

MAINTENANCE WORKFORCE PERFORMANCE ENHANCEMENT IN A FUZZY ENVIRONMENT WITH MULTIPLICITY OF CRITERIA IN MANUFACTURING SYSTEM

Desmond Eseoghene Ighravwe¹ and Sunday Ayoola Oke^{2*}

Received: September 09, 2015; Revised: November 09, 2015; Accepted: November 12, 2015

Abstract

The maintenance industrial sector has shown an increasing interest in the performance of the workforce in manufacturing systems. In this study, the performance enhancement of a maintenance workforce with a multiplicity of criteria in the manufacturing system under multi-objective decision making in a fuzzy environment is considered. The model formulation of the problem as a weighted additive fuzzy goal programming is considered. The applicability and efficacy of the proposed model was demonstrated using a combination of literature and simulated datasets and solutions were generated with a genetic algorithm (GA). The performance of the GA was analysed by comparing its results with those of a harmony search algorithm and differential evolution. The performance of the GA was satisfactory and we concluded that the proposed model had the capacity to generate a Pareto solution for the case study. The novelty of this study is the presentation of a distinctly new approach that takes care of workers' reliability, defective product issues, and the time-sharing between production and maintenance departments.

Keywords: Maintenance workforce, production planning, goal programming, performance enhancement, metaheuristics

Introduction

The maintenance industrial sector has shown an increasing interest in the performance enhancement of the workforce in manufacturing systems. By effective and efficient workforce

planning programmes, workloads and workforce size determination have been controlled to aid improvement in fatigue reduction for workers, reduced accidents, and decreased workforce

¹ Department of Mechanical Engineering, Faculty of Engineering, University of Lagos, Room 10, Mezzanine Complex, Akoka-Yaba, Lagos, Nigeria. E-mail: ighravwedmond@gmail.com

² Department of Mechanical Engineering, Faculty of Engineering and Technology, Ladoko Akintola University of Technology, Ogbomosho, Nigeria. E-mail: sa_oke@yahoo.com

* Corresponding author

costs (Belmokaddem *et al.*, 2009; Happer *et al.*, 2013; Mekidiche *et al.*, 2013). It has also triggered an improved job satisfaction and enhanced motivation for workers.

This study is based on performance enhancement of a workforce in maintenance of a manufacturing system. Treatment of the maintenance workforce is considered with the multiplicity of criteria in the manufacturing system under decision making in a fuzzy environment. Numerous quantitative and qualitative studies have been published on the performance of a workforce in general. The perspectives adopted have related to workers' productivity (Ighravwe and Oke, 2014), workers' reliability (He *et al.*, 2014), workforce effectiveness (Ighravwe *et al.*, 2015), and cost criterion (Safaei *et al.*, 2008; Mansour, 2011). Others are concerned with fuzzy goal programming (Mansour, 2011; Ighravwe and Oke, 2014; Glover *et al.*, 2015; Ighravwe *et al.*, 2015) and inventory metrics (Belmokaddem *et al.*, 2009).

Workforce performance has been enhanced over the years by using 4 principal tools: linear programming, non-linear programming, mixed-integer programming, and fuzzy goal programming (Belmokaddem *et al.*, 2009; Mansour, 2011; Yimmee and Phruksaphanrat, 2011; Mekidiche *et al.*, 2013). After having identified the workforce variables, the manager can quantify them. The manager then distributes the workloads among workers at optimal thresholds. At optimal thresholds, workers' turnover and absenteeism from work due to accidents would be incorporated into the planning system. Ighravwe *et al.* (2015) reached a useful conclusion that when employees have an accident at work in the maintenance function, there is an unintended absenteeism that is triggered, negatively influencing the overall performance of work. They noted that absenteeism and accident factors are necessities in modelling maintenance workloads. However, the authors did not explain how results may be influenced by the uncertainties that naturally exist from stocks. In developing countries with unstable government policies on stocks, the stochastic nature of stock supplies impacts negatively on workers' outputs as shortages often result in idle times.

To compound this problem, the maintenance workforce system has several objectives, including workforce cost reduction, maximisation of workforce investment, and reduction in the number of defective products. Thus, the workforce problem is therefore multi-goal-oriented. Formulating the above mentioned maintenance workforce problems as a goal programming model would therefore be helpful but this has not been conceptualised for the maintenance system.

The maintenance function has several factors that could be considered but which have been ignored in workforce research until the present (Safaei *et al.*, 2008). Naturally, a manager strongly depends on workforce reliability for the effective management of the system. Since this is difficult to measure, prior studies have ignored this but a starting point is to assign a factor to this. Furthermore, there is usually a conflict between production and maintenance as to who should be responsible for defects produced by a machine. The argument from production is that, if a machine is returned to them in a not "as-good-as-new state", there is a tendency for producing defective products. A significant factor often ignored is the time sharing problem between production and maintenance. There is usually reluctance by production to release equipment to maintenance for service. Thus, a time-sharing policy by management is compelling.

To further enhance the optimisation platform for contributing a novel study on performance enhancement, the genetic algorithm (GA) has been used as a tool. Prior to this time, the GA has also been widely applied both in industry and research. The GA has the special advantage of reproducing offsprings with improved performance metrics. It also could solve problems that have been described as NP-hard (Tavakkoli-Moghaddam and Safaei, 2006; Mansour, 2011). This study examines the effectiveness of the GA by comparing the GA results with those of differential evolution (DE) and harmony search (HS) algorithms.

The remaining sections of this study are organised as follows: The proposed model is in section 2, while discussion on the solution methods are in section 3. The model application is in section 4. The discussion of

the results is in section 5 and the conclusion of this study is in section 6.

Methodology

This section deals with the development of the nonlinear mixed-integer programming model for maintenance workforce-cum-production problems. The weighted additive fuzzy goal programming approach (WAFGP) is selected based on the ease of prioritising the fuzzy goal (Ahmadpour and Chitgar, 2012). Also, the WAFGP is considered because it has the capacity to generate several alternative solutions for large-scale problems (Velasquez and Hester, 2013). Some of the assumptions made during the development of the proposed model are as follows:

- Tasks assigned to workers are performed optimally;
- Manufacturing time is deterministic and varies from 1 period to another;
- The workers' skills can be improved through training programmes;
- Limits on the number of workers for a training programme are known; and
- The effect of fatigue on the workers' service rate is not significant.

The notations used in this study are stated in the Appendix of this study.

Objective Functions

The first objective function in the proposed model deals with the minimisation of workforce cost per hour (Equation 1). Equation (1) is used to establish the relationship between the total maintenance workforce cost and total workforce hour (Parida and Kumar, 2009).

$$\text{Min } Z_1 = \frac{\sum_{i=1}^M \sum_{j=1}^N \sum_{t=1}^T C_{ijt}^1 x_{ijt}}{\sum_{i=1}^M \sum_{j=1}^N \sum_{t=1}^T m_{ijt} x_{ijt}} \quad (1)$$

Minimisation of the workforce cost index is the second objective function (Parida and Kumar, 2009) that is considered. The workforce cost index measures the ratio of the total cost of the workforce to the value of the total cost of production (Equation 2).

