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Review of Maintenance Scheduling and Optimization Models

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ABSTRACT

A major challenge for manufacturing and service systems is establishing a proper maintenance policy. In this paper, we survey, summarize and categorize maintenance optimization models published. The role of these models in maintenance are analyzed and discussed in their merits. In broad terms, maintenance models were classified as optimization models and simulation models with different modelling approaches based on their peculiarities.With limited impact on decision making within maintenance organizations this paper helps in capturing the uncertainty in the development of models that optimally schedules both preventive maintenance and operational activities. Therefore, the need for better maintenance models to aid maintenance managers make maintenance decisions that best fit their systems.

Keywords : Maintenance Optimization Models, Mathematical Models, Simulation Models, Maintenance.

I. INTRODUCTION

Maintenance plays a very vital role throughout a system's lifecycle. A survey of the operations and management of today's industries shows that maintenance activities contribute immensely to the success of industrial concerns. Therefore, good maintenance policy can increase availability of equipment by trading off between planned and unplanned downtime, which can cause major disruptions in manufacturing processes [1]. In addition, maintenance objectives were summarized under four headings which are: ensuring system function (availability, efficiency and product quality); ensuring system life (asset management); ensuring safety and ensuring human well-being [2].

When maintenance is carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item, it is known as Preventive maintenance [3]. Furthermore, when maintenance is carried out after fault recognition (equipment breakdown) and intended to put the unit back into a state in which it can perform a required function, this phenomenon is called Corrective maintenance. Reliability-Centered Maintenance programs are gaining in popularity and have been applied in some industries with good results. The goal of these programs is to provide the appropriate amount of maintenance at the right time to prevent forced outages while at the same time eliminating unnecessary maintenance. Condition-Based maintenance type relies on knowing the condition of individual pieces of equipment [4]. It deals with monitoring of equipment parameters such as temperatures, pressures, vibrations, leakage, current, dissolved gas analysis, etc. Testing on a periodic basis and/or when problems are suspected. Monitoring carefully operator-gathered data. By keeping accurate records of the "as found" condition of equipment when it is torn down for maintenance, one can determine what maintenance was really necessary. In this manner, maintenance schedules can be lengthened or perhaps shortened, based on experience and monitoring.

Scheduling of maintenance usually occurs at a shorter time horizon and consists of determining the order of execution of activities. It involves priority setting and using available manpower as efficiently as possible. It describes the timing of activities. Scheduling maintenance activities is an important area where organizations could save time and money. It is not restricted to preventive maintenance, as it covers all other kinds of maintenance and associated maintenance resources. Scheduling is an essential activity as it influences cost and time through reducing unnecessary preventative maintenance [5]. It also plays an important role to reduce costs and enhance product performance through maintenance response time.

The aim of this survey is to review maintenance models related to system maintenance and replacement. Such models deal with optimal maintenance policies for a system consisting of single or multi units. There exists in the literature a great amount of mathematical models and practical case-studies which deal with the problem of maintenance optimization.

II. MAINTENANCE OPTIMIZATION MODELS

Maintenance optimization is aimed at improving system availability and mean time between failures, to reduce failure frequency, downtime and maintenance cost. For effective maintenance optimization process, model development is therefore necessary. A model is a representation of the construction and working of some system of interest, while the process of producing a model is referred to as modelling [6]. A model is similar to but simpler than the system it represents. It assists the analyst to predict the effect of changes on the system under investigation. The model remains a close approximation to the real system and incorporate most of its salient features. Maintenance optimization models are those models whose aim it is to find the optimum balance between the costs and benefits of maintenance, while taking all kinds of constraints into consideration [2]. Furthermore, Maintenance optimization models have to consist of these factors: a description of a technical system, its function and its importance; modelling of the deterioration of the system in time and possible consequences; a description of the available information about the system and the actions open to management and an objective function and an optimization technique which helps in finding the best balance [2].

Maintenance optimization models can be Mathematical or Simulation models. Mathematical model classifications include deterministic, (where input and output variables are fixed values with no random variables) or stochastic (at least one of the input or output variables is probabilistic, the time to failure is a random variable); static (time is not taken into account) or dynamic (time-varying interactions among variables are taken into account) [7]. For simulation models, they are presented in stochastic and dynamic forms [8].

