New Tool for the Evaluation of the Scheduling of Preventive Maintenance for Chemical Process Plants

Duy Quang Nguyen, Christopher Brammer, and Miguel Bagajewicz*

School of Chemical, Biological and Materials Engineering, The University of Oklahoma, 100 E. Boyd St., T335, Norman, Oklahoma 73019

A new methodology designed to assess the economic value of the scheduling rules for preventive maintenance on a chemical process plant is presented. The methodology is based on the use of a Monte Carlo simulation, which takes into account scenarios that include equipment failure, resources limitations, repair downtime, performance of failed but not repaired equipment due to lack of resources, and some other maintenance rules. The well-known Tennessee Eastman Plant problem is used to illustrate results.

1. Introduction

Not counting scheduled outages, a typical refinery experiences ∼10 days of downtime per year due to equipment failures with an estimated economic loss of \$20 000−\$30 000 per hour.[1] Thus, preventing equipment failures through appropriate maintenance actions is of paramount importance, both from a safety standpoint and an economic point of view. After safety levels have been achieved through appropriate maintenance, the question remains: How much preventive maintenance is economically advisable?

Maintenance can be defined as all actions appropriate for retaining an item/part/equipment in, or restoring it to, a given condition.[2] Many industries worldwide have begun to realize the importance of having an effective maintenance policy, especially because the activity is constrained by resource availability. Millions of dollars are now spent every year trying to preserve the different processes that are involved in production. The annual cost of maintenance (corrective and preventive), as a fraction of the total operating budget, can go up to 40%−50% for the mining industry,[3] 20%−30% for the chemical industry.[1] The typical size of a plant maintenance group in a manufacturing organization varies over a range of 5%−10% of the total operating force.[2] It is estimated that more than \$300 billion are spent on plant maintenance and operations by U.S. industry each year, and that ∼80% of this is spent to correct the chronic failure of machines, systems, and human errors.[2] The elimination of these chronic failures through effective maintenance can reduce the cost by 40%−60%.[2]

There is a very large amount of literature on maintenance methods, philosophies, and strategies. The modern practices and management philosophy of maintenance can be found in various textbooks (e.g., the *Maintenance Engineering Handbook*, by Mobley and Higgins[4]). In addition, there are many software packages devoted to helping organization of the task. In this paper, we will not review all previous works. Instead, we will focus on the literature that tries to assess the level of preventive and corrective maintenance that is optimal for any plant.

Maintenance optimization has been studied extensively, and a large amount of maintenance models has been published. Many models were discussed and summarized in the excellent textbook by Wang and Pham[5] and various review papers (for example, Wang,[6] Garg and Deshmukh[7]). Most of the models are deterministic models that use simplified assumptions and stochastic processes models, and some use mathematical programming techniques to solve the formulated deterministic models. The most common optimization criterion is minimum cost, and the constraints are requirements on system reliability measures: availability and average uptime or downtime. In addition, genetic algorithms (GAs) are also used to solve complicated maintenance optimization models that consider many decision variables simultaneously (for example, the optimum preventive maintenance (PM) time interval, the spare parts inventory level, the size of the labor workforce, the resources allocation, the replacement strategy, or the solution of the realistic maintenance models that do not use simplified assumptions).[1,8−11] Monte Carlo simulations, on the other hand, are usually used to estimate parameters in the model, especially reliability. Tan and Kramer[1] utilized both Monte Carlo simulations and GAs. Models for optimizing the spare parts inventory levels have been developed.[9,12,13] We discuss these techniques in more detail below.

None of the PM planning models consider constraints on the resources available in process plants, which include labor resources and materials (spare parts) resources. The limitation on manpower is usually the most critical constraint that affects the ability to perform scheduled PM tasks on time. For example, the maintenance work force, which usually is limited, cannot perform scheduled PM tasks for some equipment at scheduled PM times because of intervening repair of other failed equipment. Such dynamic situations cannot be handled by deterministic maintenance planning models or are not considered in published maintenance planning models that use Monte Carlo simulation tools. The resources constraint is more realized in the scheduling phase, so it is usually ignored in the planning phase. In fact, there are only few papers that have considered the resources constraint and they all are concerned with maintenance scheduling.[14−16]

To ameliorate all the aforementioned shortcomings, we introduce a new methodology based on the use of Monte Carlo simulations to evaluate the effectiveness of maintenance policies. The article is organized as follows: the existing methods for PM scheduling are presented first, followed by a description of our evaluation procedure. At the end of the paper, we present some illustrations. Although we do not perform a formal optimization, we show how the assessment can be used to optimize certain variables.

* To whom correspondence should be addressed. Tel.: 1-405-325-5458. E-mail address: bagajewicz@ou.edu.

10.1021/ie071231i CCC: \$40.75
Published on Web 02/15/2008

2. Maintenance Policies

There are two major objectives for maintenance: maintain safety and minimize economic losses.

In regard to *maintaining safety*, most plant incidents are a result of bad maintenance practices or when maintenance is not done properly. Equipment pieces can hardly be isolated from each other in a process plant; therefore, the effect of improper maintenance on one piece of equipment, leading to its failure, is felt in other equipment and can lead to unsafe situations. Unfortunately, some of the effects of equipment failure are not observed immediately. For instance, the blocking of heat exchanger tubes due to a lack of cleaning can cause, through time, a heat imbalance that can result in a fire or an explosion in the plant. Various hazard evaluation techniques have been developed to analyze and evaluate safety hazard in a process plant, among which the most popular technique is Hazard and Operability Analysis (HAZOP). By systematic and careful analysis of process or operation, the HAZOP team lists potential causes and consequences of process deviations, as well as existing safeguards that protect against the deviation. The HAZOP technique requires detailed information concerning the design and operation of the process. Another popular technique is Failures Modes and Effects Analysis (FEMA), which is an important component in modern maintenance programs such as Reliability Centered Maintenance (RCM). FEMA tabulates failure modes (how equipment fails) and their effects on a system or plant. Other useful techniques include (i) Fault Tree Analysis, which identifies and graphically displays the various causes of a particular accident or system failure; (ii) Event Tree Analysis, which analyzes and graphically shows the various outcomes of an accident initiated by an equipment failure or human error; and (iii) Cause−Consequence Analysis, which is a blend of Fault Tree Analysis and Event Tree Analysis. [More details about all these methods can be found in the textbook, *Guidelines for Hazard Evaluation Procedures*, from the AIChE's Center for Chemical Process Safety (2002).]

In regard to *minimizing economic losses*, maintenance reduces downtime in a plant that is associated with major failures. A large cost (lost revenue) is associated with each plant shutdown, in addition to the cost of repairs. However, not all equipment failures lead to plant shutdown. Some failures deteriorate plant performance and most have associated lost revenue in addition to the cost of repair. In addition, there are costs associated with the replacement of pieces of equipment. Good maintenance preserves equipment condition and reduces the repair/replacement costs of the equipment. Finally, in addition, one must add the labor and parts inventory costs.

Because of its significant impact on plant performance (both in economic and technical terms), maintenance management and optimization have been extensively studied by people in the field of operations research and manufacturing engineering. Modern maintenance management philosophy suggests the following:

(1) Maintenance should focus on the entire system, rather than on individual equipment/components.

(2) Maintenance should be performed in preventive or proactive mode (to preserve equipment condition and keep system functioning), rather than in purely reactive mode, in response to a particular equipment failure (because the reactive mode leads to frequent downtime and high production loss).

(3) Maintenance should be considered to be an integrated part of the production process, rather than a supporting part, and it should be viewed as an effective tool to enhance productivity and increase profit, rather than as a "necessary evil".

Modern maintenance philosophy is implemented by practices such as RCM, which includes the following important issues:

(1) If resources (personnel, materials) are limited, as is the case usually, then prioritization of equipment maintenance is necessary (even when it is a corrective action and not a preventive action); that is, important components in the system are given more attention than others. The reason is that the objective of maintenance is to keep the system functioning and minimize downtime, rather than maintain every individual equipment.

(2) Preventive and predictive maintenance (which constitute the proactive mode of maintenance) is performed at scheduled times to prevent failure; intervening failures are corrected by corrective maintenance.

(3) The planning, scheduling, and optimization (i.e., optimum resources allocation) of PM is an important part of an effective maintenance program.

Plant maintenance policies can be divided into three main types: corrective maintenance, preventive maintenance, and predictive maintenance.[17]

Corrective maintenance (CM) (or equipment repair) involves fixing equipment that is already malfunctioning. The key here is the ability to react quickly to any failure to minimize downtime and loss; that is, when equipment fails, it must be immediately repaired or replaced as long as the required resources (labor and parts) are available. It can be observed that the associated cost and economic loss of using CM alone are prohibitively high, which leads to two points: (i) if one wishes to guarantee resource availability at all times, which would allow immediate repair action for all failed equipments, very often, a large number of employees and a well-stocked inventory of spare parts are needed, which leads to large labor and inventory costs; and (ii) equipment failure is not prevented or reduced, and, hence, the associated repair costs and economic losses are high. Therefore, although CM is always needed to repair failed equipments, using CM alone is not the right choice, because the associated costs and economic losses are high.

Preventive maintenance (PM) involves preplanned maintenance at regularly recurring times, for the purpose of preserving equipment condition and preventing failure. Three main factors are considered when planning/scheduling PM activities for a specific equipment: (i) the equipment itself (how important the equipment is (role of equipment in the system), failure history, the regularity of use, etc.), (ii) economic considerations (the difference between the gain (the reduction in repair cost and economic loss) and the cost incurred), and (iii) the availability of resources that are needed in the plant.

In regard to *predictive maintenance*, the maintenance personnel monitor the equipment's condition (on-line or periodically) to detect, in advance, any failure symptoms of the equipment, and then they perform planned repairs for the failure-prone equipment, to avoid downtime.[17] A successful predictive maintenance program requires tools and techniques and also expertise of the maintenance personnel to analyze and diagnose the condition of the equipment. Popular predictive maintenance techniques include vibration monitoring and analysis, lubricating oil analysis, thermography, and visual inspection.[17]

PM, in turn, is divided into two types: time-driven PM and condition-driven PM.[18] Condition-driven PM is basically the same as predictive maintenance. Because of the fact that there is a very limited number of decision variables involved for these types of maintenance policies, they are usually not subjects for maintenance optimization research.