Mekidiche *et al.* (2013) defined the cost of production as a function of the production of product costs, which covers energy, materials, capital, information, and the cost for the workforce used for production activities, while Ighravwe and Oke (2014) defined the workforce cost as the sum of the product of the workforce size and their unit cost.

$$\text{Min } Z_2 = \frac{\sum_{i=1}^M \sum_{j=1}^N \sum_{t=1}^T C_{ijt}^1 x_{ijt}}{\sum_{i=1}^M \sum_{j=1}^N [(1 - d_{it} + d_{it} R_i) U_i P_{it}] V_{it} + \sum_{i=1}^M \sum_{j=1}^N \sum_{t=1}^T C_{ijt}^1 x_{ijt}} \quad (2)$$

The third objective function is the minimisation of the training cost and salaries for the workforce (Mekidiche *et al.*, 2013). This objective function helps in improving the disbursement of a maintenance fund for training programmes.

$$\text{Min } Z_3 = \sum_{i=1}^M \sum_{j=1}^N \sum_{t=1}^T (C_{ijt}^1 x_{ijt} + C_{ijt}^2 y_{ijt}) \quad (3)$$

The last objective function is returns on workforce investment, which is a function of the ratio of the profit to the workforce cost (Visier Inc., 2015). Improvement in a company's profit could be as a result of the reduction in the cost of goods sold (Jesswein, 2011).

$$\text{Max } Z_4 = \frac{\sum_{i=1}^M \sum_{j=1}^N PP_{it}}{\sum_{i=1}^M \sum_{j=1}^N \sum_{t=1}^T C_{ijt}^1 x_{ijt}} \quad (4)$$

Model Constraints

By exposing workers to different training programmes, the management of such a system are interested in maximising the workers' performance. To evaluate the improvement in the workers' performance during preventive maintenance, the value of the total workforce man-hours and workforce size could be considered (Equation 5).

$$\frac{m_{ijt} x_{ijt}}{T_{ijt} x_{ijt}} \geq \bar{h}_{ijt} \quad \forall i \in M; \forall j \in N; \forall t \in T \quad (5)$$

The value of the failure rate (λ) of a system will improve by training and re-training the workers. The benefits of retaining a skilled workforce in a system

include the following: early identification of possible failure through recognition of foreign sounds from an installed facility and prompt diagnosis of machine failures, and reduction in the repair time. In practice, the value of λ varies with the operating conditions of a system (equipment age, ambient conditions, and operators' expertise). Thus, a near-optimal value of λ is sought for in this study. The determination of the range of solutions for λ is determined using the Weibull distribution. Given that the number of breakdowns of an installed facility decreases following an arithmetic progression, the value of λ for the system at period t is expressed as Equation (6).

$$\lambda_t p_{it} \leq a_0 - (T-1)B_n \quad \forall t \in T \quad (6)$$

The rate at which invoices for finished goods are addressed is a function of stock levels and the quantity of goods produced (i.e., product availability). Ighravwe and Oke (2015) presented an expression for the relationships among production volume, demand, number of defective products, and the amount of finished goods inventory (Equation 7). This study considered the finished goods inventory constraint as a supply constraint (Equation 8) and expressed the inventory holding cost as Equation (9).

$$I_{it-1} + (1-d_{it} + d_{it}R_i)U_iP_{it} - I_{it} - D_{it} = 0 \quad \forall t \in T \quad \forall i \in L \quad (7)$$

$$I_{it} \leq I_{\max,i} \quad \forall t \in T \quad (8)$$

$$\sum_{i=1}^L c_i^3 I_{it} \leq INV_t \quad \forall t \in T \quad (9)$$

where $d = d_i U_i P_{it}$ and $R = R_i d$.

To control the quality of finished products, a quality control department often specifies the expected quality level (Equation 10). This policy is guided by the number of defective products and total volume of goods produced. Product quality is evaluated based on the minimum (d_{il}) and maximum (d_{iu}) amounts of defective products allowed (Equation 11).

$$1 - \frac{\sum_{i=1}^L d_{it} U_i P_{it}}{\sum_{i=1}^L U_i P_{it}} \geq Q_i \quad \forall t \in T \quad (10)$$

$$d_{il} \leq d_{it} \leq d_{iu} \quad \forall t \in T \quad (11)$$

The workforce reliability index measures the dependability of workers in executing the assigned tasks. The failure of group workers in executing assigned tasks will result in a system failure. For example, if a maintenance team in charge of lubricating machine parts fail in their duty, this will affect the quality of the maintenance activities of other teams (e.g. welding). Thus, we assumed that the workforce reliability of the different groups in a section is in series. Series reliability for a team of workers (Romeu, 2015) is expressed as Equation (12). The reliability of the whole workforce is considered as being parallel, because the failure of a team of workers in the mechanical section might not cause a shut-down of a plant (Equation 13). By combining Equations (12) and (13), the workers' reliability is obtained (Equation 14). The expected value of the workers' reliability is expressed as Equation (15).

$$\prod_{j=1}^N R_{ijt}^{x_{ijt}} = \hat{R}_{it} \quad \forall i \in M; \forall t \in T \quad (12)$$

$$1 - \prod_{i=1}^M (1 - \hat{R}_{it}) \geq \bar{R}_t \quad \forall t \in T \quad (13)$$

$$1 - \prod_{i=1}^M \left(1 - \prod_{j=1}^N R_{ijt}^{x_{ijt}} \right) \geq \bar{R}_t \quad \forall t \in T \quad (14)$$

$$R_L \leq R_{ijt} \leq R_U \quad \forall i \in M; \forall j \in N \quad \forall t \in T \quad (15)$$

The enforcement of a recommended schedule for maintenance activities is pivotal to smooth production activities. Beyond such a schedule, the duration that each section is expected to spend in carrying out the assigned maintenance tasks is equally important. This problem (maintenance duration) is modelled by considering the available manufacturing time ($\bar{M}_t$) and the proportion of total stoppage of a machine because of maintenance activities (η). This is used in establishing the interrelationships

among production, downtime, and manufacturing time (Equation 16).

$$\sum_{l=1}^L p_{lt} + \eta \sum_{i=1}^M \sum_{j=1}^N m_{ijt} x_{ijt} \leq \dot{M}_t \quad \forall t \in T \quad (16)$$

With the concept of the minimum ($\dot{M}_l$) and maximum ($\dot{M}_u$) amounts of production time, Equation (17) is used to constrain the amount of production time. The value of the workforce unavailability is expressed as Equation (18) based on the proportion of the average production time required (n_1). The value of the system reliability using the number of defective products and machine failure rate is expressed as Equation (19).

$$\sum_{l=1}^L p_{lt} \geq \frac{n_1(\dot{M}_l + \dot{M}_u)}{2} \quad \forall t \in T \quad (17)$$

$$1 - \frac{\sum_{l=1}^L p_{lt}}{\dot{M}_t - \eta \sum_{i=1}^M \sum_{j=1}^N m_{ijt} x_{ijt}} \leq U \quad \forall t \in T \quad (18)$$

$$e^{-\lambda_t \frac{\dot{M}_t}{d}} \geq R_{st} \quad \forall t \in T \quad (19)$$

The value of preventive maintenance time for each section depends on the level of the automation of a system. For a semi-automated production system, the amount of maintenance time that will be allocated for preventive maintenance activities for the mechanical section will be greater than that of the electrical section (Equation 20).

$$\sum_{j=1}^N m_{i-1,jt} x_{i-1,jt} \geq \sum_{j=1}^N m_{ijt} x_{ijt} \quad i = 2, 3; \forall t \in T \quad (20)$$

Workforce distributions in systems have effects on the running cost of a system (Mansour, 2011; He *et al.*, 2014; Ighravwe and Oke, 2014). To manage the cost of workers in maintenance systems, the ratio of the workers in a section with respect to other sections is used in controlling the workers' costs. A limitation on the number of workers that will be allowed to enter training programming is another approach of workers' costs reduction. Knowledge transfer among workers makes the need for limiting the numbers of technicians for training a good cost reducing measure. This

situation is commonly practiced in an organisation where workers are sent for a training programme outside their environment.

