APPLICATION OF THE PREVENTIVE MAINTENANCE SCHEDULING TO INCREASE THE EQUIPMENT RELIABILITY: CASE STUDY- BAG FILTERS IN CEMENT FACTORY

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Abstract. This paper solves a new model of preventive maintenance scheduling with novel methodology. The aim of solving this problem is to determine the period for which bag filter should be taken off line for planned preventive maintenance over a specific time horizon and maintain a certain level of reliability with minimal maintenance cost. A mathematical programming method (Benders’ decomposition) and a metaheuristic algorithm are presented to provide solutions. The obtained objective value from Benders’ decomposition method is considered as the stopping criterion in the metaheuristic algorithm. To demonstrate the significance and originality of the proposed model and the efficiency of the algorithms, computational analysis is provided to realistic bag filters system in the cement factory. The obtained result is a schedule that allows the cement factory to consider the preventive maintenance for bag filters over the time horizon.

1. Introduction. Preventive maintenance scheduling (PMS) is one of the research areas has attracted much attention over the past decades. The main objective of PMS is optimizing the system reliability and reducing the maintenance cost of the entire system. Keeping equipment in good condition through preventive maintenance (PM) can ensure a system with high reliability. PM is: regular and systematic inspection, cleaning, and replacement of worn parts, materials, and systems. In order to attain constant system functioning, it is necessary to be aware when a system is exposed to failure or when it requires servicing. This PM will enable these faults to be forestalled before failure occurs. The maintenance scheduling literature has a variety of application. These diverse applications include aircraft maintenance, cement industry, vehicle fleet maintenance, railway track maintenance, power generation, pavement maintenance, highway maintenance, refinery, and production facilities. Cement factory emissions into air, cause serious air pollution and affect the plant and animal life. Also the air pollution has become a major threat to the survival of plants in the industrial areas. The main sources of dust emissions in the cement industry are kilns, raw material and clinker mills. Depending on the type of

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technological installation, two different types of equipment are used for de-dusting and dust collection in the cement industry, bag filters and electro-filters.

2. Literature review.

2.1. Preventive maintenance scheduling. Allaoui et al. [1] considered PMS on the two machine flow shop problem and assumed that the machines are always available during the scheduling period. They showed that this problem is NP-hard. Naderi et al. [2] used PMS in flexible flow shop problems and assumed that machines may not be periodically available during the production scheduling. Lu et al. [3] studied the PMS for a single machine problem with availability constraints. They used a genetic algorithm based on the properties of the optimal schedule to solve their problem. Pereira et al. [4] presented a particle swarm optimization algorithm for non-periodic PMS optimization. Moghaddam [5] presented a new multi-objective model to determine pareto-optimal preventive maintenance and replacement schedules for a repairable multi-work station manufacturing system with increasing rate of occurrence of failure. Perez-Canto and Rubio-Romero, [6] presented a model for the power plant PMS. This model evaluates which generators must stop production to be checked periodically for safety reasons. Go et al. [7] considered the PMS for a containership equipped with various subsystems during its sailing according to a pre-determined navigation schedule. Chen et al. [8] expressed PMS problem of reusable rocket engine by genetic algorithm. Three types of PM activities for RRE are considered and modeled by introducing the concept of effective age. Mollahassani-pour et al. [9] proposed the PMS of generating units as a crucial issue that is effective on both economy and reliability of power system. They developed a new formulation of PMS associated with a novel cost reduction index. Gustavsson et al. [10] presented the PMS problem with interval costs, which is to schedule preventive maintenance of the components of a system over a finite and discretized time horizon, given a common set-up cost and component costs dependent on the lengths of the maintenance intervals. Fitouhi and Nourelfath, [11] expressed the integrating noncyclical PMS with tactical production planning in the multi-state systems. Doostparast et al. [12] studied the problem of reliability-based periodic PMS for systems with deteriorating components. Zhu et al. [13] presented the effect and the benefit of introducing a scheduled halt of the system as a protective maintenance measure that is evaluated by Pareto multi-objective optimization and Pareto front according to both cost and availability criteria. Pandey et al. [14] proposed a model that includes finite planning horizon and limited available resources to perform maintenance scheduling.

