However, analysis for this method requires higher levels of effort because the information concerning each potential solution is essential for accurate comparisons of information regarding each potential solution. Thus, additional time and resources are required, as high-priority needs, for performing this method.

Critical analysis entails both qualitative and quantitative methods because it involves detailed analysis and is focused on the causes of failure (Al-Najjar and Alsyouf, 2003). The characteristics of failure qualitatively describe the type, causes and consequences of failures. Then, the failure is quantified by ranking or assessing its criticality level based on human judgment. This can be performed by referring to knowledgeable and experienced personnel without any need to purchase software or initiate training. Moreover, the critical analysis method is preferable for assessing real-world practices because the accuracy and reliability of data obtained are not major problems. Practitioners can derive data from their actual operations. Besides that, matrix formation is a simple method that can be easily interpreted. It involves an uncomplicated and understandable mathematical formulation based on variables and functions. The matrix formation is also a concise and useful way to represent the relationships between variables and functions in various forms, such as L-shaped, similarity and incidence matrices. This method also requires specific information and careful verification because it may result ultimately in erroneous applications as the outcome. Hence, the application of the matrix formation in industrial practices can be said to be relevant and convenient as it does not require practitioners to understand complex mathematical formulations.

Trends in PM planning have shown a growth in the methods that had been used over time. The chart above has been used to show the transformation in the deployment of the various methods used in PM planning research and those methods that have received major attention from PM planning scholars. Hence, it has been important to show the development trends of suitable and practical methods for achieving the objectives of PM planning. Considering the literature's findings is the analysis of PM planning will be discussed in the following sections.

6.2 Analysis of PM planning

Another perspective from which to view PM planning concerns the analyses conducted in the previous literature. The analyses are described to highlight three essential points taken from the PM planning literature which are the planning-based methods, the grouping approach and the practicability of the planning-based techniques. Despite there being issues with the practicability of the aforementioned PM planning methods , Dekker (1996) highlighted the gap between theory and practice in relation to developed planning approaches. Thus, the limitations and the gaps between theory and practice for each aspect of PM planning will be explained briefly.

- *Planning-based*

According to the discussion in a previous section about trends in PM planning, failure-based planning had received less attention than cost-based or time–based studies. This was due to the limitations on interpreting failure data and information as the basis for analysis (Vaughan, 2005). However, failures and system breakdowns that occur in actual operations are the main maintenance issues that receive tremendous attention, both theoretically and practically speaking. This is because a system is recognisably an essential element of production floor processes whose failure may affect an organization's management and its operations (Wang and Hwang, 2004). Hence, both the cost-based and time-based approaches are limited by leading to there being a lack of the theoretical knowledge that ought to be uncovered in order to tackle the real-world problems being confronted by businesses. Thus, failure-based research can play a useful role by revealing reliable data from actual failures when they occur and by directing the analysis towards optimal PM planning for real-world applications.

- *Grouping approach*

In the literature, PM is comprised of a multitude of different aspects too broad to facilitate the introduction of general approaches that might cover all possible cases. Researchers have only focused on PM operations without analyzing the implementation of planning, to see if it is suitable for the systems studied. Therefore, the related planning for PM should be developed and examined in order to maximize the effectiveness of PM operations. From the previous discussion regarding trends in PM planning methods applied, the grouping approach was suggested because it is able to direct knowledge practically towards the creation of optimal PM plans. In general, as a group technology (GT) concept, grouping has been of growing interest in related maintenance environments. It may facilitate decision-making and influence planning by generating more accurate results (Dekker et al., 1997; Kellerer et al., 2013). Grouping is also an easy and simple approach for conducting planning-for-PM actions since the number of groups indicates the number of maintenance actions involved (Kuo and Yang, 2008; Rustogi and Strusevich, 2012). Previous literature has recorded that the scope of grouping covers the process of identifying similarities or recognizing identical characteristics amongst maintenance actions, systems or components and spare parts or tools, which should be evaluated and analyzed during planning-based subject analysis (Talukder and Knapp, 2002). Furthermore, the grouping approach in the PM planning has garnered attention from researchers as it provides various benefits such as simplifying maintenance actions, aiding mathematical analysis and creating a standard process plan which can lead to time and cost savings.