By using workers' costs, the percentage of the maximum number of workers (ϕ_1) that will be allowed to undergo training is expressed as Equation (21). A balance in the number of workers that will be trained at each period is considered (Equation 22). The expected amount of funds for training expenses is expressed as Equation (23).

$$\sum_{j=1}^N y_{1jt} \geq \phi_1 \sum_{i=1}^M \sum_{j=1}^N y_{ijt} \quad \forall t \in T \quad (21)$$

$$\frac{y_{ijt}}{x_{ijt}} \geq \phi_2 \quad \forall i \in M; \forall j \in N; \forall t \in T \quad (22)$$

$$\sum_{i=1}^M \sum_{j=1}^N c_{ij}^3 y_{ijt} \leq B_t \quad \forall t \in T \quad (23)$$

A change in the workforce level between 2 consecutive periods (Equation 24) and the expected numbers of workers (Equation 25) are the last sets of constraints considered.

$$x_{ijt} = x_{ijt-1} + h_{ijt} - f_{ijt} \quad \forall i \in M; \forall j \in N; \forall t \in T \quad (24)$$

$$X_{\min} \leq \sum_{i=1}^M \sum_{j=1}^N x_{ijt} \leq X_{\max} \quad \forall t \in T \quad (25)$$

By using the knowledge gained from the studies of Yaghoobi *et al.* (2008) and Mekidiche *et al.* (2013), a WAFGP model for maintenance workforce planning is formulated. The membership functions (μ_k) are obtained using Figures 1 and 2. This entails defining the quantity of a tolerance for the objectives (Δ_{kR} or Δ_{kL}) and their aspiration level (b_k).

The complete structure of the WAFGP maintenance-production model is presented as follows:

$$\text{Min } Z = \sum_{k=1}^3 w_k \frac{\delta_k^+}{\Delta_{kL}} + w_4 \frac{\delta_4^+}{\Delta_{4R}} \quad (26)$$

Subject to:

$$Z_k - \delta_k^+ \leq b_k \quad k = 1, 2, 3 \quad (27)$$

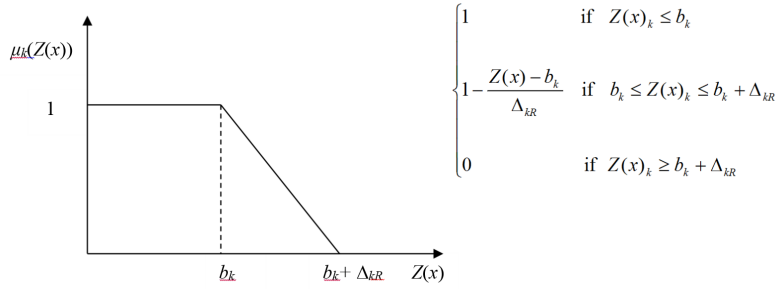


Figure 1. Membership function for the minimisation objective functions

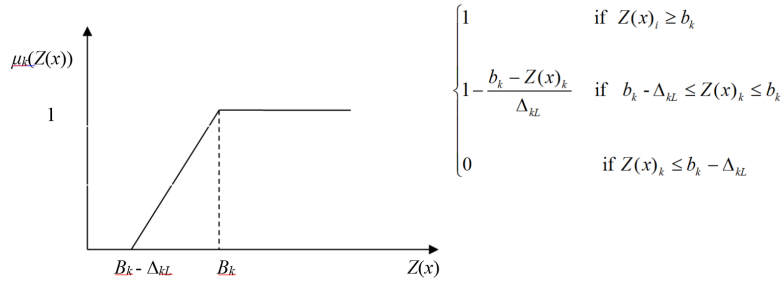


Figure 2. Membership function for the maximisation objective function

$$Z_4 + \delta_4^+ \geq b_4 \quad (28) \quad \sum_{l=1}^L c_l^3 I_{lt} \leq INV_t \quad \forall t \in T$$

$$\mu_k + \frac{\delta_k^+}{\Delta_{kL}} \leq 1 \quad k=1,2,3 \quad (29) \quad 1 - \frac{\sum_{l=1}^L d_{lt} U_l P_{lt}}{\sum_{l=1}^L U_l P_{lt}} \geq Q_t \quad \forall t \in T$$

$$\mu_4 + \frac{\delta_4^+}{\Delta_{4R}} \leq 1 \quad (30) \quad d_{lt} \leq d_{lt} \leq d_{ltU} \quad \forall t \in T$$

$$\frac{m_{ijt} x_{ijt}}{T_{ijt} x_{ijt}} \geq \bar{h}_{ijt} \quad \forall i \in M; \forall j \in N; \forall t \in T \quad 1 - \prod_{i=1}^M \left(1 - \prod_{j=1}^N R_{ijt}^{x_{ijt}} \right) \geq \bar{R}_t \quad \forall t \in T$$

$$\lambda_t p_{lt} \leq a_0 - (T-1)B_n \quad \forall t \in T \quad R_L \leq R_{ijt} \leq R_U \quad \forall i \in M; \forall j \in N \quad \forall t \in T$$

$$I_{lt-1} + (1 - d_{lt} + d_{lt} R_l) U_l P_{lt} - I_{lt} - D_{lt} = 0 \quad \forall t \in T \quad \forall l \in L \quad \sum_{l=1}^L p_{lt} + \eta \sum_{i=1}^M \sum_{j=1}^N m_{ijt} x_{ijt} \leq \dot{M}_t \quad \forall t \in T$$

$$I_{lt} \leq I_{\max, l} \quad \forall t \in T \quad \sum_{l=1}^L p_{lt} \geq \frac{n_l (\dot{M}_l + \dot{M}_u)}{2} \quad \forall t \in T$$

$$1 - \frac{\sum_{l=1}^L p_{lt}}{\dot{M}_t - \eta \sum_{i=1}^M \sum_{j=1}^N m_{ijt} x_{ijt}} \leq U \quad \forall t \in T \quad X_{\min} \leq \sum_{i=1}^M \sum_{j=1}^N x_{ijt} \leq X_{\max} \quad \forall t \in T$$

$$e^{-\lambda_t \frac{\dot{M}_t}{d}} \geq R_{st} \quad \forall t \in T$$

$$\sum_{j=1}^N m_{i-1,jt} x_{i-1,jt} \geq \sum_{j=1}^N m_{ijt} x_{ijt} \quad i = 2, 3; \forall t \in T$$

$$\sum_{j=1}^N y_{1,jt} \geq \varphi_1 \sum_{i=1}^M \sum_{j=1}^N y_{ijt} \quad \forall t \in T$$

$$\frac{y_{ijt}}{x_{ijt}} \geq \varphi_2 \quad \forall i \in M; \forall j \in N; \forall t \in T$$

$$\sum_{i=1}^M \sum_{j=1}^N c_{ij}^2 y_{ijt} \leq B_t \quad \forall t \in T$$

$$x_{ijt} = x_{ijt-1} + h_{ijt} - f_{ijt} \quad \forall i \in M; \forall j \in N; \forall t \in T$$