The optimization methods that can be employed include linear and nonlinear programming, dynamic programming, Markov decision methods, decision analysis techniques, search techniques and heuristic approaches [2, 9, 10]. From maintenance optimization models results, policies can be evaluated and compared with respect to cost-effectiveness and reliability characteristics. Various modeling methods have been proposed to represent maintenance. Each of them has its own assumptions and characteristics that induce advantages and limitations. In this work, maintenance optimization models will broadly be seen in two perspectives: Mathematical and Simulation models, where methods such as linear and nonlinear programming, dynamic programming, Markov decision methods, decision analysis techniques, search techniques and heuristic approaches can be applied.

III. MATHEMATICAL OPTIMIZATION MODELS REVIEWS

A) Analytical Methods

Analytical methods have been broadly used as a standard optimization approach to achieve optimal maintenance and replacement schedules in engineering problems. This is as a result of its ability to qualitatively and quantitatively analyze and evaluate a given problem in a view to proffer the best solution. Some researchers such as [11] worked on a preventive maintenance optimization model, which was developed, and implemented by Columbia Hospital in Milwaukee based on plant technology and safety management standards. It was used for the optimal preventive maintenance plan of its electrical distribution equipment to improve safety, serviceability, reliability and total cost. [12] developed an optimization model in order to determine optimal preventive maintenance schedules for a serial multi-station manufacturing system. The computational results of his study show that the operating features of the stations are interrelated and one must investigate the effect of preventive maintenance activities on all stations at the same time. [13] had two different preventive maintenance scheduling models for maintaining bus engines in a public transit network based on minimization of total cost over a finite planning horizon. They construct the models based on the concept of mean time to failure (MTTF) of the engines and assume an upper bound for the failure rates. [14] developed a mathematical model to determine the mean time to failure (MTTF) as a function of uptime for a workstation in a multi-stage manufacturing system. The authors assume that the uptime of the workstation has an increasing rate and is reduced if preventive maintenance actions are performed. Other works include that of [15] that studied and reviewed the application of different stochastic process such as homogenous Poisson process (HPP), non-homogenous Poisson process (NHPP), branching Poisson process (BPP), and superimposed renewal process (SRP) in preventive maintenance scheduling problems. [16] developed an integrated optimization model that simultaneously considers preventive maintenance and production scheduling decision variables. Their model minimizes total tardiness of jobs and makes a 30% reduction in expected total tardiness of jobs. Also, [17] presented an optimization model that minimizes total maintenance costs and penalty costs for used equipment under lease. They assume a Weibull distribution function for failure rate of equipment, develop a 4-parameter model, and develop a 4-stage algorithm based on an analytical approach to solve it. They apply their model to several numerical examples with different contract assumptions and find optimal policy in each situation. [18] develop an age-based nonlinear optimization model to determine an optimal preventive maintenance schedule for a single-component system. A summary of literature review on previously published research articles on preventive maintenance done for an Ageing and Deteriorating Production Systems [19]. [20] discussed flexibility as it relates to manufacturing system supply chains and general manufacturing environment. Proposed two maintenance scheduling models which was applied at any point in the supply chain. Considerations on several ways in which models may be used to optimize maintenance, such as case studies, operational and strategic decision support systems, which include mathematical models focused on finding either the optimal balance between costs and benefits of maintenance or the most appropriate time to execute maintenance. Parameters often considered in this optimization process are the cost of failure, the cost per time unit of downtime, the cost (per time unit) of corrective and preventive maintenance and the cost of repairable system replacement. The maintenance optimization model has basis on the underlying deterioration process and failure behaviour of the component [8].