Various versions of time-driven PM policy have been proposed; these were summarized in a review paper by Wang.[6] They include the following:

(1) age-dependent PM policy, where the PM times are based on the age of the unit

(2) periodic PM, where a unit is preventively maintained at a fixed time kT (for $k = 1, 2, ...$), where T is the PM interval, independent of the failure history or age of the unit

(3) failure limit policy, where PM is performed only when the failure rate or other reliability measures of a unit reach a predetermined level

(4) sequential PM, where a unit is preventively maintained at *unequal* time intervals (usually, the time intervals become shorter and shorter as time passes)

The aforementioned maintenance policies are for single-unit or multi-unit systems where an independence between units is assumed. For multi-unit systems with a dependence between units, group maintenance or opportunistic maintenance policies should be used (see the work of Wang[6]). Opportunistic maintenance is defined as follows: when a piece of equipment is undergoing maintenance, there could be an opportunity to perform maintenance on another piece of equipment. These techniques consist of "optimally utilized system downtime opportunities to perform preventive maintenance at a lower overall cost". Thus, during every system downtime opportunity, PM activities must be investigated to determine if the benefits from future reliability and production outweigh the current maintenance costs. The optimization tradeoff is between maintenance costs and production. However, performing PM during an opportunity (before it is regularly scheduled) may increase maintenance costs per unit time. On the positive side, opportunistic maintenance improves equipment reliability, reducing future system downtime and, thus, increasing production and net income. Therefore, during every system downtime opportunity, PM activities must be pursued only if the benefits from future reliability and production outweigh the current maintenance costs (see the work of Tan and Kramer[1]).

Maintenance planning, which is the heart of a maintenance program, determines which prioritized equipment undergoes preventive maintenance, which involves a preventive maintenance time plan over a time horizon of months or years, as well as factors such as inventory level, replacement strategy, maintenance work force size, etc. Maintenance scheduling organizes maintenance activities on a daily basis or a weekly basis. It allocates the labor and material resources necessary to perform maintenance, considering several factors: (i) equipments must be maintained according to maintenance planning or to be repaired, (ii) the availability of equipment for maintenance operation, and (iii) the currently available labor and material resources. Maintenance optimization research focuses on maintenance planning. Previous work on maintenance optimization is summarized below.

3. Maintenance Optimization

Maintenance optimization has been studied extensively, and a large amount of maintenance models has been published. Many models were discussed and summarized in the excellent textbook by Wang and Pham (*Reliability and Optimal Maintenance*)[5] and in various review papers.[6,7]

Most of the maintenance optimization approaches are based on deterministic models that use simplified assumptions and stochastic processes models, such as Markov processes and Renewal processes, which allow the use of mathematical programming techniques to solve problems.[5] The models differ in regard to the assumptions and mainly in PM policy; hence, different decision variables are sought. Typical simplified assumptions include the following: negligible maintenance time or repair time, the unit has an increasing failure rate, and "as good as new" (perfect) maintenance. The decision variables are dependent on the PM policy; for example, the length of the time intervals must be optimized in periodic PM.

The most common optimization criteria are based on the maintenance costs (to be minimized): the maintenance cost rate (cost per unit time), the total maintenance, and the inventory and lost production costs. The maintenance labor costs can also be taken into account. The constraints are requirements on system reliability measures, such as availability and the average uptime or downtime. For systems such as nuclear power plants or power generation systems, where reliability is much more important than cost, the optimization criteria are the highest reliability measures for a given maintenance budget.

There is an increasing tendency to use genetic algorithms (GAs) to solve complicated maintenance optimization models that consider many decision variables simultaneously (for example, the optimum PM time interval, the spare parts inventory level, the size of the labor workforce, the allocation of resources, replacement strategy, or the solution of realistic maintenance models that do not use simplified assumptions). Many maintenance models that have been solved using GAs have been published recently. Some examples are found in the work of Podgorelec et al.,[8] who used GAs to optimize maintenance time plan and maintenance personnel allocation for nuclear power plants, or Shum and Gong,[9] who simultaneously optimized maintenance timing, part replacement strategy, and workforce size. GAs also were used to solve the models of opportunistic maintenance policy.[1,10,11]

Monte Carlo simulations, on the other hand, are usually used to estimate parameters in the model, especially reliability measures of complex systems such as availability, the mean time before failure (MTBF) (or the mean time to failure (MTTF)). It must be said that, of all the tools that can address complex models with a variety of decision variables, Monte Carlo simulations are excellent for assessment purposes. In addition, to optimize maintenance schedules and prioritize jobs, as well as manage spare parts inventories, one can eventually add stochastic optimization techniques (simulated annealing or GAs). There are few techniques that utilize both Monte Carlo simulations and GAs.[1] The advantage of using Monte Carlo simulations/GAs is that the Monte Carlo simulation approach is quite general and versatile for analyzing complex maintenance policies, where many decision variables are sought or realistic situations (e.g., resource limitations) are considered, and it is computationally tractable for large systems;[1] however, the use of GAs (or other stochastic search methods) is the only choice for a nondeterministic model.

Okogbaa and Peng[19] proposed a method for PM analysis under transient response. They developed analytical maintenance models that are based on Renewal theory. The resulting model consists of both differential and integral equations and was solved numerically. Some of the setbacks of this methodology include numerical inaccuracies and computation errors. It is also very complicated and cannot be easily modified for different plants, such as in the case of a simulation.

Tan and Kramer[1] optimized the opportunistic maintenance policy, using a combination of Monte Carlo simulations and GAs. The Monte Carlo simulation was used to evaluate the cost rate, which is the total maintenance cost plus lost production costs divided by the time simulated. The GAs were then used to minimize the nondeterministically evaluated cost rate objective function. By solving maintenance optimization models that have already been published in previous works, they compared their optimization approach with other techniques such as the analytical approach and determined a favorable conclusion for the Monte Carlo simulation/GA combination. Thus, in the work of Tan and Kramer,[1] (i) the “opportunistic maintenance policy”, which is a realistic PM policy for chemical processes that usually have a dependency between units, was optimized, although this PM policy could be cumbersome to implement; (ii) the focus was on the optimization algorithm, not the maintenance model; and (iii) realistic issues such as spare parts management and resource limitations were not considered.

Spare parts management or inventory policy is an important issue in maintenance optimization, because the availability of spare parts can decide whether a requested maintenance activity can be conducted or not. A review of the models for optimizing the spare parts inventory level can be found in the work of Kennedy et al.[12] Usually, the models focus on the spare parts inventory optimization problem itself. Only a few papers have addressed the simultaneous optimization of maintenance policy and spare parts inventory; two such papers are described next. Shum and Gong[9] developed an analytical model and used GAs to optimize the maintenance frequency, part replacement frequency, and the purchasing quantity simultaneously. Ilgin and Tunali[13] presented a simulation approach integrated with GA-based optimization for determining the optimal inventory level and periodic PM intervals.

Monte Carlo simulation allows us to incorporate realistic situations such as resource constraints in our maintenance planning model. In this work, we consider the “standard” periodic PM policy for each equipment, mostly because it is suitable for managing labor resources and it is commonly used in the industry. We assume independence between units and we address resource limitations and spare parts inventory policy. All these elements of maintenance previously were not considered together. To do this, we include a set of rules regarding corrective maintenance (CM) prioritization and spare parts inventory policy to a Monte Carlo simulation tool. Incorporating decision variables such as the number of employees and inventory policy poses some difficulties for GA optimization because (i) two types of variables are present in the model (integer variables (PM time interval and number of employees) and binary variables (for inventory policy)), and (ii) a large number of decision variables is considered (and, hence, it is difficult for GAs to converge or determine the global optimum).

Our work is different from the work of Tan and Kramer[1] in one main aspect: we focus on the maintenance model, which is the “standard” periodic PM policy with consideration of the resource constraints and investigate the effect of various decision variables on maintenance performance, whereas Tan and Kramer[1] focused on the optimization algorithm.

4. Equipment Failure Data

The mean time before failure (MTBF) of different pieces of equipment can be obtained from the literature or through data logging in a plant. It is used to obtain the probability of failure of each piece of equipment. Different distributions can be used, depending on the maintenance preferences or data availability. The following are examples of commonly used distributions.

Exponential Distribution. This distribution is based on a constant rate of failure, given by the MTBF. It is usually used when there is limited information or data about the equipment.

Weibull Distribution. This is one of the most commonly used distributions in the industry. It measures the rate of failure through the MTBF and a parameter called the shape factor (β). This makes the distribution open to a wide range of failure data types, because it accounts for different failure rates. When $\beta = 1$, the Weibull distribution is reduced to the exponential distribution.

Normal Distribution. This distribution is used in cases in which wear-out failures and repair times are considered. It can only be used in the case of increasing failure rates.

Logarithmic Distribution. This is a modification of the normal distribution, and it is used when model value deviations are by proportions (e.g., factors, percentages) rather than absolute values. It is also used only in cases of increasing failure rates.

Finally, equipment dependencies must be determined and the conditional probabilities must be established. In our case, however, without any loss of generality of the methodology, we use the exponential (one parameter) distribution and we ignore the equipment dependencies. Equipment reliability data such as MTBF are obtained from reliable sources such as *Guidelines for Process Equipment Reliability Data with Data Tables*.[20]

5. Costs and Economic Losses

Unlike other approaches that usually use the maintenance cost rate (cost per unit time) and do not consider economic losses, we use the total costs plus economic losses that are incurred within the planning time horizon as the objective value, which is the variable to be minimized. The cost term includes the following:

$$\text{Cost} = \text{PM Cost} + \text{CM Cost} + \text{Labor Cost} + \text{Inventory Cost} \quad (1)$$

where “PM cost” and “CM cost” are the costs associated with preventive maintenance and corrective maintenance activities, respectively. These costs are incurred only when maintenance activities occur and are estimated as the cost of materials used in maintenance activities (such as lubrication oil in PM, parts replacement in CM). “Labor cost” is the paid salary of maintenance labors, and “inventory cost” is the cost associated with storing spare parts for equipment. The last two costs are independent of maintenance activities; they are dependent only on the size of the labor force and the inventory levels (which are the two decision variables to be made in maintenance planning). To obtain the cost term, the labor cost (labor salary) and inventory cost are calculated as the paid rate (cost rate) multiplied by the time horizon, and all the PM costs and CM costs that are incurred within the time horizon are summarized.