Solution Methods

Since the developed model is a multi-objective and nonlinear model, the solutions from the model are near-optimal. The near-optimal solutions are generated using metaheuristics as the solution methods. The performance of these metaheuristics is evaluated using a penalty function. The GA and DE algorithm which have similar characteristics are considered (Figure 3), while the results from the HS algorithm (Figure 4) are also considered (Engelbrecht, 2007; Mahdavi *et al.*, 2007). We applied metaheuristics, bounds (lower and upper) for decision variables, which are dependent on the system that a model is applied on. Thus, the bounds for the decision variables in the proposed model are system-dependent.

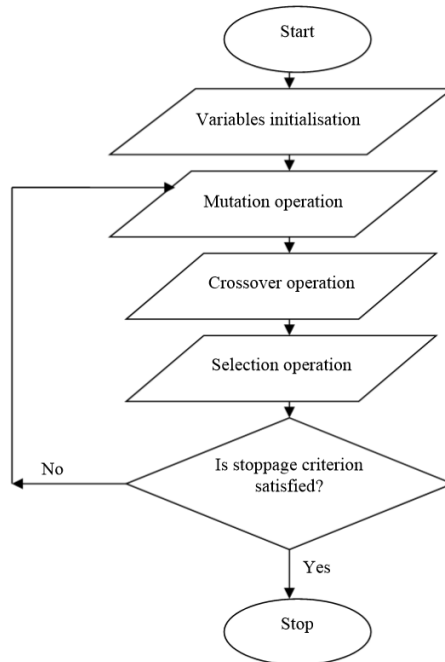


Figure 3. Genetic algorithm and differential evolution flowchart

Differential Evolution

The procedure involved in the DE algorithm implementation is given as follows (Storn and Price, 1997):

(i) Mutation stage: This operation involves the combination of 3 randomly selected vectors from the pool of parent population in creating new off-springs (Equation 31).

$$v_{ijg+1} = x_{ijg}^1 + MR(x_{ijg}^2 - x_{ijg}^3) \quad (31)$$

where $x_{ijg} \neq x_{ijg}^1 \neq x_{ijg}^2 \neq x_{ijg}^3$

(ii) Crossover stage: The decision on whether to accept the mutant vector from the mutation operation or target vector from a previous generation is based on the relationships among a uniformly generated random number, crossover rate (CR), and the index of the decision variable (Equation 32). The generated vectors are called trial vectors.

$$u_{ijg+1} = \begin{cases} u_{ijg+1} & rnd \leq CR \text{ or } j = I_{rnd} \\ x_{ijg} & rnd \geq CR \text{ and } j \neq I_{rnd} \end{cases} \quad (32)$$

where rnd is a uniformly distributed random number between (0, 1), and I_{rnd} is an integer value selected randomly from the problem dimension ($j = 1, \dots, D$).

(iii) Selection stage: The quality of the newly created off-springs (solution) and the parents in the population are compared in order to select the individuals (target vectors) that will survive to the next generation. The selection criterion for the minimisation case is expressed as Equation (33). For the maximisation selection case, fitness function is multiplied by -1 .

$$x_{ijg+1} = \begin{cases} u_{ijg+1} & \text{If } f(u_{ijg+1}) \leq f(x_{ijg}) \\ x_{ijg} & \text{Otherwise} \end{cases} \quad (33)$$

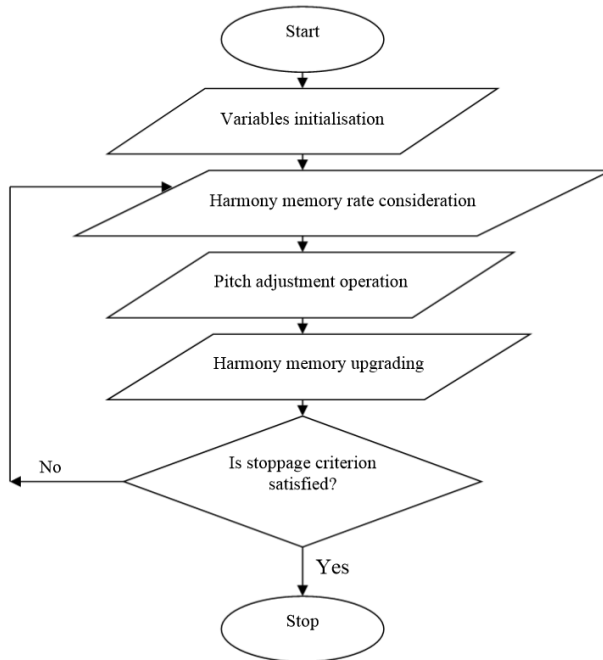


Figure 4. Harmony search algorithm flowchart

Genetic Algorithm

The GA is a metaheuristic modelled after the concept of evolution. The GA was based on the concept of survival of the fittest among individuals in a population (Engelbrecht, 2007). The basic procedure of the GA involves mutation, reproduction (crossover), and selection stages (Figure 3). The early versions of GA applications were coded using binary strings. The application of the GA by Cormier *et al.* (2001) reported an improved solution of the real-coding method over the binary coding method. The Cormier *et al.* (2001) implementation procedures are as follows:

(i) Mutation stage: The first operation deals with the generation of the mutant vector (Equation 34). The decision on whether to allow a selected parent (x_{ijg}) to under-mutate is determined using the concept of flipping an unbiased coin. This depends on the relationships between a random number (0, 1) and the mutation rate. The value of x_{ijg} is increased when a head occurs and decreased when a tail occurs (Cormier *et al.*, 2001).

$$x_{ijg+1} = \begin{cases} x_{ijg} + \bar{\delta} (x_{\max} - x_{ijg}) \\ x_{ijg} - \bar{\delta} (x_{ijg}^1 - x_{\min}) \end{cases} \quad (34)$$

where $\bar{\delta}$ is a constant parameter that lies between (0,1)

The value of $\bar{\delta}_t$ decreases with an increase in the iteration step and it is determined at each iteration step using Equation (35).

$$\bar{\delta}_t = \bar{\delta}_{t-1} r (1 - \bar{t}/\bar{T})^{\bar{B}} \quad (35)$$

where $\bar{t}$ is the current iteration step value, $\bar{T}$ is the maximum iteration step attainable, $\bar{B}$ is a constant parameter that lies between (1,5), and r is a random number that lies between 0 and 1 (Cormier *et al.*, 2001).