B) Exact Algorithms

These are algorithms that always solve an optimization problem to optimality. This implies finding solutions not approximations. Deterministic optimization algorithms and Dynamic programming have been proposed by various authors which have been considered. [21] formulated a mathematical model to find an optimal production schedule via a Gaussian Poisson function with state dependent Poisson process. They consider the total cost of production and maintenance scheduling as the objective function and use a stochastic dynamic programming approach, and demonstrate application of the model in a numerical example. [22] presented a two-layer hierarchical model that optimizes the preventive maintenance scheduling in semiconductor manufacturing operations. They develop a Markov decision process and optimize this model via a mixed integer linear programming model. [23] developed a nonlinear optimization model to minimize the total cost of maintenance and replacement actions under reliability constraints for production machine in a production system. Their model considers the Weibull distribution as the failure function of the machine and can be used as a decision support system for job shop scheduling. [24] presented a linear programming model in order to optimize the maintenance policy for a component with deterioration and random failure rate. They determine optimal mean times of minor and major preventive maintenance actions based on maximizing the availability of the component. They utilize MAPLE and LINGO for solving the linear programming model of Markov decision process. [25] present an age-based preventive maintenance optimization model for a gas turbine power plant. They develop a model with profit instead of cost as the objective function and considered power plant performance, reliability and market dynamics. [26] presented a model and algorithm for maintenance optimization of a system with series components. In their research, they assumed that all components have linearly increasing failure rate with a constant improvement factor for imperfect maintenance. Also, they consider the total cost as the objective function and the total downtime as the main constraint. Finally, their algorithm optimizes the interval of time between maintenance actions for each component over a planning horizon. [27] presented an optimization model to schedule a preventive maintenance of a power plant over a planning horizon. He considers the total cost of various operations as the objective function and uses Bender's decomposition to solve a mixed-integer linear programming model. [28] presented two mixed-integer linear programming models for preventive maintenance scheduling problems. They assumed that the total cost including possession costs, maintenance costs, and the penalty costs of early consecutive maintenance activities as the objective function for both models. They presented and proved a theorem about the NP-hard structure of the preventive maintenance scheduling problem and used GAMS to implement the optimization models. [29], did an excellent study in this area by developing three nonlinear optimization models: one that minimizes total cost subject to satisfying a required reliability, one that maximizes reliability at a given budget, and one that minimizes the expected total cost including expected breakdown outages cost and maintenance cost. [30] worked on a binary integer linear programming model in order to find the best preventive maintenance schedule in separated and linked cogeneration plants. Defining the availability of the power and desalting equipment as the objective function to be maximized, and consider the maintenance time window, maintenance completion duration, logical operational, resource limitation, maintenance crew availability, efficiency measures, and demand as the set of constraints. [31] developed an integrated maintenance scheduling and production planning optimization model for a single machine based on a cumulative damage process and the effect of preventive maintenance strategies on production schedules in order to minimize total tardiness. The computational results achieved by dynamic programming show that by increasing the number of jobs the effect of jobs due dates on the optimal maintenance policy is decreased. In a research by [32], a dynamic approach of scheduling preventive maintenance for modular designed components is presented. [10] proposed preventive maintenance and replacement scheduling models that deal with multi-component system and can be applied to a wide variety of systems using the concept of age reduction and improvement factor in these models. Also developed mathematical and statistical models to estimate the improvement factor for imperfect maintenance activities. Also, [33] worked on a dynamic preventive maintenance strategy for a multi-state aging and deteriorating production system.

C) Heuristics and Meta-Heuristics Algorithms

In mathematical optimization, Heuristics and Meta-Heuristics Algorithms are techniques designed for solving problems more quickly when classic methods are too slow, or for finding an approximate solution when classic methods fail to find any exact solution. This is achieved by trading optimality, completeness, accuracy, preciseness for speed. They are often employed when approximate solutions are sufficient and exact solutions are computationally expensive. Genetic algorithms are the major optimization approach in this method applied. [34] presented an optimization maintenance and replacement model for a single-component system. They determined an optimal preventive maintenance schedule for a new system subject to deterioration, by considering the time value of money in all future costs, increasing rate of occurrence of failure over time and the use of the improvement factor to provide for the case of imperfect maintenance actions. Also, they provide a comparison of computational results among random search, genetic algorithm, and branch and bound algorithms. [35] in their work, defined a multi-state system as a system in which all or some of components have different performance levels, from proper functioning to complete failure and the reliability of the system as its ability of satisfying the demand levels. They formulate an optimization model to determine preventive maintenance actions that affect the effective age of components. They apply a universal generating function technique and use a genetic algorithm to determine the best maintenance strategy. Additional research in which an optimization model was developed in order to determine the optimal replacement scheduling in multi-state series-parallel systems also. [36] developed a new genetic algorithm by modifying the basic operators, crossover and mutation, of a standard genetic algorithm based on the specific characteristic of preventive maintenance scheduling problem for power systems. They improve the time computational complexity of genetic algorithm by considering a code-specific and constraint-transparent integrated coding method to achieve faster convergence and to prevent production of infeasible solutions. [37] considered two activities, imperfect maintenance, and replacement, in their preventive maintenance optimization model. They modelled imperfect maintenance activities based on the concept of an improvement factor, which is determined by a quantitative assessment procedure. They use a genetic algorithm to find the optimal preventive maintenance activities while the system unit-cost life is considered as the objective function. [38] presented an optimization model to schedule the best preventive maintenance tasks of all machines in a single product manufacturing production line. They assumed that each machine should be assigned to each operator and considered the total throughput of the line as the objective function to be maximized. The researchers used C++ as a programming environment and applied genetic algorithm in order to find the best combination of preventive maintenance tasks. [39] presented an optimization model to find the optimal preventive maintenance schedule for a multi-component system. He considers total cost of operations and maintenance activities along with reliability as the criteria of the system and transfer them into the objective function by defining degree of violation from required reliability. In addition, he defines maintenance crew and duration of maintenance as the system's constraints. He applies his optimization model in a case study with six electric generators and utilizes genetic algorithm as the optimization methodology to determine the best preventive maintenance schedule. [40] investigated the recurrent nature of failure rate between preventive maintenance cycles and develop a nonlinear optimization model based on repair cost, preventive maintenance cost, and production loss cost in a production system. They apply a genetic algorithm as the optimization technique. [41] considered cost and availability as the systems criteria in their research. They optimized a model including cost in the objective function and availability as the constraint by using a genetic algorithm to find the best preventive maintenance schedule. [42] use an ant colony algorithm to optimize the problem that was previously optimized via genetic algorithm. They define series of component maintenance and inspection periods and use MATLAB as the programming environment. [43] proposed several techniques to represent the decision variables in preventive maintenance scheduling models that use heuristics and meta-heuristics optimization algorithms. They test various non-standard approaches and compare them to binary representations by a heuristic algorithm and the computational results show that effectiveness of their approaches. Other researchers include [44], they considered flexible intervals between maintenance actions. They developed a model that includes preventive and corrective maintenance actions and the associated cost with them, outage times, reliability of the system, and probability of imperfect maintenance. Because their model is a nonlinear large-scale optimization model, they utilize a genetic algorithm as the solution procedure. [45] recently presented an application of a genetic algorithm for optimization of preventive maintenance scheduling of a production machine. They consider maintenance and replacement frequency along with purchasing strategy and the size of the maintenance workforce as the decision variables and the total cost as the objective function. [46] discussed a preventive-maintenance policy for leased products considering all aspects of applicable maintenance costs. [47], have discussed a technique to minimize series-parallel system's periodic preventive maintenance cost using improved particle swarm optimization.