2.2. Maintenance in cement industry. Mjema and Mweta [15] presented an analysis of economics of investing in IT in the maintenance department of cement factory. The economics in this case was determined by conducting a quantitative analysis on the reduction of maintenance costs, on increase in productivity and on quality improvement. A comparison was made to analyses company performance in the maintenance before and after the introduction of IT in the maintenance department. The analysis shows that there were reductions of operational and inventory holding costs. Likewise, it was shown that there was also improvement in product quality and productivity. Graisa and Al-Habaibeh [16] considered maintenance and production problems in the cement industry in Libya, with particular emphasis on future implementation of total productive maintenance (TPM). They solved
productivity problems and developed a strategic framework of TPM for improving Libyan industry. Shafeek [17] studied the continuous improvement of maintenance process for the cement industry. Continuous maintenance improvement (CMI) is an ongoing effort to improve maintenance aimed at maintenance process simplification and reduction or elimination of maintenance process waste. The purpose of this paper was to describe the most important areas of maintenance management system for heavy industries for helping maintenance managers to focus on measuring the effectiveness of maintenance system.

2.3. Solution methods. Mathematical programming methods or metaheuristic algorithms have been proposed to solve maintenance scheduling problems. Mathematical approaches are mainly based on linear, integer, mixed-integer programming, decomposition, branch-and-bound and dynamic programming. Canto,[18] used Benders’ decomposition for power plant PMS to knowing which generating units to take off line for regular safety inspection. Cao et al. [19] developed two efficient solution methods, based on Benders’ decomposition for yard truck and yard crane scheduling problems for loading operations in container terminal. Parastegari et al. [20] applied the Benders’ decomposition method and particle swarm optimization to solve alternating current constrained hydro-thermal generation scheduling problem. Khatami et al. [21] used Benders’ decomposition to solve the stochastic mixed-integer model for concurrent redesign of forward and closed-loop supply chain network. Ebrahimi et al. [22] used Non-dominated Sorting Genetic Algorithm (NSGAII) and Multi Objective Genetic Algorithm (MOGA) to solve the hybrid flow shop scheduling. Some other related works can be found in the literature, where all of their contribution are to use an exact algorithm or a metaheuristic algorithm to solve the PMS problems. Also, very few studies considered PMS in the industry environment. Therefore, because of the existing of the discussed gap, this paper introduces a hybrid method to solve the PMS problem. In this method, a modified Benders’ decomposition algorithm is applied to solve the model exactly. Then we use objective value from Benders’ decomposition as the stopping criterion in the metaheuristic algorithm (NSGA II) with new solution representation. Also this problem is applied in the real industry (cement factory).

3. Problem description.

3.1. Inspection period, study periods and maintenance duration. In PM scheduling, all bag filters are inspected in H intervals of equal durations. In each inspection, based on the bag filter deterioration state and its role in the reliability of the system, one of the three PM actions may be performed (inspection only, low level repair and replacement). The study periods may be expressed as 13 months or 52 weeks. Maintenance duration depends on the type of bag filters. Bag filters are divided into three groups based on their size, including: (1) large bag filters (bag house) used in the kiln department, (2) medium bag filters used in the cement mill department and (3) small bag filters used in other departments. Maintenance duration will be included repair time plus replacement time.

3.2. Scenario structure about cement production. Cement production rate effects on the bag filters maintenance scheduling. Hence, we consider different scenarios according to the cement production. One period is equal to one month. Due to the limitation transportation, the cement demand reduces at the weekend and holidays. So we consider two portions in each month: business days and weekend
days. Demand in the first portion is greater than in the second one. Each portion is divided into three sub-portions that from higher to lower demand are: upper, middle, lower. This classification provides six sub-periods with specific duration. Cement demand may be different during a year (for example: cement demand in the summer is more than that in the winter). So, we consider three different scenarios for cement production: high ($S_h$), medium ($S_m$), and low ($S_L$). This is the best way to model uncertainty in the cement production related to the bag filters maintenance scheduling, canto[18].