- *Practicability of the planning-based approaches*

Throughout the review undertaken, it was noted that the developing PM planning usually focused on determining how much PM should be carried out on related systems or components, and how frequently PM should be performed on related systems or components. The process of planning for PM is complex due to the fact that many parameters and maintenance factors need to be considered. In order to develop a practical PM plan, its feasibility and practicability in an industry needs to be considered, especially when dealing with failures and system breakdowns in actual operations. Therefore, determining the practicability of planning-based PM is an outcome which reflects the fundamental requirement for planning to support the robustness of the analysis that may lead to the development of optimal PM planning. In the literature, the methods applied to solve maintenance issues often provide results, which achieve the objectives of PM planning without proving the practicability and reliability of the results. As an example, from the operational perspective, the issue of system breakdowns is normally associated with failure, the understanding of which is fundamental for planning future actions in actual operations.

The grouping approach has been adopted to simplify analysis, since the systems are grouped together due to their similar failure characteristics. Hence, the grouping analysis conducted requires supportive evidence derived from the performance of a cost-benefit analysis for the group of systems or components studied prior to the allocation of a time schedule for PM. Analyses related to cost and time are inevitable parts of various types of research as the results provide some supportive evidence about the work's economic advantages prior to decision-making (Löfsten, 1999). Cost-benefit analyses are simple and convenient for practitioners to undertake when they involve the computation of the actual costs of maintenance in conjunction with the maintenance duration. Hence, the results of cost-benefit analyses will assist decision-making processes in the sense that they can provide outcome which reflect the practicability of suggested solutions in the real world.

7. Conclusion and remarks for future research direction

Based on the discussions derived from the literature's assertions, it has been identified that most of the applied PM methods have tended towards the development of complex mathematical equations in order to solve maintenance issues. However, according to Almomani et al. (2012), relatively few studies have focused on the determination of optimal PM planning. The authors have advanced a method for simplifying maintenance operations by grouping systems, which ca enhance PM planning. Yet, the condition of systems should be taken into consideration when developing an optimal plan prior to the ratification of a grouping process. Therefore, it is preferable to have a model or framework to act as guidance in the proper procedures necessary for optimal PM planning.

The direction of future research should focus mainly on the development of frameworks for two major aspects of PM: the approach to implementing it and the creation of environments that enable planners to cope with industrial practices. Grouping seems to be a practical suggestion that can be implemented. A grouping of related systems and failures in a systematic and comprehensive way could lead to the solving of maintenance issues. Environmentally speaking, the practicability of optimal PM planning should be tested and validated during actual operations, particularly by the establishment of case studies in real industrial settings.

Moreover, the states of systems should be considered in their environmental settings as that would also influence the analysis of any proposed PM framework. In the literature, the state of a system is an indicator of the condition of a system because it influences the analysis procedure for solving maintenance issues during PM planning. As discussed in Section 2.4.2, the state of systems is divided into two categories, i.e. single-unit and multi-unit systems. Single-unit systems have received more attention from past researchers compared with multi-unit systems. This is due to the complexity of developing maintenance models through mathematical formulation which is the basis for developing a maintenance model for multi-unit systems (Ab-Samat and Kamaruddin, 2014). However, the concentration on single-unit systems may not serve to show the significance of PM planning for tackling real-world maintenance problems (Lin and Wang, 2012), since multi-unit systems are interdependent structures and problems occurring on one system may affect its components and those of other systems as well (Khanlari et al., 2008). The complexity and flexibility of multi-unit systems which are more suitable and applicable for study as real-world environments involve multiple systems running production processes alongside each other.

Therefore, a detailed framework which incorporates reliable data and a grouping procedure at the system level needs to be proposed. In fact, many relevant decisions related to PM actions on systems or components can be made, where reliable data and grouping can serve as PM planning analysis procedures. The result will be more practical PM planning which provides more accurate and better updated inputs. With the aid of such a framework, maintenance management could apply it as a standard procedure plan for effective PM operations. Recommendations for future work are as follows:

- The calculation of cost-benefit analyses should be rendered much simpler in order to reduce the limitations on setting up the mathematical assumptions on which they are based. This is because the more assumptions yield more computability due to overlook at details to make necessary computation. These assumptions are set up to reduce the fidelity of mathematical models to real-life contexts. Cost-benefit analyses should also consider the costs of manpower and spare parts which will affect the whole total maintenance cost due to different systems consisting of different components and spare parts.

Comment [PB1]: I can't work out what this means.

- Developing computer-based integrated PM planning and scheduling based on simulation and GT would be helpful and assist more practically with making decisions about PM planning on systems in clusters. Thus, incorporating PM planning into production scheduling should be considered in order to achieve better planning results in terms of systems performance and productivity.

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