Preventive maintenance task balancing with spare parts optimisation via big-bang big-crunch algorithm

Authors: **D.E. Ighravwe, S.A. Oke and K.A., Adebiyi**

International Journal of Systems Assurance Engineering and Management, author's final copy

Published work available at: DOI: 10.1007/s13198-016-0529-9 (Springer), http://link.springer.com/article/10.1007/s13198-016-0529-9

Page specification: pp. 1–12

Title: Preventive maintenance task balancing with spare parts optimisation via big-bang big-crunch algorithm

Authors: D.E. Ighravwe, S.A. Oke and K.A., Adebiyi
Issue Date: 2016, pp. 1-12
Publisher: International Journal of Systems Assurance Engineering and Management, author’s final copy

Published work available at: DOI: 10.1007/s13198-016-0529-9 (Springer), http://link.springer.com/article/10.1007/s13198-016-0529-9

Abstract: Work balancing increasingly plays an important role in both the production and maintenance functions. However, the literature on work balancing problems in transfer line manufacturing systems provides little information on the contributions of maintenance technicians and spare parts with a focus on penalty, technicians’ costs and incentives for staff. Unlike existing reports, the current investigation attempts to solve the maintenance task balancing problem. It combines preventive maintenance technicians’ assignments with product demand and spares utilisation in a transfer line manufacturing system. It uses an optimisation framework that measures the success of post-line balancing solution performance in a system from a holistic perspective. The novelty of the approach lies in the integration of technicians and spare parts theory and the introduction of penalty, technicians’ costs and incentive for staff. The proposed optimisation method was applied to a case study for detergent manufacturing system as a means of testing the effectiveness and robustness of the approach. The results show that the proposed model appears to be effective. Some simulations were also carried out to complement practical results.
Description: Research Article

Preventive maintenance task balancing with spare parts optimisation via big-bang big-crunch algorithm

[1,2] D.E. Ighravwe, [1,3]S.A. Oke, and [2]K.A. Adebiyi
[1]Department of Mechanical Engineering, University of Lagos, Lagos, Nigeria
[2]Department of Mechanical Engineering, Ladoke Akintola University of Technology, Ogbomoso, Nigeria
[3]Industrial and Production Engineering Unit, Department of Mechanical Engineering, Covenant University, Ota, Nigeria
Corresponding author: sa_oke@yahoo.com

Abstract
Work balancing increasingly plays an important role in both the production and maintenance functions. However, the literature on work balancing problems in transfer line manufacturing systems provides little information on the contributions of maintenance technicians and spare parts with a focus on penalty, technicians' costs and incentives for staff. Unlike existing reports, the current investigation attempts to solve the maintenance task balancing problem. It combines preventive maintenance technicians' assignments with product demand and spares utilisation in a transfer line manufacturing system. It uses an optimisation framework that measures the success of post-line balancing solution performance in a system from a holistic perspective. The novelty of the approach lies in the integration of technicians and spare parts theory and the introduction of penalty, technicians' costs and incentive for staff. The proposed optimisation method was applied to a case study for detergent manufacturing system as a means of testing the effectiveness and robustness of the approach. The results show that the proposed model appears to be effective. Some simulations were also carried out to complement practical results.

Keywords: Demand, maintenance task balancing, spare parts cost, maintenance technicians, big-bang big-crunch algorithm

1. Introduction
Traditionally, an optimal allocation of tasks to technicians on production lines is achieved through the removal of bottlenecks that could lead to system's downtime, production volume and production inefficiency. Since bottlenecks are common problems in production systems, equipment bottlenecks in manufacturing systems are usually equipment-related and human-related in nature. In considering human-related bottlenecks, the emphasis is usually on management and workers' problems. In discussing equipment-related bottlenecks, a direct connection with spare parts availability, maintenance strategy, equipment availability and breakdowns of equipment should be established. Equipment utilisation and queue length have been established as two key criteria used for identifying bottlenecks in production systems (Lawrence and Buss, 1994; Law and Kelton, 2000). Furthermore, buffer allocation and equipment throughput improvements are commonly used as a means for addressing equipment bottleneck problems. Since these factors are the significant determinant of system's performance, the focus of most researchers is on how to allocate buffers to bottleneck machines (Powell and Pyke, 1996; Faria *et al*., 2006; Patti *et al*. 2008). However, in an attempt to do this lesser attention has

been given to machine throughput, which is a major life-line of progress in manufacturing processes.

Business owners require that maintenance and production workers should seek for ways of achieving machine throughputs at reduced costs. However, these established approaches for throughput improvements have been limited to production systems and studies on maintenance systems are almost non-existent. Despite the fact that bottlenecks may be caused by low machine speeds, maintenance frequency, spare parts unavailability, poor maintenance works, unbalanced maintenance schedules and untimely machine maintenance, concerns for advantageous integration of maintenance and production workers' parameters continue to be downplayed, an action that is detrimental to the system survival. The generation of optimal solutions for the above-mentioned factors will improve machine throughputs when combined with production models.