3.3. System reliability. The reliability of the system is derived by its components reliabilities and the system configuration. Here the Weibull distribution is used to calculate the reliability of a bag filter undergoing a given maintenance policy. It is defined as:

\[ R_{i,o,h} = R_{i,f,h-1} + m_2(1 - R_{i,f,h-1}), \quad \forall h, i \]  

(1)

\[ R_{i,h}(t) = R_{i,o,h} \exp\left(-\frac{(t - (h-1)TR_p)^\beta}{m_2\sigma}\right), \quad (h-1)TR_p \leq t \leq hTR_p, \quad \forall h, i \]  

(2)

where:
- $\beta, \sigma$: Shape and scale parameters for the Weibull distribution
- $TR_p$: Time interval between inspections
- $R_{i,o,h}$: Reliability of the $i$th bag filter at the beginning of $h$th inspection period
- $R_{i,f,h-1}$: Reliability of the $i$th bag filter at the end of $(h-1)$th inspection period
- $R_{i,h-1}(t)$: Instant reliability of the $i$th bag filter during the $h$th period
- $m_1, m_2$: Improvement factors due to various PM actions ($0 \leq m_1, m_2 \leq 1$)

Equation (1) shown the reliability of the $i$th bag filter at the beginning of the $h$th period. It implies that the bag filter reliability at the beginning of the period is equal to the reliability at the end of the previous period plus improved reliability as a result of the maintenance at current period. Then, the reliability of the $i$th bag filter at the beginning of the $h$th period is substituted into Equation (2). In the Equation (2), the parameter textitm1 is determined by the hazard rate function of the bag filter. The coefficient $m_2$ in Equation (1) reflects the effect of the PM action performed on the bag filters reliability.

3.4. Modeling the problem under study.

\[ \text{Minimize} \sum_{i \in I} \sum_{s \in S} \sum_{k \in K} \sum_{n \in N} P_s(U_i \times y_{i,s,k,n} + X_{i,k} \times C_{i,s,k,n} \times t_n) \]  

(3)

Subject to:

\[ R_{i,o,h}^{[s]} \geq R_{i,min}^{[s]} \]  

(4)

\[ \sum_{k \in K} X_{i,k} = D_i \quad \forall i \in I \]  

(5)

\[ \sum_{i \in I} X_{i,k} \leq M_k \quad \forall k \in K \]  

(6)

\[ X_{i,k} - X_{i,k-1} \leq Z_{i,k} \quad \forall i \in I, \forall k \in K \]  

(7)
\[
\begin{aligned}
&\sum_{n=1}^{k} Z_{i,k_n} - Z_{j,k} \geq 0 \quad \forall k \in K, \\
&Z_{i,k} + Z_{j,k} \leq 1 \quad \forall k \in K, \\
&X_{i,k} + X_{j,k} \leq 1 \quad \forall k \in K \\
&Z_{i,k} = Z_{j,k} + D_i + \varepsilon \\
&1 \leq K \leq \delta - D_i - \varepsilon, \\
&\sum_{k=1}^{n} (Z_{i,k} + Z_{j,k} + D_i + \varepsilon = 2) \\
&Z_{i,k} = Z_{j,k} + D_i + u \\
&1 \leq K \leq \delta - D_i + u, \\
&\sum_{k=1}^{n} Z_{i,k} = 1 \quad \forall i \in I, \\
&\vartheta_{i,s,k,n} \times C_i \leq C_{i,s,k,n} \leq \vartheta_{i,s,k,n} \times \bar{C}_i \quad \forall i \in I, \forall s, \forall k \in K, \forall n \in N \\
&\sum_{i \in I} C_{i,s,k,n} = b_{s,k,n} \quad \forall s, \forall k \in K, \forall n \in N \\
&y_{i,s,k,n} \geq \vartheta_{i,s,k,n} - \vartheta_{i,s,k,n-1} \quad \forall i \in I, \forall s, \forall k \in K, \forall n \in N \\
&X_{i_1,k} + \vartheta_{i,s,k,n} \leq 1, \quad \forall i_1 \in I_1, \forall s, \forall k \in K, \forall n \in N \\
&X_{i_2,k} + \vartheta_{i,s,k,n} \leq 1, \quad \forall i_2 \in I_2, \forall s, \forall k \in K, \forall n \in N \\
&X_{i_3,k} + \vartheta_{i,s,k,n} \leq 1, \quad \forall i_3 \in I_3, \forall s, \forall k \in K, \forall n \in N \\
&U_{i_1} \times y_{i_1,s,k,n} \leq \sum_{n \in N} C_{i_1,s,k,n} \times t_n, \quad \forall i_1 \in I_1, \forall s, \forall k \in K \\
&U_{i_2} \times y_{i_2,s,k,n} \leq \sum_{n \in N} C_{i_2,s,k,n} \times t_n, \quad \forall i_2 \in I_2, \forall s, \forall k \in K \\
&U_{i_3} \times y_{i_3,s,k,n} \leq \sum_{n \in N} C_{i_3,s,k,n} \times t_n, \quad \forall i_3 \in I_3, \forall s, \forall k \in K \\
&X_{i,k}, Z_{i,k}, y_{i,s,k,n}, \vartheta_{i,s,k,n} \in [0,1] \quad \forall i \in I, \forall s, \forall k \in K, \forall n \in N
\end{aligned}
\]