The economic loss term includes two types of losses: (i) economic losses that are associated with failed (or malfunctioning) equipment that has not been repaired (for example, a fouling heat exchanger can continue to operate but at a reduced heat transfer rate), and (ii) economic losses that are due to unavailability of equipment during repair time (if the equipment has an on-line backup, the economic loss due to unavailability is set to zero and the priority of the equipment is set to the lowest rank). The latter economic loss type is calculated as the loss rate (in dollars per day) multiplied by the duration of the period within which the loss is realized. A paid rate (salary) of $40 000 per maintenance labor unit per year is used.

To determine the economic loss rates, an analysis is performed on each piece of equipment, to determine the economic effects of equipment failure (equipment mal-functioning) or equipment unavailability, which include the loss of production throughput (capacity) or even production shutdown, the deterioration of product quality, the consequences of accidents that may happen, etc. These effects are then converted to a monetary value.

Equipment reliability (a common performance measure of a maintenance program) is usually used as a constraint in minimum cost maintenance models. In our case, maintenance performance measures, equipment reliability, and production uptime are indicated by the term "economic loss"; that is, better equipment reliability or longer production uptime results in smaller economic loss. There is a tradeoff between the cost and the performance (indicated by the term economic loss) of a maintenance program: asking for better performance requires more cost. Thus, by minimizing cost plus economic loss, we simultaneously optimize the cost and the performance of maintenance.

6. Safety

Of course, safety is always a matter of concern. Some equipment failure leads to accidents, as noted previously, which results in economic loss, but some also could lead to personnel injuries. As tempting as it might be to associate personnel injuries to economic losses—which, of course, there are—one should actually ensure that, regardless of the cost, the safety associated with human injury prevention is handled in a different way. We believe this aspect, aside from the economic losses that must be listed anyway, needs to be associated to a constraint limiting the likelihood of events that lead to human injury and death. We realize that assessing the threshold probability is difficult, so another way of handling this problem more generally is through multi-objective programming, which involves minimizing cost and maximizing safety simultaneously. The appropriate tradeoff can then be inferred from the Pareto optimal curve. This is left for future work.

7. Maintenance Rules and Scheduling

We assume the following:

(1) Preventive maintenance (PM) is planned to occur at regularly recurring intervals.

(2) At some regular intervals (usually once a week), a schedule for equipment maintenance is crafted, according to a set of rules that are described next.

(3) The time to identify the cause of failure and determine the appropriate repair action is negligible, i.e., the repair time is the time for repairing reparable parts and/or replacing irreparable parts only.

(4) Maintenance workers can address both types of maintenance activities (PM and CM) and can provide maintenance service to any type of equipment. If this is not the case, the problem of labor resource allocation must be considered.

(5) Opportunistic maintenance, equipment dependencies, and delayed detection of failure are ignored.

The rules we use are as follows:

(1) Each reported repair need, corresponding to each failure, is classified using several priority categories: emergency, urgent, pressing, and affordable. Each repair priority category is characterized by the time one can afford to not repair the equipment before there is a catastrophic failure that will lead to an unacceptable loss. The sustainable category is characterized by a very long time.

Table 1. Levels of Failures for Maintenance Concerns (following Tischuk[21])

probability of subsequent catastrophic failure	Consequence of Failure: high	medium	low
high	1	2	3
medium	2	3	4
low	3	4	5

(2) If many pieces of equipment fail at a time (as it is usually the case), the equipment is scheduled for repair, from highest priority to lowest priority.

(3) Repairs in the emergency category take precedence immediately; that is, any planned maintenance—preventive or not—is suspended and all available resources are devoted to the equipment repair. If spare parts are not available, the repair starts when these parts arrive.

(4) All equipment that has not been repaired because of emergencies is added back to the list of equipment that needs repair.

(5) No delay in performing maintenance occurs after the resources are available.

(6) If equipment has undergone CM within a predetermined period of time prior to the scheduled action, such action is suspended, so that resources can be used elsewhere.

(7) If the repair of equipment has been delayed more than a predetermined threshold value (due to the unavailability of resources), the priority for repair of that equipment is upgraded one level.

Priority categories are established using a double-entry matrix (Table 1). A high, medium, and low probability of occurrence is loosely associated with the probability of the occurrence happening in a week, a month, or between a month and, for example, a year. High consequences of failures include failures in which a failure occurs and the unit or (even the plant) may need to be shutdown, creating large revenue losses, or where a major spill to the land occurs, creating major environmental hazards, resulting in large fines. Also, significant safety risks to employees within the plant are present. Medium consequences of failures include failures in which a failure occurs and then the unit will need to be operated at a reduced rate, causing revenue losses in production, or where a Level 2 environmental accident occurs (a Level 2 incident is a spill to land that is significant and defined by the EPA but does not result in a major environmental event), resulting in some monetary losses. Safety risks to employees are still present but not to the extent as are present in high-consequence situations. Finally, low consequences of failures include failures that, when they are occurring, cause no significant deviation from normal operation and involve only minor environmental issues (such as a drip leak). Almost no safety concerns are present.

High−high and medium−high then are assigned to urgent status, low−high, high−medium, and medium−medium are assigned to pressing status, and the remainder are classified in the affordable category.

Although the aforementioned scheme seems reasonable, optimizations at each week to determine the best CM schedule seem even more appealing. Although this is not addressed in this work, it is entirely possible to be undertaken within the framework that we present.

8. Failure Modes of Equipment

As illustrated in the illustration section, one type of equipment may have different failure modes involving different parts of the equipment; for example, equipment can fail because of the deterioration of mechanic parts (one possible consequence is complete failure that requires equipment replacement) or electronics parts malfunction (a partial failure that can be repaired). Different failure modes require different repair costs and repair times and induce different economic losses. Because only the failure rate or the MTBF of the equipment as a whole is available, rather than the failure rates or the MTBFs of different failure modes of equipment, a sampling of the different failure modes of equipment is done as follows:

(1) Assign a probability of occurrence for each type of failure mode; for example, when equipment fails, there is a 60% probability that the failure is due to failure mode A and a 40% probability for failure mode B. The probability is assigned based on the information of how common a failure mode is.

(2) Sample failure events of equipment using reliability data of the equipment.

(3) At the time of failure of the equipment, sample the type of failure mode that actually occurred, in accordance with the failure modes' probability of occurrence.

9. Preventive Maintenance (PM) Frequency

The preventive maintenance (PM) frequency (or PM time interval) is the most important decision variable. In practice, for convenience, the PM time interval is determined in accordance with a calendar time-table (for example, one month or one year). In our case, the PM time interval is expressed as a fraction of the MTBF (PM time interval $= a \times$ MTBF, where the fraction a is to be optimized (for each piece of equipment)). More-frequent PM improves the condition of the equipment (it also better utilizes maintenance labor resource); however, too-frequent PM is not a good idea, because it increases maintenance cost and may interfere with production and increase the possibility of human error in maintenance.

10. Spare Parts Inventory Policy

Several decision variables are concerned in the spare parts management: inventory level, ordering time, purchasing quantity, part replacement interval, etc. It is well-known that there is a tradeoff in keeping inventory. If one keeps spare equipment or spare parts, one incurs a holding cost, which includes the storage cost and the cost associated with the time-value of the equipment (equipment depreciation). On the other hand, if one does not keep an inventory, one incurs in shortage cost, which includes the cost of emergency ordering equipment/parts and the economic loss associated with delayed repair of failed equipments (because the failed equipments can be repaired only when the new equipment parts are available to replace the broken parts). If the economic loss is large, one should keep inventory; however, if the loss is small or negligible, then the option of not keeping inventory may be the right choice.

In this work:

(1) We do not consider the inventory policy for the materials/tools necessary for preventive maintenance (PM) activities. We assume that a minimal inventory level of those materials/tools is maintained, such that they are always available for PM activities (because the materials demand for such preplanned activities is known beforehand, the demand can be easily met). Therefore, the PM activities are constrained only by available labor resources, rather than by materials resources.

(2) Inventory policy for spare parts associated with corrective maintenance (CM) is considered with only one decision variable: whether to keep inventory for the spare parts or a new entire set of equipment ready to repair/replace specific equipment when it fails. We assume that, if one decides to keep inventory for a specific piece of spare part/equipment, then a minimal inventory level is maintained: one redundant copy is kept and when it was used to replace the failed one, the new one is ordered immediately to maintain the inventory level of one. The inventory cost is then determined corresponding to this minimum inventory level policy.

With regard to spare parts management issue, our work is different from the approaches of Shum and Gong[9] and Ilgin and Tunali[13] in two aspects: (i) different decision variables are sought, and (ii) our work uses Monte Carlo simulation tools, whereas their works did not.

11. Evaluation Using Monte Carlo Simulation

This technique is based on repeated sampling of the equipment failure and evaluation of the cost of maintenance activities, as well as the economic losses that are associated with the failed states of equipments. The method continues sampling and computing an average until the average converges to a finite value.

The sampling procedure to simulate equipment status within a finite time horizon in accordance with a maintenance policy is described as follows:

(1) Failure times of equipments are sampled using the reliability function (failure rate) of the equipment.

(2) At failure times of equipment, the type of failure modes that caused equipment failure is sampled in accordance with the probability of occurrence.

(3) The cost of CM, the repair time and the economic losses are determined corresponding to the type of failure modes identified.

(4) Preventive maintenance requests for equipments are generated in accordance with the predetermined preventive maintenance schedule (predetermined PM policy)

(5) The planning time horizon is divided into time intervals of weeks. In each week, the folllowing must occur:

(i) All the CM requests (when equipments failed) and all the scheduled PM requests are identified.

(ii) CM request and PM requests for equipment with highest priority will be fulfilled.