(ii) Reproduction stage: Trial vectors are generated during the reproduction operation. To achieve this, 2 parents (x_{ijg}) are randomly selected from the selection pool (P_i). These parents are used in reproducing 3 off-springs (x_{ijg+1}), Equation (36).

$$P_1, P_2 = \begin{cases} O_1 = 0.5P_1 + 0.5P_2 \\ O_2 = 1.5P_1 - 0.5P_2 \\ O_3 = -0.5P_1 + 1.5P_2 \end{cases} \quad (36)$$

(iii) Selection stage: The determination of individuals which will survive to the next generation is evaluated. Two off-springs (E_o^1 and E_o^2) are selected among the 3 off-springs based on an elitism approach (Cormier *et al.*, 2001). The selection between the off-springs and parent is carried out using the Boltzmann tournament selection (Goldberg, 1990). First, the Boltzmann tournament is used in selecting 1 off-spring (E_{win}) between the (E_o^1 and E_o^2) using an anti-acceptance probability (P^1), Equation (37). E_{win} is compared with a selected parent (E_{pp}) based on the logistic acceptance probability (P), Equation (38).

$$P^1 = \frac{\text{Exp}(-E_o^1/T_g)}{\text{Exp}(-E_o^1/T_g) + \text{Exp}(-E_o^2/T_g)} \quad (37)$$

$$P = \frac{\text{Exp}(-E_{win}/T_g)}{\text{Exp}(-E_{win}/T_g) + \text{Exp}(-E_{pp}/T_g)} \quad (38)$$

where T_g is the temperature at generation g and it is determined using a simulated annealing scheme.

Harmony Search Algorithm

The implementation of the HS algorithm (Geem *et al.*, 2001) involves 3 basic stages: memory consideration, pitch adjustment, and memory update.

(i) Memory consideration stage: This step entails the use of a random value, which is between (0, 1), in selecting new values for variables (x_{ijt}^{kk}) from the harmony memory (Equation 39).

$$x_{ijt}^{kk} = \begin{cases} x_{ijt}^{kk} \in \{x_{ijt}^1, x_{ijt}^2, x_{ijt}^3, \dots, x_{ijt}^{kk}\} & \text{With probability of HMCR} \\ x_{ijt}^{kk} \in X' & \text{Otherwise} \end{cases} \quad (39)$$

where HMCR is the harmony memory considering rate, with a value between (0,1).

(ii) Pitch adjustment stage: Each pitch (x_{ijt}^k) is adjusted based on the pitch adjusting rate (PAR), Equation (40).

$$x_{ijt}^{kk} = \begin{cases} x_{ijt}^{kk} \pm rnd * bw_t & \text{With probability of PAR} \\ x_{ijt}^{kk} & \text{Otherwise} \end{cases} \quad (40)$$

where bw_t is the bandwidth at iteration step $\bar{t}$.

The value of (bw_t) decreases exponentially from 1 iteration step to another (Alia and Mandava, 2011), based on Equation (41). Alia and Mandava (2011) reported that the value of $bw_{\max}$ for each variable can be estimated using minimum ($bw_{\min}$) and maximum ($bw_{\max}$) values for bw (Equation 42).

$$bw_t = bw_{\min} + \frac{bw_{\max} - bw_{\min}}{\bar{T}} \bar{t} \quad (41)$$

$$bw_{\max} = \frac{1}{20(\bar{x}_{\max} - \bar{x}_{\min})} \quad (42)$$

(iii) Memory update stage: This involves the comparison of a new solution with the worst solution (harmony) in the harmony memory, Equation (43).

$$sol = \begin{cases} f(x_{ijt}^{kk}) & \text{If } f(x_{ijt}^{kk}) \leq f(x_{ij, \text{worst}}^{kk}) \\ f(x_{ijt-1}^{kk}) & \text{Otherwise} \end{cases} \quad (43)$$

Model Application and Results

This section used the example provided by Ighravwe and Oke (2014) and complemented it with simulated data to implement the

proposed model. The maximum number of operation days/month was 29 days and the value of η was 15%. Four periods were considered during the proposed model implementation. The quantities of the products demanded for period 1 was 554,422,066 kg, while 545,500,727 kg was demanded in period 2. For period 3, the quantity of products demanded was 533,511,537 kg. In period 4, 542,970,466 kg of products were demanded.

The maximum amount of the inventory at each period was 1,015,114 kg. The budget for the inventory holding cost was a function of the maximum inventory and the unit inventory holding cost. The company's profit was about 25% of the value of the goods sold. Information on the workforce cost and workforce limits is in Table 1. Other conditions used in the proposed model implementation are as follows:

- The expected range for worker's reliability was between 0.49 and 1 (He *et al.*, 2014; Glover *et al.*, 2015);
- The minimum number of workers for the system was 13 workers, while the maximum number of workers was 21 workers;
- The minimum amount of production time at each period was 70% of the available manufacturing time;
- The number of operation days per month was between 23 and 29 days, with an average of 22 hours/day operation;
- The minimum quality of goods produced at any period was 99%;
- The unit cost of hiring was 85% of each category of the workers' salary; and
- The unit cost of hiring was 150% of each category of the workers' salary.

During the implementation of the proposed model, the population size for each solution method was 30. Each solution run contained

Table 1. Initial workers level and cost

Sections	Cost (₦)		Worker level	
	Full-time	Part-time	Full-time	Part-time
Mechanical	58,240	48,240	1-7	4-9
Electrical	52,780	42,780	1-5	1-4
Hydraulic	46,090	36,090	1-3	1-3

100 iterations. The fitness functions at each iteration step were estimated using the exterior penalty function (Coello, 2002). A set of 40 solutions was generated with each algorithm (Figure 5). The performance of the algorithms was evaluated based on the best, worst, and average solutions (Table 2). In addition, the 40 sets of solution for each of the algorithms were used to establish the boundary of the algorithms' solutions (Equation 44) at $\alpha = 5\%$ (Engelbrecht, 2007). The results in Figure 5 represent the converge values of the algorithm for 40 different runs.

$$\text{Boundary} = \mu_{\text{solution}} \pm t_{\alpha, n-1} \sigma_{\text{solution}} \quad (44)$$

$$\sigma_{\text{solution}} = \sqrt{\frac{\sum_{i=1}^n (\nu_i - \bar{\nu})^2}{n(n-1)}} \quad (45)$$

Based on the statistical analysis of the algorithms' results (Table 2), the Pareto solution (Rardin, 1998) from the GA is better than the DE and HS algorithms. The WAFGP problem was solved using the GA. The result for Z_1 was 125.54 N/h, while 64.89×10^{-4} was

obtained as the solution for Z_2 . We observed that maximum values for membership functions for Z_1 (0.9149) and Z_2 (0.9888) were not obtained. The solution for Z_3 was ₦ 5,673,000.00 (Nigerian Naira) and a value of 184.61 was obtained as the solution for Z_4 . The membership function for $Z_3(1)$ and $Z_4(1)$ reached maximum values. The compromise solutions were also generated for the workforce variables (Table 3) and production variables (Table 4).