where

- \( I \) = Index set for bag filters,
- \( I_1 \) = Index set for large bag filters,
- \( I_2 \) = Index set for medium bag filters,
- \( I_3 \) = Index set for small bag filters,
- \( S \) = Index set for cement production scenario,
- \( K \) = Index set for periods in cement production scenario,
- \( N \) = Index set for sub-periods in a period,
- \( P_s \) = Probability for production cement scenarios,
- \( R^{[s]}_h \) = System reliability in the \( h \)th period,
- \( R^{[\min]}_s \) = Minimum system reliability decreed during the planning horizon,
- \( U_i \) = Start-up cost of bag filter \( i \),
- \( D_i \) = Maintenance duration for bag filtre \( i \) (in all periods),
- \( M_k \) = Maximum number of maintenances in period \( k \),
- \( t_n \) = Duration of sub-period \( n \),
- \( b_{s,k,n} \) = Intended budget for maintenance of all bag filters in sub-period \( n \) of period \( k \) in scenario \( s \),
- \( C_{i,s,k,n} \) = Maintenance cost of bag filter \( i \), in sub-period \( n \) of period \( k \) in scenario \( s \),
- \( \bar{C}_i \) = Maximum cost assigned to the maintenance of bag filter \( i \).
3.5. **Description of objective function and constraints.** Costs are selected as the objective function for this problem. The objective function (3) is divided into two types of costs; start-up cost (this is the cost to run a bag filter after being disconnected) and maintenance cost (the cost to put a bag filter into preventive maintenance). Constraint (4) endorses the minimum required system reliability during the entire planning horizon. Constraint (5) shows that the maintenance of bag filter \( i \) takes a given number of periods, \( D_i \). The inequality (6) represents the period constraint. Constraint (7) guarantees that the maintenance of a bag filter is carried out in consecutive periods. Constraint (8) establishes the order to follow in bag filter maintenance. In constraint (9), bag filters \( i \) and \( j \) cannot be in maintenance simultaneously. Constraint (10) provides a sequence introducing a number of periods “e” between bag filters \( i \) and \( j \) shut down for maintenance, and \( \delta \) as the time horizon. Equation (11) is an overlap constraint that shows the maintenance of bag filters \( i \) and \( j \) has an overlap of “u” periods. Constraint (12) represents that the maintenance for each bag filter is only once along the all periods. Maintenance cost for each bag filter is between two values determined by the decision maker. For example, there are 1200 bags and baskets in the bag house. Replacing all of them is very costly in each duration. According to the budget assigned to each maintenance duration, it is decided that some of the bags and baskets are replaced in a bag filter. Constraint (13) shows that maintenance cost is between minimum and maximum values. Equation (14) is the budget constraint for maintenance of all bag filters in sub-period \( n \) of period \( k \) in scenarios. Constraint (15) establishes the start-up logic for bag filters. Constraint sets (16) express the correlation between \( X_{i,k} \) and \( \vartheta_{i,s,k,n} \) and . Constraint sets (17) shows that start-up cost of bag filter \( i \) should be lesser than maintenance cost of bag filter \( i \), in sub-periods of period \( k \) in scenarios.

4. **Benders’ decomposition and metaheuristic algorithms to solve the problem under study.** Benders’ decomposition initially proposed by Benders, [23] that is one of the techniques in mathematical programming with guaranteed convergence. There are two stage in Benders’ decomposition algorithm. The variables of the original problem are split into two subset, so that a first-stage master problem (MP) is solved with the first set of variables, and then the solution of the first stage is used for the second stage. The second set of variables in the second stage is determined by a given first-stage solution. If the sub-problem (SB) shows that master problem is infeasible or not optimal yet, then feasibility and optimality Benders cuts are generated and added to the master problem. After computing the lower and upper bounds of the optimal value of the objective function of the original problem, the following constraint is checked:

\[
Z^{Upper} - Z^{Lower} < \epsilon
\]
In constraint (18), \( \epsilon \) is a small tolerance value to control the convergence of the algorithm. The stopping criterion in Benders’ decomposition is when the lower bound and upper bound are close enough. Figure 1 illustrates this process as Benders’ decomposition flow chart.