D) Hybrid Algorithms

This is an algorithm that combines two or more algorithms that solve the same problem. This is generally done to combine desired features of each, so that the overall algorithm is better than its individual components. Some works have been undertaken in maintenance scheduling optimization applying this.

[48] combined genetic algorithm with simulated annealing in order to optimize a large-scale and long-term preventive maintenance and replacement scheduling problem. In their research, the acceptance probability of a simulated annealing method is considered as a measure for individual survival in the genetic algorithm. By using this approach, they achieve a near optimal solution in a short period of time compare to the computational time of simple genetic algorithm. [49] developed a general framework for preventive maintenance optimization in chemical process operations. They assumed a Weibull model for failure rate and consider different maintenance activities that can be performed. They developed a methodology that combines Monte Carlo simulation with a genetic algorithm to solve opportunistic maintenance problems with a nondeterministic objective function. [50] developed an optimization model for preventive maintenance scheduling of multi-component and multi-state systems. A combination of genetic algorithm and simulation was utilized to optimize the model. [42] presented another paper about the combination of an ant colony algorithm and genetic algorithm to optimize a large-scale preventive maintenance problem. They divide the objective function of their

problem into two sections and then utilize each algorithm to improve the sections separately. They observed that using hybrid algorithm in a large-scale problem is more efficient than the simple algorithm.

IV. SIMULATION OPTIMIZATION MODELS

Based on the complexity of the analytical models, limitations to simplifying these models and unrealistic assumptions, many studies have used simulation techniques for modeling and optimization of maintenance.

A) Monte Carlo Simulation

Monte Carlo Simulation is a computerized mathematical technique than allows access to possible risks in quantitative analysis and decision making. It furnishes the decision maker with range of possibilities and outcomes using tools as probability distribution. This approach have also been applied in modelling system maintenance schedules. [51] presented the results of a systematic collection of actual failure times and preventive and corrective maintenance activities of 900 buses over a period of five years. They consider the total cost and availability as the objective functions and apply a Monte Carlo simulation approach to evaluate the model. [52] also developed a simulation model, which is based on the Monte Carlo simulation approach, to determine the total failure frequency and the optimum maintenance interval for a parallel-redundant system. [53] presented an approach for sequential preventive maintenance scheduling based on the concept of age reduction due to imperfect maintenance actions. They applied Monte Carlo simulation to describe how their computational results can be used in decision support systems of maintenance scheduling problems. [54] developed a simulation model to find the best preventive maintenance strategy in semiconductor manufacturing plants. The authors modelled the effective age of equipment, availability of equipment, maintenance activity backlog, and preventive maintenance policies and consider different wafer production scenarios in a Monte Carlo continuous time simulation model. They also analyzed and compared the different maintenance strategies on the status of manufacturing equipment and operating conditions of the wafer production flow.