Results and Discussion

At period 1, which is the starting period, the number of workers fired from the different workforce categories was zero (Table 2). The combination of the number of workers for each period showed that the company needed between 18 and 22 workers. During workforce planning, the expected ratio of the workforce distribution should be about 1: 1.5: 2 for the hydraulic, electrical, and mechanical workers, respectively.

The quality of maintenance services that will be expected from the different workforce

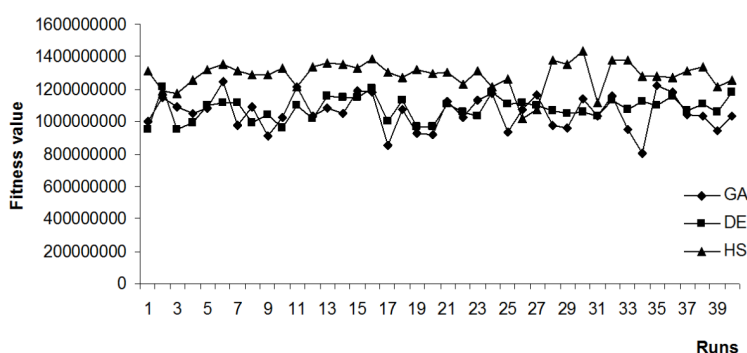


Figure 5. Fitness value for the metaheuristics

Table 2. Analysis of solution methods performance

Algorithms	F_{best}	F_{average}	F_{worst}	$F_{\text{boundary}} (\alpha = 5\%)$
GA	834,795,665	1,034,043,045	1,223,160,128	994,777,892 – 1,073,308,197
DE	956,090,404	1,103,730,761	1,252,292,170	1,035,986,522 – 1,171,475,000
HS	1,084,323,411	1,286,656,563	1,419,203,265	1,243,333,854 – 1,329,979,271

Table 3. Results for the workforce variables

Variables	Periods	Hydraulic workers		Electrical workers		Mechanical workers	
		x_{11t}	x_{12t}	x_{21t}	x_{22t}	x_{31t}	x_{32t}
Workers	$t = 1$	2	2	2	3	8	2
	$t = 2$	2	2	2	4	6	4
	$t = 3$	2	2	2	3	8	4
	$t = 4$	2	2	2	3	8	4
		f_{11t}	F_{12t}	f_{21t}	F_{22t}	f_{31t}	F_{32t}
Fired workers	$t = 1$	0	0	0	0	0	0
	$t = 2$	0	0	2	1	2	2
	$t = 3$	0	0	2	1	2	2
	$t = 4$	0	1	2	1	1	2
		h_{11t}	h_{12t}	h_{21t}	h_{22t}	h_{31t}	h_{32t}
Hired workers	$t = 1$	0	0	1	0	2	2
	$t = 2$	0	0	2	2	2	2
	$t = 3$	0	0	0	0	2	2
	$t = 4$	0	1	1	1	2	2
		y_{11t}	y_{12t}	y_{21t}	y_{22t}	y_{31t}	y_{32t}
Training	$t = 1$	2	2	2	2	4	4
	$t = 2$	2	2	2	2	4	4
	$t = 3$	2	2	2	2	4	4
	$t = 4$	2	2	2	2	4	4
		m_{11t}	m_{12t}	m_{21t}	m_{22t}	m_{31t}	m_{32t}
Service time (hr)	$t = 1$	322.51	314.32	291.92	326.76	322.82	318.02
	$t = 2$	287.84	311.53	291.17	294.46	287.43	288.23
	$t = 3$	326.53	325.64	305.36	319.57	327.56	289.53
	$t = 4$	289.82	327.14	314.36	288.67	328.91	290.93
		R_{11t}	R_{12t}	R_{21t}	R_{22t}	R_{31t}	R_{32t}
Worker's reliability (10^{-2})	$t = 1$	80.22	79.98	82.51	81.32	80.19	80.54
	$t = 2$	81.2	82.61	81.94	81.98	83.24	79.32
	$t = 3$	82.56	80.43	80	80.32	81.32	79.17
	$t = 4$	81.85	81.54	81.63	81.17	81.1	81.91

Table 4. Results for the production variables

Variables	Period 1	Period 2	Period 3	Period 4
Production time (hr)	482.08	480.36	480.85	483.61
Inventory (kg)	1,015,115.00	828,141.30	765,685.90	638,773.20
Failure rate (per day)	58.78×10^{-3}	60.17×10^{-3}	58.56×10^{-3}	60.34×10^{-3}
Defective ratio (per month)	66.24×10^{-4}	66.12×10^{-4}	70.68×10^{-4}	68.57×10^{-4}

distributions will generate defective products of between 0.66 and 0.72% of the total number of products produced in each period (Table 2). With these limits on the percentage of defective products, a control chart can be designed to monitor the performance of the company.

Based on the workforce distribution (Table 2), the costs of workers for each section were determined (Table 4). The company needed about ₦ 4,058,380.00 for workers' salaries for the all periods. The amount of funds for workforce training was about ₦ 1,614,620.00 (see Table 5 for additional information).

of hired and fired hydraulic workers for the 4 periods (Table 2). At each period, 16 workers went for training. We observed that the total number of workers that went for training from the mechanical section was equal to the sum of the workers that went for training from the electrical and hydraulic sections.

By comparing the values of the workers' reliability generated with the combined sequential quadratic programming and branch and bound solution method (He *et al.*, 2014) with the GA results (Table 2), it was inferred that the GA workers' reliability results are reasonable. From the results in Table 2, we observed that the full-time mechanical workers

Table 5. Workers cost for the different periods

Periods	Hydraulic		Electrical		Mechanical	
	x_{11t}	x_{12t}	x_{21t}	x_{22t}	x_{31t}	x_{32t}
1	92,180	72,180	105,560	128,340	465,920	96,480
2	92,180	72,180	105,560	171,120	349,440	192,960
3	92,180	72,180	105,560	128,340	465,920	192,960
4	92,180	72,180	105,560	128,340	465,920	192,960

US\$ 1 = ₦ 200

The determination of the amount of funds for the workers' salaries and training expenses will help in making informed decisions on the proportion of the organisation resources that should be appropriate to workforce-related expenses. For companies which are planning to go into production, the proposed model will serve as a guide on how much funds should be deposited for workers' expenses. For instance, the interrelationship between the cost of workers and maintenance time for all the periods considered was about 125.54 Naira/hour. This value showed that the company will not incur high costs when implementing the workforce structure in Table 2.

The range of funds that will be borrowed from banks can be determined based on the outputs of the proposed model. For example, the company does not need funds for full-time hydraulic workers' expenses for either fired or hired workers in period 1. The reason is that the proposed model generated a zero number

had the lowest reliability (0.79). The highest (0.83) worker reliability was from the part-time mechanical workers. Further analysis revealed that the mechanical section had the lowest (0.81) average sectional reliability. The electrical section had the highest (0.81) average sectional reliability. The results for the average workers' reliability for each period showed that the combination of the different workforce structure (Table 2) yielded about 0.81 as the average workers' reliability.