4.1. **Sub-problems.** Each sub-problem is considered per period, because start-up cost constraints are modeled by groups of periods. The number of sub-problems is equal to the number of scenarios multiplied by the number of periods in each scenario. Each sub-problem is:

\[
\begin{align*}
\text{Minimize} & \sum_{i \in I} \sum_{n \in N} (U_i \times y_{i,s,k,n} + X_{i,k} \times C_{i,s,k,n} \times t_n) \\
\text{Subject to:} & \\
R_h^{[S]} & \geq R_{min}^{[S]} \\
\rho_{i,s,k,n} \times C_i & \leq C_{i,s,k,n} \leq \rho_{i,s,k,n} \times C_i^c & \forall i \in I, \forall n \in N \\
\sum_{i \in I} C_{i,s,k,n} & = b_{s,k,n} & \forall n \in N \\
\begin{cases}
U_{i_1} \times y_{i_1,s,k,n} & \leq \sum_{n \in N} C_{i_1,s,k,n} \times t_n, & \forall i_1 \in I_1 \\
U_{i_2} \times y_{i_2,s,k,n} & \leq \sum_{n \in N} C_{i_2,s,k,n} \times t_n, & \forall i_2 \in I_2, \\
U_{i_3} \times y_{i_3,s,k,n} & \leq \sum_{n \in N} C_{i_3,s,k,n} \times t_n, & \forall i_3 \in I_3,
\end{cases} \\
X_{i,k} = X_{i,k}^c : \omega_{i,k}
\end{align*}
\]
X_{i,k}, Z_{i,k}, \vartheta_{i,s,k,n} \in [0, 1] \quad \forall i \in I, \forall n \in N

where

X_{i,k} = \text{The value obtained from master problem in the previous iteration}

\omega_{i,k} = \text{Dual variable associated to constraint (24)}

Constraints (18), (16), (17) and (23) are similar to constraints (3), (10), (11) and (17) respectively.

4.2. Master problem.

\textit{Minimize} \theta \tag{25}

\textit{Subject to:}

\begin{equation}
R_h^{[S]} \geq R_{min}^{[S]} \tag{26}
\end{equation}

\begin{equation}
\sum_{k \in K} X_{i,k} = D_i \quad \forall i \in I \tag{27}
\end{equation}

\begin{equation}
\sum_{i \in I} X_{i,k} \leq M_k \quad \forall k \in K \tag{28}
\end{equation}

\begin{equation}
X_{i,k} - X_{i,k-1} \leq Z_{i,k} \quad \forall i \in I, \forall k \in K \tag{29}
\end{equation}

\begin{equation}
\sum_{k_n = 1}^{k} Z_{i,k_n} - Z_{j,k} \geq 0 \quad \forall k \in K, \tag{30}
\end{equation}

\begin{equation}
Z_{i,k} + Z_{j,k} \leq 1 \quad \forall k \in K, \tag{31}
\end{equation}

\begin{align}
\{Z_{i,k} &= Z_{j,k} + D_i + e \\
1 \leq K &\leq \delta - D_i - e, \tag{32}
\}
\end{align}

\begin{align}
\sum_{k=1}^{K} (Z_{i,k} + Z_{j,k} + D_i + e = 2) \\
Z_{i,k} &= Z_{j,k} + D_i + u \\
1 \leq K &\leq \delta - D_i + u, \tag{33}
\end{align}

\begin{equation}
\sum_{k \in K} Z_{i,k} = 1 \quad \forall i \in I \tag{34}
\end{equation}

\begin{align}
\{\theta \geq \varphi^{(1)} + &\sum_{i \in I} \sum_{k \in K} \omega^{(1)}_{i,k} \times (X_{i,k} - X^{(1)}_{i,k}), \\
\theta \geq \varphi^{(2)} + &\sum_{i \in I} \sum_{k \in K} \omega^{(2)}_{i,k} \times (X_{i,k} - X^{(2)}_{i,k}), \\
\vdots & \\
\theta \geq \varphi^{(\xi)} + &\sum_{i \in I} \sum_{k \in K} \omega^{(\xi)}_{i,k} \times (X_{i,k} - X^{(\xi)}_{i,k}), \tag{35}
\}
\end{align}

\begin{equation}
X_{i,k}, Z_{i,k} \in [0, 1] \quad \forall i \in I, \forall k \in K
\end{equation}

The Benders’ cut added in every iteration cuts off some infeasible assignments. The Benders’ cuts reproduce the \( \theta \) as an objective function, constraint (25). In constraint (35) the \( \varphi^{(\xi)} \) is the sum of the objective function values obtained from sub-problem of the iteration \( \xi \).