Within the last few decades, researchers and industrial practitioners have considered re-sequencing and tool-change strategies (Masood, 2006), workload durations and idle time considerations (Hong and Cho, 2001), sequence dependence and set-up times (Seyed-Alagheband *et al*., 2010), processing time and expected total cost (Shin and Min, 1991) as means of improving production and maintenance activities. Other approaches for the improvement of maintenance and production activities are space and time relationships (Bautista and Pereira, 2007), hierarchy of workforce (Sunger and Tavuz, 2014), spares and machining space requirements (Bautista and Pereira, 2011) as well as the total idle time and the number of workstations (McGovern and Gupta, 2007).

Based on the above cited studies, it is obvious that maintenance solutions to bottleneck production lines will entail the generation of optimal values for time, costs, spare parts, spaces and workload variables. By generating optimal values for these variables, the balancing of maintenance tasks for maintenance technicians will be achieved. For years, several analytical methods and tools have been developed for optimising these variables, among which are bounded dynamic programming, integer linear programming, ant colony optimisation and genetic algorithm (Bautista and Pereira, 2007, 2009, 2011; McGovern and Gupta, 2007; Chica *et al*., 2011). Most of these studies are targeted at production systems. The implication of this is that technicians' task balancing is often based on practicing engineers' intuitions rather than scientifically-aided tools.

It is only recently, in 2011 and 2012, in which what appears to be two pioneering articles on technicians' task balancing in maintenance appeared. This study differs from Rana and Purohit's (2012) contribution, which is a pioneering article on task balancing of maintenance activities, in many respects. First, our article is on preventive maintenance activities while Rana and Purohit's (2012) investigation was on maintenance, generally. Secondly, this study considered technicians' penalty cost during task balancing which has not been documented in literature to the best of our knowledge. Thirdly, the idea of technicians' incentives was not considered in Rana and Purohit's (2012) and previous studies.

Despite the contributions of earlier researchers, preventive maintenance on production line still experiences some fundamental challenges. In sum, company managers face the challenge of optimising preventive maintenance schedules on production lines. Given the above literature gap, there is the need for novel, innovative studies on preventive maintenance schedules for production lines. This study adds to the literature on technicians' task balancing by focusing on preventive maintenance activities with due consideration to spare parts availability. To address the above problem, five basic questions which when addressed will improve the performance of a production system throughputs are:

i. What level of maintenance technicians is required for the smooth operation of production lines?
ii. What order should preventive maintenance be carried out on production lines?
iii. Which production line requires the highest amount of maintenance time?
iv. What level of spare parts inventory should be retained within a production system for preventive maintenance activities? and
v. What quantity of products should be expected from outsourced production activities?

A robust answer to these questions will involve the use of multi-objective models. Such models should seek to minimise technicians and spare parts related costs, while maximising production line availability. Furthermore, the problem of nonlinearity in such models may result in the generation of local optimal solution for decision variables when solving using conventional optimisation approaches (simplex method, big-M method). Thus, this study handled the problem of nonlinearity in the proposed model using big-bang big-crunch algorithm (BB-BC) as a solution method. Hence, the aim of this study is to develop a technicians balancing nonlinear optimisation model that incorporates the BB-BC algorithm. The BB-BC algorithm is a newly developed versatile tool.

The remaining sections of this study are organised as follows: Section 2 contains the proposed model and discussion on the BB-BC algorithm. The application and results obtained from the proposed model are presented in section 3. Section 4 contains discussion of results, while the conclusions of this study are presented in section 5.

2. Research Methodology

The model proposed is concerned with the optimisation of existing, fired and hired technicians required to execute maintenance tasks on production lines. Furthermore, the model seeks to generate optimal values for spare parts inventory, spares ordering quantities, finished goods inventory, production volume and the quantities of goods expected from outsourced activities. Some of the notations used in presenting the proposed model are as follows:

Decision variables

x_{ijt} number of maintenance technicians in section *i* belonging to technician category *j* at period *t*

h_{ijt} number of maintenance technicians hired for section *i* belonging technician category *j* at period *t*

f_{ijt} number of maintenance technicians fired from section *i* belonging to technician category *j* at period *t*

μ_{ijlst} amount of maintenance workload (hr) for a technician in section *i* belonging to technician category *j* during preventive maintenance tasks on production line *l* for schedule *s* at period *t*

R_{lst} binary variable whose value is 1 if preventive maintenance is carried out on line *l* during schedule *s* at period *t*, otherwise 0

p_{lt} production time on production line *l* at period *t*

I_t quantity of finished goods inventory at period *t*

INV_T quantity of spare parts inventory at period *T*

ξ_t quantity of goods expected from subcontractors at period *t*

Q_{ilt} quantity of spare part *i* ordered for production line *l* at period *t*

Model parameters

d_t quantity of goods demanded at period *t*

PR_l production rate of production line *l*

$¢^{1}_{ijt}$ unit cost for hiring a technician for section *i* belonging to technician category *j* at period *t*