The total amount of maintenance work in the system for period 1 was 6056.38 h, while for period 2 it was 5836.42 h. A total of 6,652.37 hr was obtained as the total maintenance time for period 3, while the period 4 total maintenance time was 6523.65 h (Table 4), given that each of the workers was expected to clock 280 hours/month. From the information on the maintenance time in Table 5, the decision makers will budget funds that will cover between 236.40 and 772.37

hour/month as overtime. The results obtained for the total amounts of overtime (2388.82 h), showed that the ratio of total amounts of overtime to regular time was about 0.1: 1 for the maintenance system.

has some limitations. First, our model was designed for manufacturing systems which have separate workers for production and maintenance activities. Second, our model cannot be used to address space requirements

Table 6. Expected amount of overtime for each workers' category (h)

Periods	Hydraulic		Electrical		Mechanical	
	x_{11t}	x_{12t}	x_{21t}	x_{22t}	x_{31t}	x_{32t}
1	42.51	34.32	11.92	46.76	42.82	38.02
2	7.84	31.53	11.17	14.46	7.43	8.23
3	46.53	45.64	25.36	39.57	47.56	9.53
4	9.82	47.14	34.36	8.67	48.91	10.93

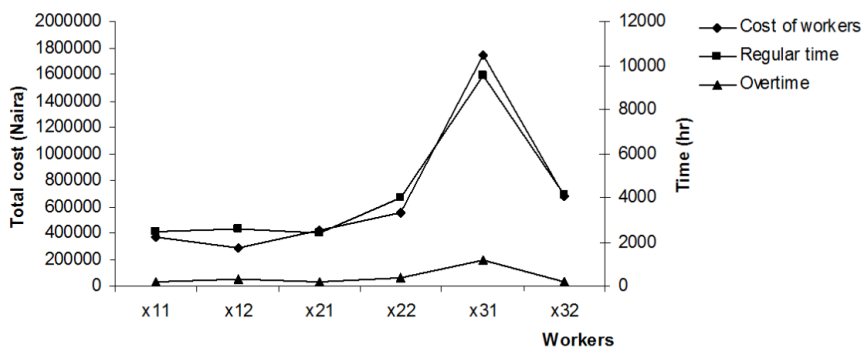


Figure 6. Total cost and maintenance time for the workers

Despite the presence of overtime for maintenance activities, the company's ability to meet the demand for their products was not affected, because there was a finished goods inventory at the end of each planning period. To generate the various amounts of the finished goods inventory, the average amount of production time for each period was about 481.73 h. This implies that the company needed to operate a minimum of 24 days/month with a daily operation time of 20 hr. The average failure rate per day was 0.059 and the expected average return investment on the workforce was about 46.16 for each period.

Although the proposed model had the capacity to generate useful information for the production and maintenance departments, it

for a warehouse and the time value of finished goods inventory manufacturing systems.

Conclusions

Workforce planning involves the analysis of multi-objectives which is affected by many factors. In workforce planning, performance indices' preferences are not equally important. This study used nonlinear mixed-integer programming to propose a multi-objective APP model for maintenance workforce and production variables optimisation. The WAFGP was adopted in handling the multi-objectives in the model. The WAFGP model performance

was examined using real industry data from literature and simulated datasets. The model was solved using the GA, HS, and DE algorithms. All the algorithms gave promising results for the workforce planning problem. The results obtained showed that the GA results outperformed those of the HS and DE algorithms in terms of the fitness function value.

The maintenance system needs a minimum workers' reliability of 0.72, and maximum workers' reliability of 0.83 to operate effectively. The implications of this range of workers' reliability on production activities is that the company will have a closing inventory of 376,341.80 kg and machine uptime of 1,926.90 hr. However, the maintenance department needs about 25,068 hr as maintenance time with an expected machine failure rate of about 0.05678 hour/day.

The proposed model's advantages over previous models based on knowledge gaps in the literature are:

- It addresses the problem of workforce reliability which was not considered in Ighravwe and Oke (2014);
- The issue of the amounts of defective products from manufacturing, which was not considered in the Belmokaddem *et al.* (2009) workforce model, was addressed; and
- The problem of time sharing between the maintenance and production departments, as well as the machine failure rate which the Mansour (2011) study did not address, were considered in this study.

The proposed model can be improved by considering the effects of supply chain management on production and maintenance time under a fuzzy environment. There is the possibility of applying the proposed model in brewery, pharmaceutical, cement, and foundry plants in future studies.

Acknowledgements

The authors thank the 2 anonymous reviewers for their suggestions that improved the quality of this paper. Thanks also to the editor that facilitates the processing of the work.

References

- Ahmadpour, M. and Chitgar, S. (2012). Using goal programming for transportation planning decisions problem in imprecise environment. *Australian Journal of Basic and Applied Sciences*, 6(2):57-65.
- Alia, O.M. and Mandava, R. (2011). The variants of the harmony search algorithm: An overview. *Artif. Intell. Rev.*, 36:49-68.
- Belmokaddem, M., Mekidiche, M., and Sahed, A. (2009). Application of a fuzzy goal programming approach with different importance and priorities to aggregate production planning. *J. Appl. Quanti. Met.*, 4(3):317-331.
- Coello, C.A.C. (2002). Theoretical and numerical constraint-handling techniques used with evolutionary algorithms: A survey of the state of the art. *Comput. Method. Appl. M.*, 191:1245-1287.
- Cormier, G., Boudreau, R., and Theriault, S. (2001). Real-coded genetic algorithm for Bragg grating parameter synthesis. *J. Opt. Soc. Am. B*, 18(12):1771-1776.
- Engelbrecht, A.P. (2007). *Artificial Intelligence: An Introduction*. John Wiley & Sons, London, UK, 628p.
- Geem, Z.W., Kim, J.H., and Loganathan, G.V. (2001). A new heuristic optimisation algorithm: Harmony search. *Simulation*, 76(2):60-68.
- Glover, F., Better, M., Kelly, J.P., and Kochenberger, G. (2015). SIMOPT-Reliability for improved workforce planning. Available from: <http://www.optek.com/sites>. Accessed date: Apr 1, 2015.
- Goldberg, D.E. (1990). A note on Boltzmann tournament selection for genetic algorithms and population-oriented simulated annealing. *Complex Systems*, 4:445-460.
- Happer, P., Kleinman, E., Gallagher, J., and Knight, V. (2013). Cost-effective workforce planning: Optimising the dental team skill-mix for England. *J. Enterp. Inform. Manag.*, 26(1-2):91-108.
- He, M., Hu, Q., Wu, X., and Jing, P. (2014). A combination algorithm for selecting functional logistics service vendors based on SQP and BNB. *Journal of Chemical and Pharmaceutical Research*, 6(5):2013-2018.
- Ighravwe, D.E. and Oke, S.A. (2014). A non-zero integer non-linear programming model for maintenance workforce sizing. *Int. J. Prod. Econ.*, 150:204-214.
- Ighravwe, D.E. and Oke, S.A. (2015). Unpublished paper. Big-bang big-crunch optimisation for integrated maintenance and production workforce planning under economic consideration. Ladoke Akintola University of Technology, Ogbomosho, Nigeria.
- Ighravwe, D.E., Oke, S.A., and Adebisi K.A. (2015). Maintenance workload optimisation with accident occurrence considerations and absenteeism from work using genetic algorithm. *Int. J. Manag. Sci. Eng. Manag.*, 1-9. DOI: 10.1080/17509653.2015.1065208.
- Jesswein, K. (2011). Analysing financial statements with potentially misreported cost of goods sold figures. *J. Finan. Acc.*, 6:1-10.
- Mahdavi, M., Fesanghary, M., and Damangir, E. (2007). An improved harmony search algorithm for solving optimisation problems. *Appl. Math. Comput.*, 188:1567-1579.