4.3. Metaheuristic algorithm.
4.3.1. Solution representation. In the metaheuristic algorithms the first step to solve a problem is usually to specify the way of solution representation. In this method, for each bag filter an integer random number between \([1,w^1]\) is generated that \(w^1\) is the number of week in the time horizon. Also in order to determine the sequence of bag filters to maintenance in each week, random numbers are generated between \([0, 1]\). The bag filter having smaller number is maintenance sooner. As an example, it is assumed that there are 15 bag filters and 20 weeks that shown in Figure. 2.

![Figure 2. Solution representation](image)

The maintenance scheduling of 15 bag filters on 20 weeks will be as follows:

Week 2: Bag filter6, Week 4: Bag filter4, Week 5: Bag filter1, Bag filter11, Week 8: Bag filter5, Week 9: Bag filter10, Week 12: Bag filter15, Bag filter9, Bag filter2, Week 14: Bag filter12, Week 15: Bag filter3, Week 17: Bag filter8, Bag filter13, Week 20: Bag filter14, Bag filter7

4.3.2. Crossover. Crossover is a mechanism for diversification. The crossover creates two new children by combining both parent chromosomes genes. For this study we perform uniform crossover. In order to do that, two chromosomes in the current generation are selected. We consider the chromosome with better fitness value as parent 1 and the other one as parent 2. Then a new chromosome with random number between (0,1) should be generated and name it Mask. The mask size should be equal to the maximum length of bag filters. If the generated number for one specific gene in mask is less than 0.7, the corresponding value of parent 1 is copied into it, otherwise the corresponding value of parent 2 is used that shown in Figure. 3.

![Figure 3. A crossover example](image)
4.3.3. Mutation. The remaining percent of the generation is produced using mutation operator. Two bag filters of one chromosome is selected. The associated values with these two bag filters are replaced.

4.3.4. Non-dominated Sorting Genetic Algorithm (NSGAII). In this algorithm to have the variety in solution, crowding distance has been used to measure population density. The same NSGAII that proposed by Ebrahimi et al. [22] is used in this paper. Also we have considered the obtained objective value from Benders’ decomposition algorithm as a stopping criterion in the NSGAII. This algorithm is illustrated as Figure 4: The stopping criterion in Benders’ decomposition is when the lower bound and upper bound are close enough. Since we have a minimization problem, the lower bound of the objective is the best possible objective (the lower bound is the optimal value of the master objective) and the upper bound represents the worst case. We have considered the obtained objective value from Benders’ decomposition algorithm as a stopping criterion in the NSGAII.

5. Case study. To demonstrate the significance of the proposed model and the efficiency of the Benders’ decomposition method and NSGAII, computational analysis is provided to realistic bag filters system in the cement factory in Iran (Faraz Firuzkuh Cement Company, FFCC). The Lingo and MATLAB were used as optimization software to solve the Benders’ decomposition model and NSGAII algorithm respectively. Table 1 gives the input parameters for maintenance scheduling model.

The problem under study has the following features:
- Number of bag filters: 35
- Number of cement production scenarios: 3
- Number of periods: 13
- Number of sub-periods: 6
- Probability for production cement scenario: $P_{Sl} = 0.3$, $P_{Sm} = 0.5$, and $P_{Sh} = 0.2$.
- Descending order for cement production quantity for periods are as follows: (5)-(4)-(6)-(3)-(2)-(7)-(13)-(8)-(9)-(1)-(10)-(11)-(12). The maximum of production quantity is in the month (5) and minimum of production quantity is in the month (12).
- Upper, middle and lower durations in a period are, 25%, 60% and 15% respectively.