B) Discrete-Event and Continuous Simulation

Discrete-Event Simulation produces a system which changes its attitude only to specific events distributed over time. They rely on countable phenomena. For the Continuous Simulation, it refers to a computer model of a physical system that continuously tracks system response according to a set of equations usually differential equations. Discrete Simulations may be applied to represent continuous phenomena, but the resulting simulation produces approximate results. Maintenance models have also been developed with either of these methods. [55] presented a simulation model to determine the maintenance schedule for an automated production line in a steel rolling mill plant. By using the historical data of maintenance activities in the simulation model, the optimal preventive maintenance schedule is obtained in the form of checklist. [56] presented a simulation model in order to determine the shutdown frequency for periodic system overhaul, preventive and corrective maintenance, and inspections in a sugar manufacturing plant. They utilized a time dependent simulation model to minimize the total cost including maintenance costs and downtime losses. [57] developed a two-stage knowledge base for a maintenance supervisor assistant system. This knowledge base interacts with the maintenance manager on a periodic basis to select the proper preventive maintenance plan for the next period. [58] developed a simulation model in order to evaluate different preventive maintenance strategies for a fleet of vehicles of the St. Louis metropolitan police department. [59] developed a simulation model in order to investigate effect of different preventive maintenance strategies in a just-in-time production system. He constructs a simulation model on a 5-station production system and considers throughput rate, average equipment utilizations, and total work-in-process as the performance measures of the production system. [60] presented a simulation model to find the optimal maintenance planning in train maintenance depot for an underground transportation facility in UK. He utilizes ARENA as the simulation software and shows the effectiveness of the maintenance policies obtained by the simulation model. [61] presented a simulation model to obtain the preventive maintenance schedule for components of a detergent-packing line and considers two different situations in his model. In order to minimize the total cost, he develops a simulation model to optimize the maintenance schedule of components for each situation. [62] presented a simulation model to measure the impact of preventive maintenance scheduling on the production rate of a machine. They use statistical analysis on the simulation outputs in order to determine the impact of recommended yearly preventive maintenance on the production throughput of the machine. Finally, they concluded that the preventive maintenance policy does not affect the production rate but can reduce yearly maintenance costs of the system. [63] developed a finite time horizon model to achieve preventive maintenance scheduling of manufacturing equipment based on setback based residual factors and use simulation to solve the model. [63] presented a preventive maintenance optimization model for a multi-component production process. They define a combination of mechanical service, repair, and replacement activities for each component and use Markov decision process to present the transition function of probability for maintenance activities. In addition, they consider required reliability of the system as the constraint and total preventive maintenance cost as the objective function of the model. A simulation approach was utilized to find the optimal schedule as the solution procedure. Also, [64] developed a simulation model to determine the level of reliability, availability and corrective and preventive maintenance at the early stage of design. [65] proposed a simulation model in order to analyze the dynamic structure of maintenance systems. The researchers consider various subsystems such as preventive maintenance subsystem, defects subsystem, condition-based subsystem, failure subsystem, corrective maintenance subsystem, and performance subsystem and utilized SIMULINK to build up the model. [66], presented a detection of anomaly point in sensor monitoring data for preventive maintenance.

V. CONCLUSION

Following the increasing role of maintenance in the total running cost of manufacturing, good planning for maintenance is becoming an essential part of planning for the whole organization. Maintenance optimization models, which forms part of decision making mechanism in organizations, provide an objective and quantitative way of making decisions. This should be defendable and suitable since it allows for evaluation of the economic consequences of the decisions. Thus, maintenance optimization models are the only approach which relates reliability with economics in a quantitative manner good for justifying maintenance. In this paper some of the existing maintenance optimization models were discussed. They were broadly categorized as mathematical models and simulation models with different modelling approaches based on their peculiarities. Some are according to the nature of the model: discrete or continuous time models. For others, the state is always known and are classified as Deterministic models (no random variables) and Stochastic models (the time to failure is a random variables). Other categories include: machine interference/repair models, group/block/cannibalization/opportunistic models, inventory/ maintenance models and inspection/maintenance model. From the review undertaken, it was observed that most studies focus on single-component systems or simple and specific systems, which is not always applicable for real and general systems.

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