- Mansour, M.A.A-F. (2011). Solving the periodic maintenance scheduling problem via genetic algorithm to balance workforce levels and maintenance cost. *American J. Eng. Appl. Sci.*, 4(2):223-234.
- Mekidiche, M., Belmokaddem, M., and Djemmaa, Z. (2013). Weighted additive fuzzy goal programming approach to aggregate production planning. *Int. J. Intell. Sys. Appl.*, 4:20-29.
- Parida, A. and Kumar, U. (2009). Maintenance productivity and performance measurement. In: *Handbook of Maintenance Management and Engineering*. Ben-Daya M., Duffuaa S.O., Raouf, A., Knezevic J., and Ait-Kadi D., (eds). Springer, Heidelberg, Germany, p. 17-41.
- Rardin, R.L. (1998). *Optimisation in Operations Research*. Prentice Hall, Upper Saddle River, NJ, USA, 919p.
- Romeu, J.L. (2015). Understanding series and parallel systems reliability. *Selected Topics in Assurance Related Technologies*, 11(5):1-8.
- Safaei, N., Banjevic, D., and Jardine, A.K.S. (2008). Multi-objective simulated annealing for a maintenance workforce scheduling problem: A case study. In: *Simulated Annealing*. Tan, C.M., (ed). I-Tech Education and Publishing, Vienna, Austria, p. 27-48.
- Storn, R. and Price, K. (1997). Differential evolution - A simple and efficient heuristic for global optimisation over continuous spaces. *J. Global Optim.*, 11:341-359.
- Tavakkoli-Moghaddam, R. and Safaei, N. (2006). Solving a generalized aggregate production planning problem by genetic algorithms. *J. Indust. Eng. Int.*, 2(1):53-64.
- Velasquez, M. and Hester, P.T. (2013). An analysis of multi-criteria decision making methods. *Int. J. Operat. Res.*, 10(2):56-66.
- Visier Inc. (2015). From HR metrics to workforce analytics: Five key workforce insights that every employer should capture for greater business impact. Available from: <http://www.workforce.com/ext/resources>. Accessed date: Mar 26, 2015.
- Yaghoobi, M.A., Jons, D.F., and Tamiz, A. (2008). Weighted additive models for solving fuzzy goal programming problems. *Asia Pac. J. Oper. Res.*, 25(5):715-733.
- Yimnee, R. and Phruksaphanrat, B. (2011). Fuzzy goal programming for aggregate production and logistics planning. *Proceedings of the International Multi-Conference of Engineers and Computer Scientists 2011; March 16-18, 2011; Hong Kong, China*, p. 1082-1087.

Appendix

Indices:

- I maintenance section
 J maintenance workers category
 N total number of workers category
 M total number of sections
 T total number of planning periods
 k Goal

- l Product
 t Planning period
 L Total number of products
 K Total number of goals

Variables:

- x_{ijt} number of workers in section i belonging to worker category j at period t
 y_{ijt} number of workers in section i belonging to worker category j at period t that undergo training at period t
 d_{it} percentage of defective product i at period t
 h_{ijt} number of hired workers in section i belonging to worker category j at period t
 P_{lt} production time for product l at period t
 Z_k objective function k
 R_{ijt} reliability of a worker in section i belonging to worker category j at period t
 m_{ijt} amount of maintenance time for a worker in section i belonging to worker category j at period t
 λ_t rate of the system at period t
 f_{ijt} number of fired workers in section i belonging to worker category j at period t
 I_{lt} amount of product l finished goods inventory at period t

Parameters:

- C_{ij}^1 unit cost of a worker in section i belonging to worker category j
 C_{ij}^2 unit training cost of a worker in section i belonging to worker category j
 INV_t budget total cost for finished goods inventories at period t
 PP_{lt} profit from product l at period t
 U_{lt} production rate of product l at period t
 h_{ijt} expected improvement in worker performance for workers in section i worker's category j at period t
 Q_t products' quality level at period t
 d_{lU} maximum amount of defective of product l
 d_{lL} minimum amount of defective product l

$\hat{R}_{it}$	reliability of maintenance section i at period t	φ_i	percentage of workers that will undergo training with respect to worker's category
$X_{\max}$	maximum workforce size	a_0	initial number of breakdown at period t
$I_{\max,l}$	maximum finished goods inventory for product l	B_n	average change in the number of breakdowns at period t
φ_2	ratio of trained workers for a section with respect to worker category	R_t	overall reliability of workers at period t
R_{st}	reliability of the system at period t	$\dot{M}_u$	maximum amounts of production time at period t
D_{lt}	demand for product l at period t	$X_{\min}$	minimum workforce size
U	workforce unavailability	R_U	maximum reliabilities expected from workers
x_{ijg}	target vector at generation g	b_t	total amounts of funds budgeted for worker training at period t
w_k	weight for goal k	d	average operation days per period
f	fitness function	n_1	proportion of average production time
Δ_{kR}	upper bound for fuzzy goal k	$\dot{M}_t$	available manufacturing time
v_{ijg}	mutant vector at generation g	μ_k	membership function for goal k
x_{ij}^{kk}	decision variable in harmony search algorithm for pitch kk	b_k	aspiration level for goal k
$\bar{\delta}$	constant parameter	sol	solution
$\bar{x}_{\min}$	minimum value of decision variable	Δ_{kL}	lower bound for fuzzy goal k
$\bar{x}_{\max}$	maximum value of decision variable	u_{ijg}	trial vector at generation g
$\bar{t}$	current iteration step value	η	proportion of total stoppage of machine because of maintenance activities
E_o^h	fitness value of off-spring h	cr	crossover rate
T_g	temperature at generation g	$\bar{B}$	constant parameter
$bw_{\min}$	minimum value of bandwidth	$\bar{T}$	maximum iteration step
MR	mutation rate	P_i	parent i in selection pool
PAR	pitch adjusting rate	e_{pp}	fitness value of parent pp
$bw_{\max}$	maximum value of bandwidth	g	generation
R	random number	p^1	anti-acceptance probability
I_{Rnd}	an integer value selected randomly from the problem dimension	bw_t	bandwidth at iteration step $\bar{t}$
C_l^3	unit inventory cost for product l	P	logistic acceptance probability
	finished goods inventory at period t	$\dot{M}_l$	minimum amounts of production time at period t
T_{ijt}	budgeted maintenance time for a worker in section i belonging to worker category at period t	rnd	uniformly distributed random number
R_L	minimum reliabilities expected from workers	x_{ijg}^q	randomly selected variable from a pool of parent solution at generation g
V_{lt}	unit cost of product l at period t		
R_l	rework rate of product l		