This study could be of interest to cement factory with production activity, due to its applicability, and particularly. The implementation of the work developed in this paper could be beneficial for same factory. In addition, given that reliability is included in the model presented by means of certain constraints, such as cement demand supply, it is possible to maintain a specific quality service level, increasing customer satisfaction.

5.1. Results. The stopping criterion in Benders’ decomposition is when the lower bound and upper bound are close enough. Since we have a minimization problem, the lower bound of the objective is the best possible objective (the lower bound is the optimal value of the master objective) and the upper bound represents the worst case. The convergence was reached after 32 iterations. The cost of each scenario is multiplied by its probability. Figure 5 represent the convergence. We have considered the obtained objective value from Benders’ decomposition algorithm as a stopping criterion in the NSGAII. Table 2 gives the maintenance scheduling for
Figure 4. Solution procedures of NSGAII algorithm

An analysis was used to search the pareto set for the case study according to the data from 8 years ago. Figure 6 represents a set of bag filter maintenance schedule and provides the optimal trade-offs among bag filter performance, cost and environmental impacts. Decision makers can choose the trade-offs so as to arrange suitable maintenance schedules. In a general trend, with the increase of bag filter performance, holistic costs and environmental impacts decrease. Figure 7 represents the progress of NSGAII for obtaining the optimal solution. The most relevant contribution of this work is the use of Benders decomposition method to solve the problem of cement factory preventive maintenance scheduling. Other important contributions can be described as follows:
Consideration of precedence, non-stop, interval, and overlap constraints. No references to these constraints have been found before. They have been completely described and modelled.

Simultaneous use of maintenance variables and start-up variable. This formulation gives a new perspective on the problem.

Integration in the same model of maintenance, economic unit commitment, maintenance constraints

The inclusion of these constraints has been considered before, but differently from the way they are presented here. Moreover, the above expressions for constraints are not the same.

**Figure 5.** Converges of the lower and upper bounds versus iterations

**Figure 6.** Trade offs between two objectives

6. **Conclusions.** In today’s business environment, the maintenance of equipment is one of the most important challenge that manager encounter. The great advantage of preventive maintenance for each equipment is optimizing the system reliability and reducing the maintenance cost of the entire system. This paper mainly discusses how to incorporate the strategic and tactical decision together in the preventive maintenance scheduling. For this purpose, a new mathematical programming model was developed in this paper. In order to solve the problem,
Figure 7. The progress of NSGAII for obtaining the optimal solution

Table 1. The input parameters for model

| Bag filter size | Bag filter size | Scale parameter | Shape parameter | Repair-Replacement time (hr) | Repair-Replacement cost ($) |
|----------------|----------------|-----------------|-----------------|-----------------------------|-----------------------------|
| Small          | Small          | 2500            | 2.5             | 50                          | 120                         | 20                          | 40                          |
Table 2. Maintenance scheduling for bag filters

| B/p | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|-----|---|---|---|---|---|---|---|---|---|----|----|----|----|
| 1   | √ |   |   |   |   |   |   |   |   |    |    |    |    |
| 2   | √ |   |   |   |   |   |   |   |   |    |    |    |    |
| 3   |   | √ |   |   |   |   |   |   |   |    |    |    |    |
| 4   |   |   | √ |   |   |   |   |   |   |    |    |    |    |
| 5   |   |   |   | √ |   |   |   |   |   |    |    |    |    |
| 6   |   |   |   |   | √ |   |   |   |   |    |    |    |    |
| 7   |   |   |   |   |   | √ |   |   |   |    |    |    |    |
| 8   |   |   |   |   |   |   | √ |   |   |    |    |    |    |
| 9   |   |   |   |   |   |   |   | √ |   |    |    |    |    |
| 10  |   |   |   |   |   |   |   |   | √ |    |    |    |    |
| 11  |   |   |   |   |   |   |   |   |   | √   |    |    |    |
| 12  |   |   |   |   |   |   |   |   |   |   | √   |    |    |
| 13  |   |   |   |   |   |   |   |   |   |   |   | √   |    |
| 14  |   |   |   |   |   |   |   |   |   |   |   |   | √   |
| 15  |   |   |   |   |   |   |   |   |   |   |   |   |   | √   |
| 16  |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √   |
| 17  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 18  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 19  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 20  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 21  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 22  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 23  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 24  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 25  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 26  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 27  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 28  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 29  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 30  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 31  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 32  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 33  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 34  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |
| 35  |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   |   | √ |