(iii) Continuing with CM requests and PM requests of equipment with lower priority until the resource available is used up (labor resource and materials resource are considered). More specifically, when a maintenance action is performed in response to a maintenance request, the available labor hour is subtracted by the labor hour needed to perform that maintenance activity. When all labor hour is used up, no more maintenance action is possible. However, in case labor resources are available but the spare parts needed to repair the failed equipments are not available (when no inventory for the parts is kept), the CM of the equipment is not possible. In that case, an emergency-related order of the needed parts is made (and an "extra" cost is incurred because of the emergency status in ordering/delivering, the cost of the ordered parts is taken into consideration in the "CM Cost" term) and the repair must be delayed until the ordered parts arrive. Two parameters are involved in such situation: the "extra" cost incurred and the waiting time for the ordered parts to arrive. This extra cost is ignored in this work (it is usually small). When a requested CM is not possible because of materials unavailability (and due to Assumption Three stated previously, no labor hour is wasted on that ignored CM), the available labor resource is transferred to the next maintenance request in the list. The total labor hour available

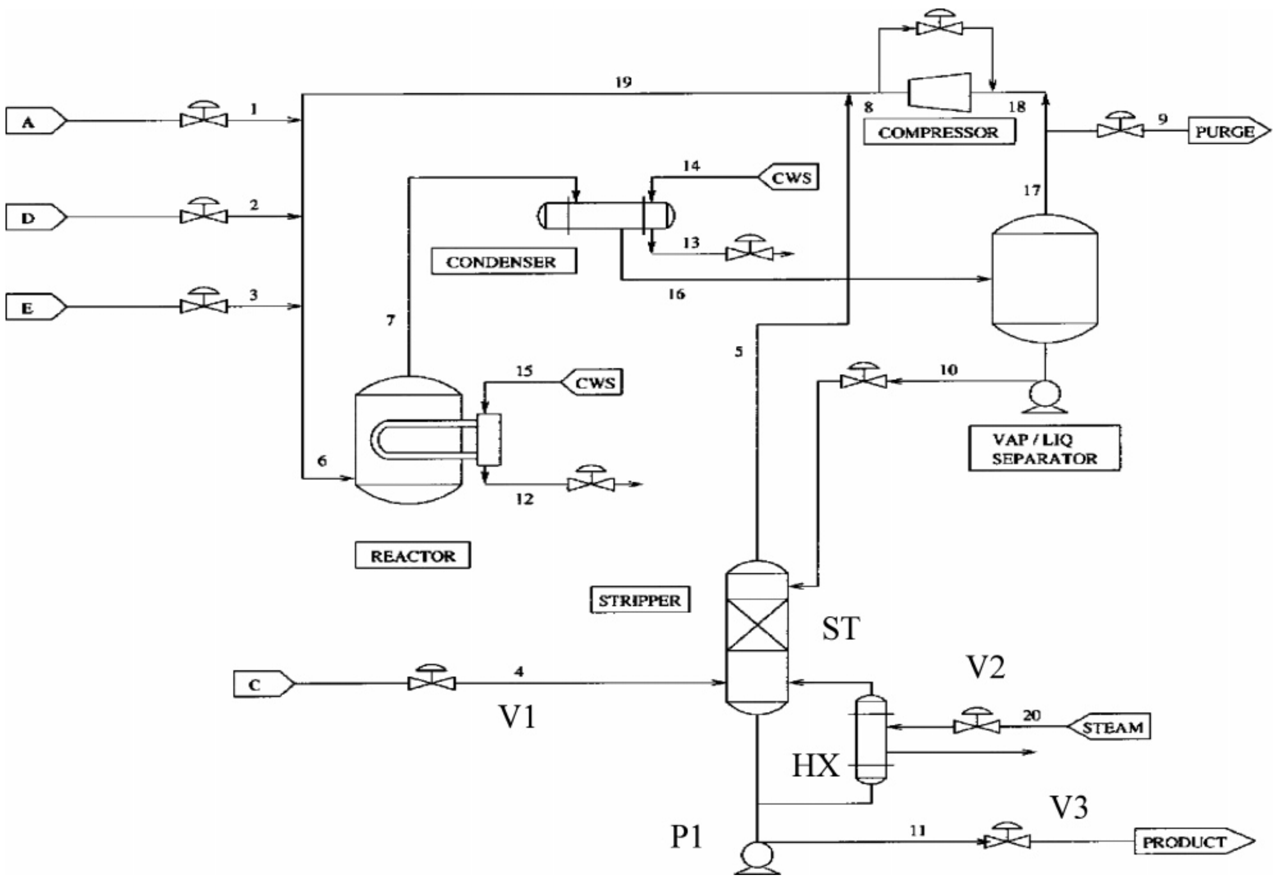

Figure 1. Flow diagram of the Tennessee Eastman process (adapted from Bhushan and Rengaswamy[23]).

at the beginning of a week is calculated as the number of employees × 40 labor hours/person/week. Of course, this is just an approximate calculation of the maintenance activities management problem. Rigorous calculation must consider travel time of employees to locations of equipment, the number of "unoccupied" employees at the current time to take care of unfulfilled maintenance requests.

(iv) If a CM request or PM request is not fulfilled, it has to be delayed to next week. Delayed CM request is scheduled to be fulfilled at the early of next week or when the needed parts for repairing the equipments are available. Delayed PM request is scheduled to be fulfilled exactly 7 days after the original PM schedule.

(v) If a CM action on equipment was performed prior to a scheduled PM request for that equipment, for a predetermined period (current value is 7 days), that PM request will be ignored.

(vi) If CM action for an equipment has been delayed more than a predetermined period (current value is 21 days), the priority level of that equipment will be upgraded one level.

(6) When a maintenance action is performed on a single equipment at time *t*, that equipment is assumed to be as good as brand new and failure events for that equipment will be re-sampled (updated) starting from time *t*.

(7) The next week is considered and the calculation is repeated. The procedure continues until the end of the planning time horizon is attained.

12. Illustration

In this section, we investigate the effect on maintenance cost and maintenance performance of the following factors: (i) maintenance policies used in process plant, which include corrective maintenance and preventive maintenance; (ii) the size of the labor force; (iii) the preventive maintenance frequency (PM time interval); and (iv) the inventory policy (whether to keep inventory for a specific equipment or part).

These are the most important decision variables in maintenance planning. When the effect on maintenance performance of a variable is being investigated, the other variables are kept constant at some values. The rigorous approach requires simultaneous optimization of the decision variables; nevertheless, the results shown here give helpful insights about the important factors in a maintenance program. The sample plant on which this analysis is performed is the well-known Tennessee Eastman (TE) plant. The TE process is well-described in the literature (see the work of Ricker and Lee[22]). The process flow diagram of the plant is given in Figure 1, and the corresponding list of equipment is given in Table 2.

The average MTBFs were obtained from the book *Guidelines for Process Equipment Reliability Data with Data Tables*.[20] The maintenance time (the time needed for CM and PM) was either obtained from Bloch and Geitner[24] or estimated (if the information is not available). The economic losses were obtained by performing an analysis of the economical impact of equipment failures on the plant production. The maintenance cost is the cost of materials (e.g., the cost of parts replacement or equipment replacement, the cost of lubrication oil, etc.) needed for maintenance activities. The equipment was priced using the information provided in Peters et al.[25]

Equipment Failure Analysis. To predict failures in a plant, the equipment in the plant must be studied individually and in detail. This study mostly surrounds the failure analysis of the equipment. There are different levels of detail expected from a failure analysis. This detail varies with information obtained from different sources or plant-specific issues that may arise

Table 2. List of Equipment of the Tennessee Eastman (TE) Process

equipment	quantity	MTBF[a] (days)	time needed for corrective maintenance (CM) (h)	time needed for preventive maintenance (PM) (h)	priority
valves	11	1000	2−5	2	3
compressors	1	381	12−18	6	1
pumps	2	381	4−12	4	4
heat exchangers	2	1193	12−14	8	2
flash drum	1	2208	24−72	12	1
stripper	1	2582	48−96	12	1
reactor	1	1660	12−72	12	1

[a] Mean time between failure.

Table 3. Equipment Failure Analysis for the Tennessee Eastman (TE) Process

equipment	number of units	failure	part failure	PM action	CM action
heat exchanger	2	•leak •increased pressure drop •increased wear and tear	•bolts and nuts •excess fouling of tube •control valves	•tighten/lubricate bolts •cleaning yearly	•replace bolts and nuts •replace tube
recycle compressor	1	•overheating •reduced capacity	•bearings/rotating parts •condenser coils/filters	•lubrication •clean	•replace parts
exothermic two-phase reactor	1	•stress •corrosion	•structural member •filter gauges	•impinge water jet •change (6 mo) •calibration (1 yr)	•replace parts
pump	3	•suction pressure too low •seal leak •excessive power	•worn impeller •broken/bent seal •clogged impeller	•lubrication •impeller back •flush	•replace pump
valves	11	•fails to open •fails to close •leakage through valve	•threads/lever •valve seat •corrosion	•lubricate •clean •paint	•replace part
product condenser	1	•leakage •reduction in water quality	•fuel corrosion layer	•change filter •change water	•replace part

Table 4. Data for Valve V1 (refer to Figure 1)

						Economic Loss ($/day)	
failure mode	failure mode description	probability of occurrence	time needed for CM (h)	CM cost ($)	inventory cost ($/yr)	due to equipment failure	due to unavailability of equipment
1	severe corrosion	0.1	2	250	35	1000	1000
2	moderate corrosion	0.1	2	250	31	1000	1000
3	slight corrosion	0.1	0	0	0	100	100
4	severe wear	0.1	2	250	35	1000	1000
5	moderate wear	0.1	2	250	32	1000	1000
6	slight wear	0.1	2	250	28	400	400
7	severe fatigue	0.1	5	90	6	1000	1000
8	slight fatigue	0.1	4	90	5	100	100
9	overload	0.1	4	60	4	1000	1000
10	misalignment	0.1	4	60	4	1000	1000

for the equipment. Table 3 summarizes the failure analysis for the TE process.