A modified Benders’ decomposition algorithm was applied to solve the model exactly. Benders’ decomposition is a way to dividing the main problem into a set of sub-problems and a master problem to simplifying the solution. This method became convergence after 32 iterations. In other words, after 32 iterations the lower and upper bounds were close enough. Then we used the obtained objective value from Benders’ decomposition method as the stopping criterion in the NSGAII. We developed new solution representation in this algorithm. The proposed model was applied in a real industry. Also, the scheduling of preventive maintenance was obtained in each period and every week. The obtained scheduling was adequate for
| Week | Small bag filter | Medium bag filter | Large bag filter | Reliability at the end of week |
|------|------------------|-------------------|------------------|-------------------------------|
| 1    |                  |                   |                  | 97.2%                         |
| 2    | 3                |                   |                  | 93.6%                         |
| 3    | 9                |                   |                  | 97.6%                         |
| 4    |                  | 23,30             |                  | 91.3%                         |
| 5    | 1                |                   |                  | 92.4%                         |
| 6    | 26               |                   |                  | 92.0%                         |
| 7    |                  |                   |                  | 95.7%                         |
| 8    |                  |                   |                  | 95.4%                         |
| 9    | 15               |                   |                  | 93.6%                         |
| 10   |                  |                   |                  | 96.0%                         |
| 11   |                  | 21,28,29          |                  | 90.8%                         |
| 12   |                  | 1,5,35            |                  | 91.1%                         |
| 13   |                  |                   |                  | 95.5%                         |
| 14   |                  |                   |                  | 94.8%                         |
| 15   |                  |                   |                  | 96.2%                         |
| 16   |                  |                   |                  | 93.9%                         |
| 17   | 6                |                   |                  | 92.4%                         |
| 18   |                  |                   |                  | 94.6%                         |
| 19   | 7,20             |                   |                  | 90.4%                         |
| 20   |                  |                   |                  | 95.0%                         |
| 21   |                  |                   |                  | 96.2%                         |
| 22   | 15               |                   |                  | 93.9%                         |
| 23   | 24               |                   |                  | 93.4%                         |
| 24   |                  |                   |                  | 91.1%                         |
| 25   |                  |                   |                  | 92.2%                         |
| 26   |                  |                   |                  | 94.6%                         |
| 27   | 2                |                   |                  | 90.4%                         |
| 28   | 34               |                   |                  | 90.0%                         |
| 29   |                  |                   |                  | 91.7%                         |
| 30   |                  |                   |                  | 90.0%                         |
| 31   |                  |                   |                  | 90.6%                         |
| 32   | 16,19            | 2.5               |                  | 93.2%                         |
| 33   | 8                |                   |                  | 90.7%                         |
| 34   | 25               |                   |                  | 91.3%                         |
| 35   | 33               |                   |                  | 91.8%                         |
| 36   |                  | 12,13             |                  | 90.7%                         |
| 37   | 22               |                   |                  | 90.0%                         |
| 38   |                  | 14                |                  | 90.8%                         |
| 39   | 14               |                   |                  | 91.2%                         |
| 40   |                  |                   |                  | 92.1%                         |
| 41   |                  |                   |                  | 92.0%                         |
| 42   | 32               |                   |                  | 90.3%                         |
| 43   |                  |                   |                  | 93.0%                         |
| 44   | 11,2500          | 2.5               |                  | 91.0%                         |
| 45   |                  |                   |                  | 92.1%                         |
| 46   |                  |                   |                  | 91.9%                         |
| 47   | 17,31            |                   |                  | 90.2%                         |
| 48   |                  |                   |                  | 91.7%                         |
| 49   | 3,27             |                   |                  | 90.0%                         |
| 50   |                  |                   |                  | 93.4%                         |
| 51   |                  |                   | 17               | 91.6%                         |
| 52   |                  |                   |                  | 95.7%                         |
the modeled requirements, due to the imposed constraints, and optimized the cost as objective function. The trade-offs among bag filter performance, environmental impact and cost was used in order to support decision makers in evaluating the effects of various maintenance plan. We believe this paper provides a good starting point in this research area. Considering routing decision in the addressed problem are a valuable future research. Furthermore, since the computational time increase significantly when problem size and the number of scenarios increase, developing heuristic and metaheuristic methods to large size problem is a challenging area for future studies.

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