As a common practice in process plants, it is assumed that there are spare pumps in place ready to replace the failed ones, so the associated economic losses of pump failures are negligible. Moreover, bypass valves are also installed ready to operate manually once the valves (usually control valves) fail so the associated economic losses of valve failures are small. Therefore, the main economic losses are attributed to failures of main process equipment (compressors, heat exchangers, reactors, etc.) where the spare ones are not available. A part of the full data, the data for the valve V1 (shown in the process flowsheet), is shown in Table 4. For the valve V1, the MTBF is 1000 (days), the time needed for PM is 2 (hours), and the PM cost is $50, not including labor. The time and cost of corrective maintenance (CM) and the economic losses, as well as the inventory cost, vary with the type of failure and are given in Table 4 (different failure modes need different materials/spare parts, which are necessary for repairing the equipment, hence the associated inventory costs are different).

Because the TE plant has no specific chemical and no specific associated chemical reaction associated to it, we tentatively assigned a low economic loss associated to a failure of all equipment that have a spare (only $10 per day for pumps and $1000 per day for valves). For major equipment that does not have a spare (reactor, column, compressor, heat exchangers, etc.), we assigned a larger value associated to the associated plant shutdowns. The value is $60 000 per day, which is about one tenth of the estimated economic loss in a typical refinery in a day (0.5−0.7 millions, from Tan and Kramer).[1]

The inventory cost (in terms of U.S. dollars per year) for one spare part was calculated as a summation of three costs: (i) the opportunity cost of the money invested in inventory (i.e., the interest on the money spent on inventory), which is estimated to be 3% of the value of the spare part; (ii) the cost associated with the depreciation of the spare part, which is estimated to be 3% of the value of the spare part; and (iii) the storage or holding cost of the spare part, which varies depending on the size of the spare part. Generally, the inventory cost (in terms of U.S. dollars per year) for a spare part is ∼6%− 15% of the spare part's value (if extra costs such as insurance and tax on inventory are included, it is estimated that the inventory cost accounts for 20%−25% of the value of the item being stockpiled (source: http://www.effectiveinventory.com/article35.html)). The full data (including MTBFs, maintenance time, costs, and

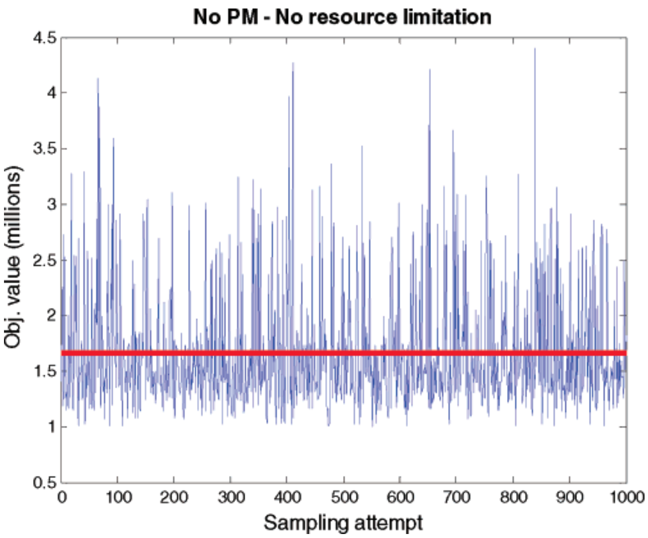

Figure 2. Objective value at various sampling attempts (no preventive maintenance (PM), no resource limitations).

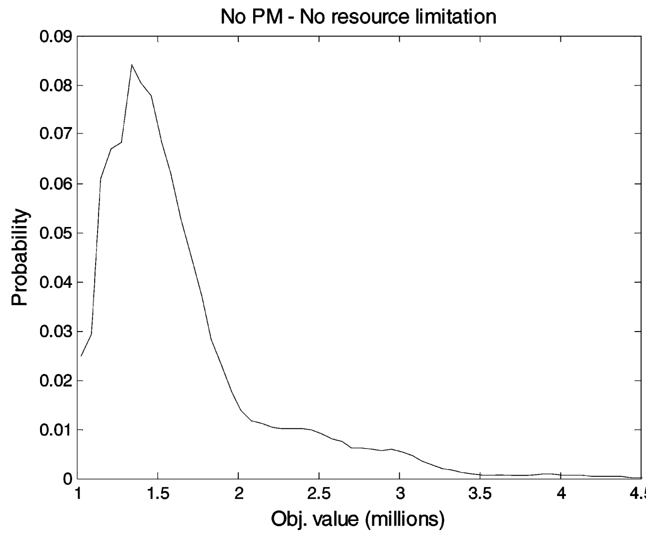

Figure 3. Probability distribution of the objective value (no PM, no resource limitations).

economic losses) for all the equipment in the example can be obtained by contacting the authors.

The previously shown data are used in the Monte Carlo simulation-based maintenance model to obtain the results shown below. The planning time horizon is 2 years (730 days). The average objective value, including the two terms (the cost term and the economic loss term), is shown as a function of various factors. The average value is calculated as the mean value obtained after N simulation runs:

$$\text{average} = \frac{1}{N}\sum_{i=1}^{N} \text{Objective value}_i$$

Our objective is to reduce this overall economic (cost) objective.

13. Results

No PM−No Resource Limitations. The no PM−no resource limitations methodology assumes that only corrective maintenance (CM) is used and there are 10 maintenance personnel (which is more than enough for a 19-equipment plant; hence, labor resources are always available) and spare parts are always available. The objective value (total costs plus losses) at various simulation trials is shown in Figure 2.

Among the terms included the objective function, the labor cost and inventory cost are the "fixed" costs which are not dependent on the equipment status or the maintenance policy, the PM cost is dependent on the maintenance policy only (it is zero in this case), whereas the CM cost and the economic losses are dependent on the equipment status. Because the failure events of equipment are random in nature, the CM cost and the economic losses are random numbers; hence, the objective value is also a random number, as clearly shown in Figure 2.

Small values of the objective value are slightly larger than 0.997 million, which is the labor cost plus inventory cost (the fixed costs). These values correspond to the case that equipment failures hardly occur during the planning time horizon; hence, the CM cost and the economic losses essentially vanish.

On the other hand, large values of the objective function (>3 million) correspond to the case that equipment failure occurs frequently. Because these are extreme cases, their probability is low, as can be observed in Figure 3, which shows the probability distribution of the objective value. The low probability of such extreme cases can also be inferred from Figure 2, because only a small number of simulation runs renders an objective value of >3.0 million.

The probability distribution of the objective function exhibits a peak. The peak and the proximity region around it correspond to the "normal" case, where only a limited number of equipment failures occur during the time horizon. Hence, the objective value (the expectation) is moderate. There are two extreme cases: (i) there is hardly any equipment failure during the time horizon, which corresponds to small objective values in the left-hand side of the peak, and (ii) equipment failures occur frequently, which leads to large objective values in the right-hand side of the peak. It is natural that the probability of the "normal" case is high, whereas the probability of the two extreme cases is small, as clearly shown in Figure 3. We note that modifying the asymmetric shape of this distribution (reducing the risk of having large losses) as well as reducing the mean value are two conflicting objectives, which require the use of risk management techniques.[26,27] We leave this for future work.

The average objective value (calculated as $(1/N)\sum_{i=1}^{N}$ (Objective value$_i$)) is shown in Figure 4, as a function of the number of simulation trials.

The simulation is terminated when the average objective value converges to a finite value (that is, it remains within a given tolerance). Figure 4 shows the stability of the average objective value for our case when the number of simulation attempts is >1000, when the simulation was terminated. The average total costs plus losses is 1.66 million, of which 0.8 million corresponds to labor cost, 0.197 million to inventory cost, 0.118 million to corrective maintenance cost (CM cost), and 0.543 million to the average total economic loss. It can be observed that the labor, inventory, and CM costs constitute the major portion (67%) of the objective value, with the economic losses comprising only the remaining 33%. In the results shown next, 10 000 simulation runs are used.

No PM−Labor Limitations. The aforementioned case is considered but with varied number of employees devoted to maintenance. Figure 5 shows the total costs plus losses, the economic losses, and the labor cost, each as a function of the number of maintenance workers.

If there are too few available maintenance workers, the maintenance requests would rarely be fulfilled on time or may never be fulfilled, which, in turn, results in increased economic losses. If there are more maintenance workers than needed, the

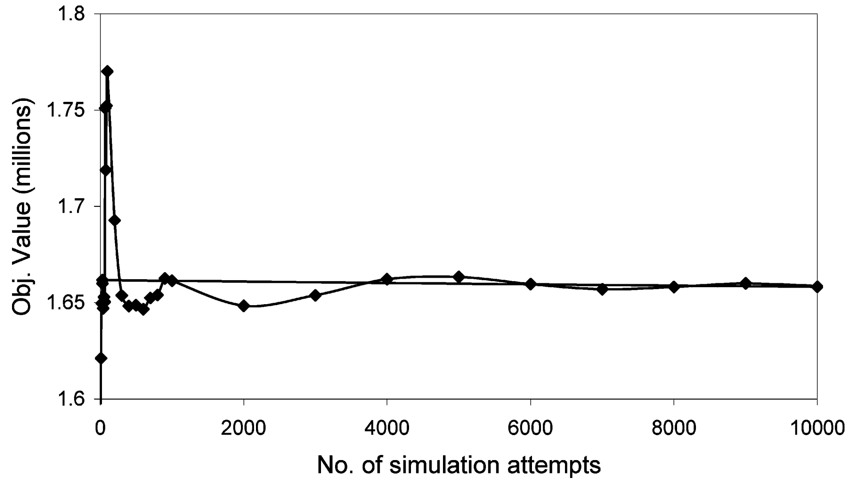

Figure 4. Average objective value versus the number of simulation runs (no PM, no resource limitations).

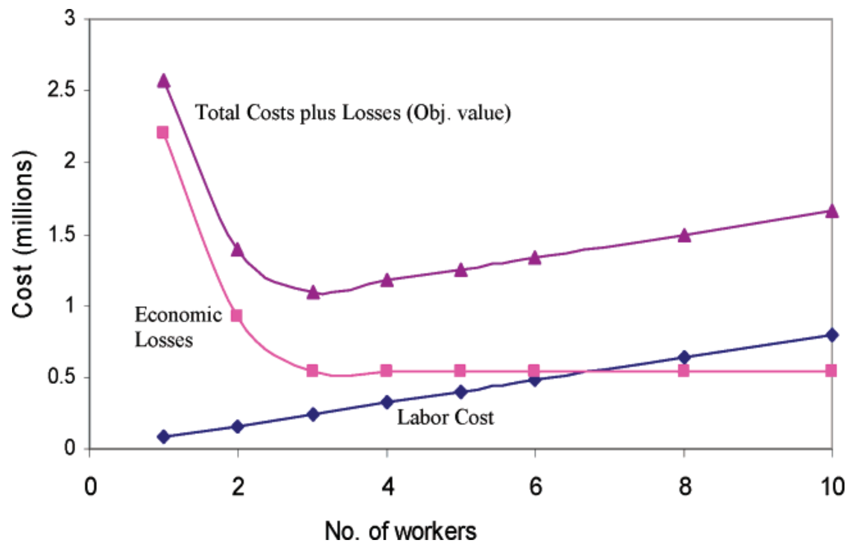

Figure 5. Effect of labor availability on maintenance cost and performance (no PM).

maintenance requests are always fulfilled on time (economic loss is minimized) but the labor costs become unnecessarily high. Figure 5 shows that when the number of labor increases, the economic loss decreases and reaches a constant minimum value when that number is equal or more than three (that is, if less than three maintenance workers are available, the maintenance activities are constrained by insufficient labor resource) while the labor cost increases progressively. In fact, the average value of the total number of CM orders that must be delayed (this number is calculated over all equipment in the entire time horizon), which is a direct indicator of economic losses, is 0.5158, 0.2027, 0.1049, and 0.1042, corresponding to 1, 2, 3, and 4 workers, respectively. Thus, it can be observed that increasing the number of workers from 1 to 3 will decrease the number of delayed CM requests significantly; however, increasing the labor force size above the number three hardly has any effect. The optimum labor force size for this case is three workers.

No PM−Spare Parts, Fixed Labor Spare Parts Policy Effect. Assume that only CM is used and 10 maintenance workers are available. As noted previously, if spare parts are always available, the inventory cost is 0.197 million. We compare results of the following three cases: (a) all spare parts are available; (b) spare parts on some equipment are available (only spare parts necessary for repairing (or replacing) the 11 valves, 2 pumps, and 1 compressor are available); and (c) no spare parts are available. The results are shown in Table 5.

Table 5. Results for the Case Only CM is Used with Consideration of Spare Parts Policy

	Result		
parameter	Option a: all spare parts are available	Option b: some spare parts are available	Option c: spare parts are not available
inventory cost	197 210	36 776	0
economic losses	543 173	655 189	770 404
all costs (including inventory)	1 115 089	954 157	916 727
total costs + losses	1 658 262	1 609 346	1 687 131

The maintenance requests can be fulfilled only when the necessary tools/equipment parts are available. Hence, if the spare parts are not stockpiled, the inventory cost is reduced or eliminated at the expense of increased economic losses. Because the equipment's repair must be delayed until the needed parts are available through emergent purchasing, extra economic loss is incurred during the time that the equipment repair is delayed, because of the unavailability of spare parts (besides the loss associated with equipment failure), or eliminating/reducing the inventory leads to increased economic loss, which is a well-known phenomenon. The spare parts necessary for repairing (or replacing) the main equipment in the process (such as the reactor, stripper, heat exchanger, or flash drum) are expensive

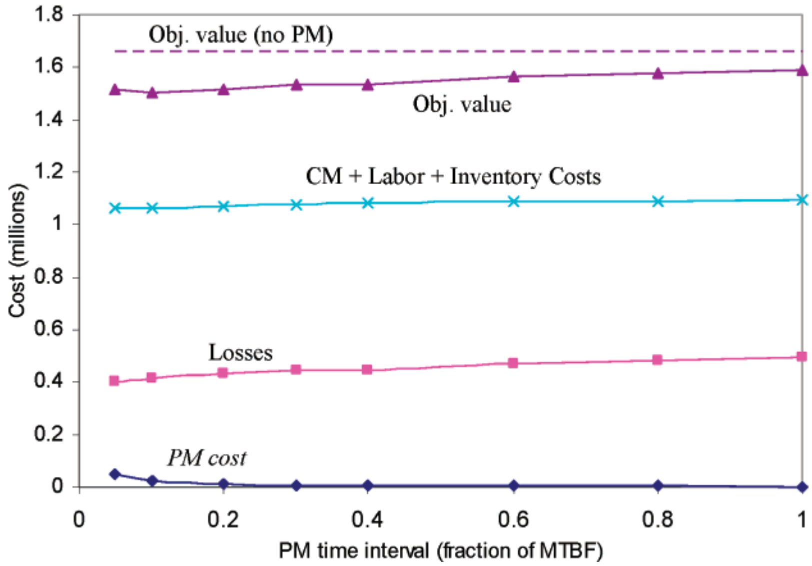

Figure 6. Effect of PM on non-interfering units.

and their associated inventory costs are high. If these spare parts are not stockpiled (option b), we can save a significant amount of money in the inventory cost ($160 434) at the expense of an increase in economic losses ($112 016). Although the totals seem to be similar, one does gain benefit by choosing option b, because this option renders a lower objective value. In the other hand, if one decides not to stockpile any spare parts, the inventory cost is eliminated but the economic losses increase by $227 231, which results in increased total costs plus losses. The calculated results suggest that option b (keeping an inventory of spare parts necessary for repairing the 11 valves, 2 pumps, and 1 compressor) is the best option, because the total costs plus losses for this case is the smallest. Although the differences between the different values are low for this small example, we note that they might be significant if fixed costs (labor and buildings) are added when inventory is kept, which increases the costs of options a and b over option c. In addition, longer waiting periods may increase economic losses significantly, which will make the economic losses in option c become substantially higher than those in options a and b. For larger examples, we expect to observe more-pronounced differences and a minimum for some inventory level, not the extremes.

PM is Used without Resource Limitation. We make the following assumptions:

(1) No labor resource limitation (10 maintenance workers are available) and spare parts are always available

(2) PM of the 11 valves, 2 pumps, and 1 compressor does not interfere with production, whereas PM of the main process equipment (the reactor, the stripper, the heat exchanger, the flash drum) does. In other words, the main equipment is unavailable (and economic loss is incurred) while being preventively maintained, whereas the other equipment is not.

We call the time at which the first PM on the equipment is done the "PM starting time" of that equipment. The PM starting time is usually a decision variable to be optimized in maintenance optimization models (such optimization is left for future work). In this article, we assign reasonable values for the PM starting times and focus on investigating the effect of PM frequency (PM time interval). The PM starting time for the 11 valves and 2 pumps is 30 days, whereas the PM starting time for the compressor is 60 days and for the main equipment is 180 days.

Figure 6 shows the PM cost, the total economic loss, and the total costs plus losses as a function of PM time interval for valves, pumps, compressor, and equipment whose PM does not interfere with production. We call them "non-interfering units". Figure 7 shows the same for "interfering units" (the main equipment), whose PM does interfere with production and induce economic losses during the maintenance time. The PM time interval is expressed as a fraction of the MTBF. To illustrate the effect of PM in each group, when the effect of PM done in one group of equipment is being investigated, the other group is subjected to CM only. Another way (not explored in this article) is fixing PM policy for one group while investigating PM policy for the other group.

It is expected that when PM is performed on equipment, the condition of the equipment is preserved and failure is prevented, which results in less equipment failure, less repair cost, increased uptime, less production loss, and less economic losses. In fact, the average values of the total number of CM (i.e., equipment repair) over all equipment in the entire time horizon in three cases—(i) no PM; (ii) PM for non-interfering units is used, with a time interval = 0.9 × MTBF; and (iii) PM time interval (Non-interfering units) = 0.1 × MTBF—are calculated to be 16.02, 10.5, and 5.12, respectively. Thus, applying PM reduces the number of equipment failures. However, the benefit of PM is certainly realized when the interference of PM activities on production is negligible. In such situation, increasing the PM frequency leads to less repair costs and less economic losses at the expense of increased maintenance costs. This situation is applicable to the non-interfering units whose PM does not interfere with production. Figure 6 confirms the expected results: it clearly shows that the losses decrease and the CM cost also decreases (that makes the curve "CM cost + Labor + Inventory costs" go down; recall that the labor cost and inventory cost are fixed costs) as one increases the PM frequency. The benefit of PM is also confirmed: the objective value when PM is applied is lower than the objective value when only CM is used. Nonetheless, even the interference of PM activities on production is negligible; doing PM too frequently is not a good idea either, because (i) it leads to high PM cost, which may be greater than the benefit it provides, as is the case when the PM time interval is 0.05 × MTBF (shown in Figure 6), and (ii) it increases the chance for human errors in maintenance to occur, which causes the equipment (after PM)

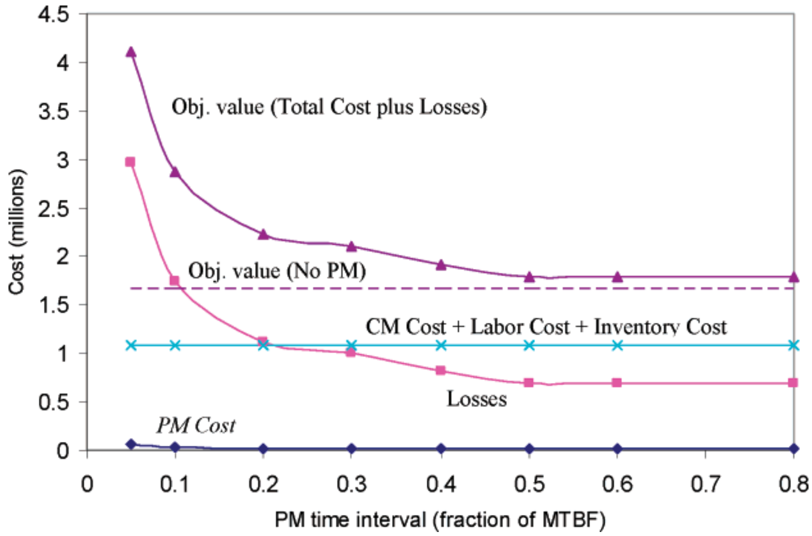

Figure 7. Effect of PM in interfering units.

to be impaired and induces extra economic loss. The optimal PM time interval for the non-interfering units is shown to be 0.1 × MTBF.

On the other hand, if the PM activities do interfere with production, then significant economic losses occur while the equipment is being preventively maintained (e.g., due to the unavailability of equipment during the maintenance time). This is illustrated in Figure 7. In such situations, there are two competing effects of PM on the equipment availability and the associated economic loss:

(1) The equipment unavailability due to failure is reduced.

(2) Equipment unavailability during PM activities increases; the plant then must shut down and the corresponding economic losses increase.

As a result, the economic loss may increase or decrease. Therefore, in this case, if PM frequency is increased, (i) the repair cost is reduced but the PM cost increases, and (ii) the economic loss may increase or decrease. These competing effects lead to increased or decreased objective values (total costs plus losses) when PM is applied. An increased costs plus losses discourages the application of PM to equipment whose PM interrupts production, which is the case shown in Figure 7; this figure shows that when the frequency of PM on the main process equipment is increased, the PM cost, the economic losses, and the total costs plus losses increase.

Information for the main process equipment in the TE process reveals the following:

(1) The MTBFs of the equipments are long (3−7 years); hence, their failures seldom occur during the planning time horizon (2 years). As a result, the benefit of PM in preventing equipment failure during this time horizon is hardly realized.

(2) The preventive maintenance times are relatively long, when compared with the repair time (about one-third of repair time), and the economic losses attributed to equipment unavailability are relatively large. The result is that, if PM frequency is increased, the benefit of PM in preventing failure is small, whereas the undesired effect of PM activities in increasing economic losses is significant, such that the total costs plus losses increase.

In this specific example, the application of PM to this main process equipment is not recommended. Generally, it may be beneficial or desirable to apply PM for this type of equipment, but the PM should not be done so frequently. A good maintenance practice for this main process equipment is to maintain the equipment at the time that the process plant is shut down for periodical overhaul/maintenance. Note also that the curves in Figure 7 are flat (unchanged) in the region where the PM time interval is greater than 0.5 × MTBF. The reason is simple: the PM time interval equal to or longer than 0.5 × MTBF, when added to the PM starting time, is greater than the planning time horizon; hence, the next PM time after the first PM is outside the planning time horizon and, therefore, is not conceived within the planning time horizon, and, thus, increasing the PM time interval beyond the value of 0.5 × MTBF will not cause any effect. These discussions suggest that the planning time horizon is an important parameter in Monte Carlo simulation and should be appropriately selected. This is discussed later.

CM and PM with Labor Limitations. The effect of available labor resource on maintenance performance is investigated when both CM and PM are used. The results shown below are obtained under two conditions: (i) the spare parts are always available, and (ii) PM is applied only for non-interfering equipment.

Figure 8 shows the maintenance labor cost, the economic losses, and the total costs plus losses, each as a function of the number of maintenance workers in the case where the PM time interval is 0.1 × MTBF. Figure 9 shows the same for the case where the PM time interval is 0.9 × MTBF.

The dependence of labor cost, the economic losses, and the total costs plus losses (objective value) on the number of maintenance workers in the case where both CM and PM are used (Figures 8 and 9) is same as the dependence in the case where only CM is used (Figure 5), because of the same reasons explained previously. The only difference is that the economic losses and the objective value in this case are lower than the corresponding values in the case where only CM is used, thanks to the beneficial effect of PM in preventing equipment failure. It is interesting that the optimal labor work force size for this case is again three workers. Applying PM has two competing effect on the workload of the workers: (i) the CM duty is reduced, because PM reduces the number of equipment failures, as noted previously, and (ii) a PM duty is introduced, which increases the workload. The average number of labor hours per week needed to do maintenance in the three cases where (i) there is no PM, (ii) the PM (non-interfering units) cycle is 0.9 × MTBF, and (iii) the PM (Non-interfering units) cycle is 0.1 × MTBF is calculated to be 1.38, 1.61, and 4.6, respectively. Thus,

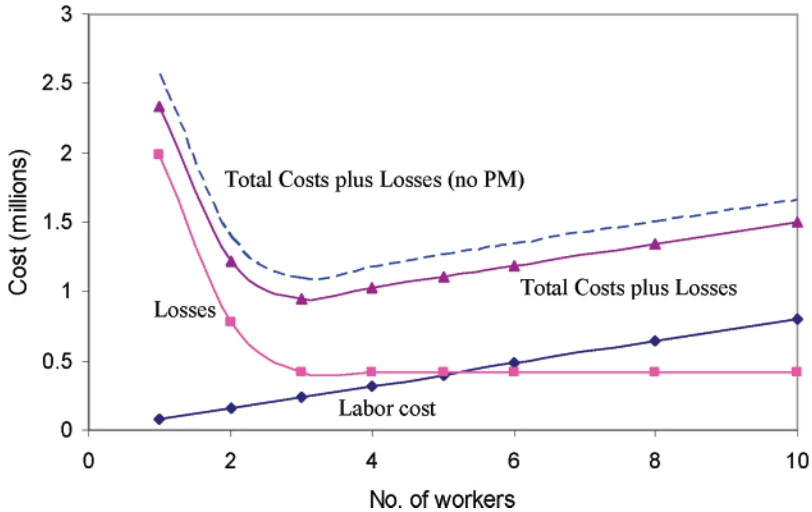

Figure 8. Effect of labor resource (PM for non-interfering units, PM cycle = 0.1 × MTBF).

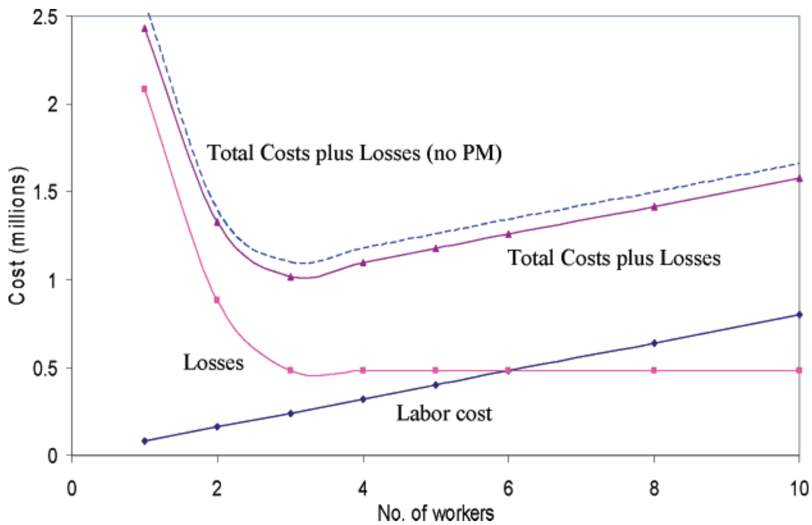

Figure 9. Effect of labor resource (PM for non-interfering units, PM cycle = 0.9 × MTBF).

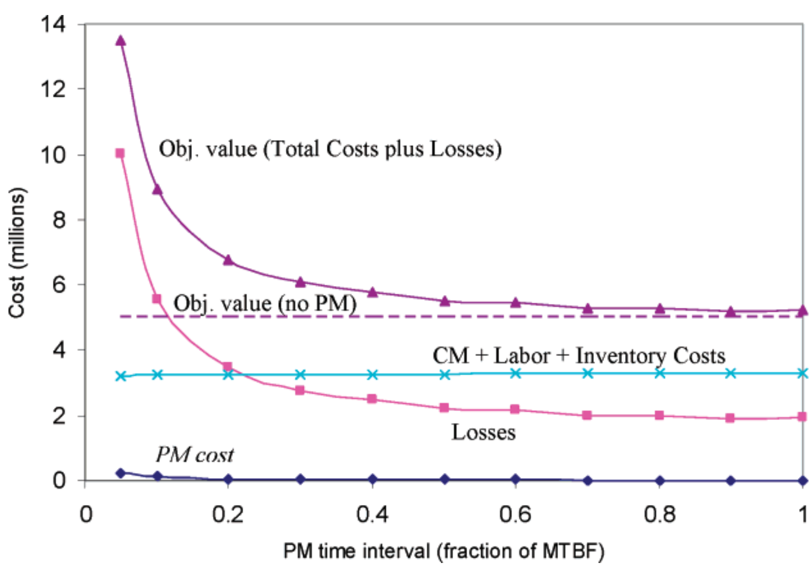

Figure 10. Effect of PM frequency for interfering equipment (planning time = 6 yrs).

because of the fact that the PM time for non-interfering equipments is short (shown in Table 2), using PM increases the workload (per week), but only by a small amount, and the average number of labor hours needed per week is still far below the available number of labor hours (120 per week when there are three employees). As a result, the effect of the introduction of PM on the punctuality of doing CM is expected to be negligible. In fact, when PM is used with a PM time interval of 0.1 × MTBF, the average value of the total number of CM orders that must be delayed, corresponding to 1, 2, 3, and 4

Table 6. Summary of Results for a Planning Time Horizon of Six Years

decision variable	option a: all spare parts are available	option b: some spare parts are available	option c: spare parts are not available
Optimal inventory policy, 10 workers			
objective value	5 006 963	4 845 611	5 050 701
Optimal labor work force size, CM only			
number of labor	2	3	4
objective value	4 323 302	3 327 121	3 567 091
Optimal labor work force size, PM = 0.5 × MTBF			
number of labor	2	3	4
objective value	4 153 433	3 180 114	3 423 790
Optimal PM frequency, PM for non-interfering units, 10 workers			
PM cycle	0.05 × MTBF	0.1 × MTBF	0.2 × MTBF
objective value	4 779 611	4 771 032	4 796 858

workers is 0.5249, 0.2229, 0.1344, and 0.1339, respectively, whereas the corresponding numbers when no PM is used are 0.5158, 0.2027, 0.1049, and 0.1042, respectively. Therefore, in this specific example, the introduction of PM, which leads to a small increase in maintenance workload (per week), is easily serviced by the three available workers.

The inventory policy for the spare parts necessary for CM is not affected by PM policy; hence, the effect of inventory policy in the case where both CM and PM are used is not investigated. Next, we investigate the effect of the planning time horizon parameter on the Monte Carlo simulation.

Effect of Planning Time Horizon. The planning time horizon of 2 years was used in obtaining the aforementioned results. The simulation with a longer planning time horizon would more accurately capture the events as is in reality. For example, it better captures the failures of equipment with large MTBF values. However, a longer planning time horizon requires more computation time. We investigate whether the results shown above (the optimal work force size, optimal PM frequency, and inventory policy) would change if the planning time horizon is changed from 2 years to 6 years. The results are summarized in Table 6. This table shows that the optimal values of decision variables are unchanged when the planning time horizon is changed: the optimal inventory policy is still keeping inventory for the spare parts necessary for repairing the valves, pumps, and compressor; the optimal workforce size is three workers; and the optimal PM frequency (for non-interfering units) is 0.1 × MTBF. These optimal values of the decision variables and the associated minimum objective values are shown in column 4 of Table 6.

The effect of PM for the interfering equipment (the main process equipment) is reinvestigated using a planning time horizon of 6 years. The results are shown in Figure 10. This figure shows that increasing the PM frequency for interfering equipment will increase economic losses and the objective value, as was observed in Figure 7. It also shows that the economic losses and the objective value do change as expected when the PM time interval is equal or greater than 0.5 × MTBF (they do not change if a horizon time of 2 years is used). The minimum objective value is found at a PM time interval of 0.9 × MTBF, but the change in objective value in the proximity region around the minimum point (for a PM time interval from 0.7 × MTBF to 1.0 × MTBF) is small (~0.5% of the objective value). Thus, using a time horizon of 6 years can identify the optimal PM frequency for interfering equipment, whereas using the time horizon of 2 years cannot. Generally, the planning time horizon should be at least equal to the MTBF of the equipment whose PM policy is being investigated.

There is no numerical problem that affects the ability to perform of the maintenance simulation such as the scaling problem. In other words, the model is guaranteed to perform properly for any set of input parameters. However, the results obtained are highly dependent on the estimated parameters such as CM cost and PM cost, inventory cost, and economic loss. Although the determination of CM cost and PM cost is straightforward (these costs are available in real-life plants or can be easily estimated), the estimation of inventory cost requires more effort, because there are many elements that comprise this cost (storing cost, depreciated value of equipment, etc.). The estimation of economic loss is the most difficult, because it requires the analysis of economical effect of equipment failure, which usually calls for detailed process simulation of the failure. Overestimation of the economic loss can result in too-frequent PM (to reduce the loss), and overestimation of the inventory cost can result in too few spare parts being stockpiled. Generally, it is recommended that one should pay more effort to obtain the best estimates for the parameters associated with main/ important equipments in the process (such as control valves, heat exchangers, compressors) and disregard equipment that are not important or have a back-up copy available on-line (such as bypass valves and pumps). Finally, we do not severe discontinuities in the objective, so that sensitivity would be an issue when genetic algorithm (GA) optimization methods are applied.

Table 7. Computing Time

	time horizon = 2 yrs	time horizon = 6 yrs
CM only	29 s	1 min
PM time interval (non-interfering units) = 0.1 × MTBF	1 min, 37 s	4 min, 38 s
PM time interval (interfering units) = 0.1 × MTBF	49 s	2 min, 5 s

Table 7 concludes the illustration section. It shows some computation times; the number of simulation runs is 10 000, and the computer used is a personal computer (PC) with 2.8 GHz CPU and 1024 MB RAM. The table shows that the computation time is relatively short and that, when the planning time horizon is tripled, the computation time is almost tripled, as expected. Therefore, we have high hopes that larger systems will be manageable in a reasonable computation time.

13. Conclusions

In this work, a Monte Carlo simulation-based maintenance planning model was developed. The economic losses are used as a performance measure of a maintenance policy and are included in a single composite objective function, along with the total costs plus economic losses. This allows one to obtain an unconstrained maintenance optimization model. Two realistic maintenance operation issues that usually are not considered in published maintenance planning models are incorporated in the model. They are (i) ranking equipment according to their consequences of failure and (ii) the consideration of labor resource constraints and material resource constraints. The ranking levels and the available resources are used in scheduling the maintenance activities. The effect on maintenance performance of each of the decision variables, including labor force size, maintenance policy, and spare parts inventory policy, is investigated one at a time. The results confirm the benefit of using preventive maintenance. Our future work will involve incorporating the model with genetic algorithm (GA)-based optimization to optimize the three decision variables simultaneously.

Acknowledgment

The authors would like to acknowledge the help of undergraduate students Kehinde Adesoye and Joseph Mills in gathering and organizing the data required for this article.

Literature Cited

(1) Tan, J. S.; Kramer, M. A. A General Framework for Preventive Maintenance Optimization in Chemical Process Operations. *Comput. Chem. Eng.* **1997**, *21* (12), 1451−1469.

(2) Dhillon, B. S. *Engineering Maintenance*; CRC Press: Boca Raton, FL, 2002.

(3) Murthy, D. N. P.; Atrens, A.; Eccleston, J. A. Strategic maintenance management. *J. Qual. Maint. Eng.* **2002**, *8* (4), 287−305.

(4) Mobley, R. K.; Higgins, L. R. *Maintenance Engineering Handbook*; McGraw−Hill: New York, 2002.

(5) Wang, H.; Pham, H. *Reliability and Optimal Maintenance*; Springer Series in Reliability Engineering; Springer−Verlag: London, 2006.

(6) Wang H. A survey of maintenance policies of deteriorating systems. *Eur. J. Oper. Res.* **2002**, *139* (3), 469−489.

(7) Garg, A.; Deshmukh, S. G. Maintenance Management: Literature Review and Directions. *J. Qual. Maint. Eng.* **2006**, *12* (3), 205−238.

(8) Podgorelec, V.; Kokol, P.; Kunej, A. Nuclear Power Plant Preventive Maintenance Planning Using Genetic Algorithms. In *Intelligent Problem Solving: Methodologies and Approaches: 13th International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems, IEA/AIE 2000*; Lecture Notes in Computer Science, No. 1821; Springer−Verlag: Berlin, 2000; pp 611−616.

(9) Shum, Y. S.; Gong, D. C. The Application of Genetic Algorithm in the Development of Preventive Maintenance Analytic Model. *Int. J. Adv. Manuf. Technol.* **2006**, *32*, 169−183.

(10) Savic, D. A.; Walters, G. A.; Knezevic, J. Optimal Opportunistic Maintenance Policy Using Genetic Algorithms, 1: Formulation. *J. Qual. Maint. Eng.* **1995**, *1* (2), 34−49.

(11) Saranga, H. Opportunistic Maintenance Using Genetic Algorithms. *J. Qual. Maint. Eng.* **2004**, *10* (1), 66−749.

(12) Kennedy, W. J.; Patterson, J. W.; Fredendall, L. D. An overview of recent literature on spare parts inventories. *Int. J. Prod. Econ.* **2002**, *76* (2), 201−215.

(13) Ilgin, M. A.; Tunali, S. Joint optimization of spare parts inventory and maintenance policies using genetic algorithms. *Int. J. Adv. Manuf. Technol*. **2007**, *34* (5), 594−604.

(14) Gopalakrishnan, M.; Ahire, S. L.; Miller, D. M. Maximizing the Effectiveness of a Preventive Maintenance System: An Adaptive Modeling Approach. *Manage. Sci.* **1997**, *43* (6), 827−840.

(15) Ahire, S.; Greenwood, G.; Gupta, A.; Terwilliger, M. Workforce-Constrained Preventive Maintenance Scheduling Using Evolution Strategies. *Decis. Sci.* **2000**, *31* (4), 833−858.

(16) Yao, X.; Fernández-Gaucherand, E.; Fu, M. C.; Marcus, S. I. Optimal Preventive Maintenance Scheduling in Semiconductor Manufacturing. *IEEE Trans. Semicond. Manuf.* **2004**, *17* (3), 345−356.

(17) Mobley, R. K. *An Introduction to Predictive Maintenance*, 2nd Edition; Elsevier: Boston, 2002.

(18) Smith, A. M.; Hinchcliffe, G. R. *RCM Gateway to World Class Maintenance*; Elsevier: Boston, 2004.

(19) Okogbaa, O. G.; Peng, X. A Methodology for Preventive Maintenance Analysis under Transient Response. In *Reliability and Maintainability Symposium, 1996 Proceedings*; Institute of Electrical and Electronics Engineers (IEEE): Piscataway, NJ, 1996; pp 335−340. (ISBN-13: 9780780331129, DOI: 10.1109/RAMS.1996.500683)

(20) *Guidelines for Process Equipment Reliability Data with Data Tables*; Center for Chemical Process Safety of the American Institute of Chemical Engineers: New York, 1989.

(21) Tischuk, J. L. *The Application of Risk Based Approaches to Inspection Planning*; Tischuk Enterprises (U.K.), Ltd.: Aberdeen, U.K., 2002.

(22) Ricker, N. L.; Lee, J. H. Nonlinear Modeling and State Estimation for the Tennessee Eastman Challenge Process. *Comput. Chem. Eng*. **1995**, *19* (9), 983−1005.

(23) Bhushan, M.; Rengaswamy, R. Comprehensive Design of a Sensor Network for Chemical Plants Based on Various Diagnosability and Reliability Criteria. 2. Applications. *Ind. Eng. Chem. Res.* **2002**, *41* (7), 1840−1860.

(24) Bloch, H. P.; Geitner, F. K. *Maximizing Machinery Uptime*; Elsevier: Boston, 2006.

(25) Peters, M. S.; Timmerhaus, K. D.; West, R. E. *Plant Design and Economics for Chemical Engineers*, 5th Edition; McGraw−Hill: New York, 2003.

(26) Barbaro, A. F.; Bagajewicz, M. Managing Financial Risk in Planning under Uncertainty. *AIChE J*. **2004**, *50* (5), 963−989.

(27) Aseeri, A.; Bagajewicz, M. New Measures and Procedures to Manage Financial Risk with Applications to the Planning of Gas Commercialization in Asia. *Comput. Chem. Eng.* **2004**, *28* (12), 2791−2821.

Received for review September 11, 2007
Revised manuscript received November 30, 2007
Accepted January 2, 2008

IE071231I