$¢^{2}_{ijt}$ unit cost for firing a technician from section *i* belonging to technician category *j* at period *t*

T_{ijt} unit training cost for a technician in section *i* belonging to technician category *j* at period *t*

$_{l}$ penalty for releasing a production line *l* beyond due date

$\hat{}_{l}$ bonus for releasing a production line *l* before due date

Indices

i maintenance section

j technician category

l production line

t planning period

s Schedule

T total number of planning periods

S total number of schedules

M total number of maintenance sections

N total number of technician categories

L total number of production lines

Some of the proposed model assumptions are as follows:

i. Production activities can be outsourced;

ii. The total number of production lines is greater than one;

iii. Preventive maintenance activities can be carried out on only one production line at a time;

iv. Demand for the company's products is stochastic;

v. Spare part shortages are allowed; and

vi. The production rates at production lines are different.

2.1 Model Objectives

A maintenance system with a large technicians' size may experience increase in production line availability. However, there is the need to ensure balance between the availability technicians and the production lines. This serves as a means of controlling the technicians' cost and production time. To address this problem, the objective of maximising production line availability is considered. Production line availability is measured using available manufacturing time and the total time required for preventive maintenance activities for each production line (Equation 1). Total manufacturing time is taken as the sum of production and maintenance times of a production line.

$$\text{Max } G_1 = \frac{\sum_{l=1}^{L}\sum_{t=1}^{T} P_{lt} - \circ}{\sum_{l=1}^{L}\sum_{t=1}^{T} P_{lt}} \cdot 100\ \% \qquad (1)$$

$$\text{°} = \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{l=1}^{L}\sum_{s=1}^{S}\sum_{t=1}^{T} \text{µ}_{ijlst} \Big/ MNLST \qquad (2)$$

where ° is the average amount of time required for preventive maintenance activities for different schedules on a production line, µ_{ijlst} is the amount of workload (hr) for a technician in section *i* belonging to technician category *j* during preventive maintenance tasks on production line *l* for schedule *s* at period *t*, and P_{lt} is the total manufacturing time for production line *l* at period *t*.

Production line availability varies from one period to another. From maintenance activities' perspective, these variations are often caused by changes in technicians' size. Also, improvements in technicians' service time affect production line availability. The changes in technicians' sizes are caused by hiring and firing decisions, while service time improvement may be due to training programme implementation. The cost for service time improvement is modelled using arithmetic progression. The total cost for technicians' hiring, firing and service time improvement is expressed as Equation (3). For a system in which the full-time and casual maintenance workers work in the same group, their service rate improvement costs may be considered to be the same. There is a possibility of considering different service rate improvement costs for different technician categories.

$$\text{Min } G_2 = \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{t=1}^{T}\left(\text{¢}_{ijt}^{1} h_{ijt} + \text{¢}_{ijt}^{2} f_{ijt}\right) + \sum_{t=1}^{T}\sum_{i=1}^{M}\left(a_i + \left(1 + \text{ª}_i\right)\right)\sum_{j}^{N} x_{ijt} \qquad (3)$$

where ª_i is the rate of change of cost of technicians' service rate improvement in maintenance section *i*, and a_i is initial cost of technicians' service rate improvement for maintenance section *i*.

To further control the amount of preventive maintenance time, the objective of minimising the technicians' penalty cost for releasing a production line beyond due date is pursued. Also, the cost for technicians' bonuses for releasing a production line before due date is considered (Equation 4). The decision on when to award a penalty or bonus is based on the average between the minimum ($\text{¡}_{\min,lst}$) and maximum ($\text{¡}_{\max,lst}$) preventive maintenance times that are agreed between the production and maintenance managers (Equations 5 and 6).

$$\text{Min } G_3 = \sum_{l=1}^{L}\sum_{t=1}^{T}\sum_{s=1}^{S}\Big(\;_l\left(\left[\left(\max\left(\bar{\text{ï}}_{lst},0\right)\right)\right]\right) + \left(\hat{\;}_l\left[\left(\min\left(\bar{\text{ï}}_{lst},0\right)\right)\right]\right)\Big) R_{lts}\sum_{i=1}^{M}\sum_{j=1}^{N} x_{ijt} \qquad (4)$$

$$\bar{\text{ï}}_{lst} = \text{¡}_{lst} - \text{¡}_{benchmark} \qquad (5)$$

$$\text{¡}_{lst} = \sum_{i=1}^{M}\sum_{j=1}^{N} \text{µ}_{ijlst} \Big/ MN \qquad (6)$$

where ¡$_{lst}$ is the actual amount of time for maintenance tasks, ¡$_{benchmark}$ is the expected amount of time for preventive maintenance tasks and $\overline{¡}_{lst}$ is deviation value of ¡$_{lst}$ from ¡$_{benchmark}$.

Spare parts availability affects the release time of production lines. The combination of the correct technicians' size and spare parts has the potential of improving production line availability. Since spare parts stocking is an activity which increases inventories costs, decision makers often desire a minimum total spare parts cost. When intuition is used to determine total spare parts cost, the problem of spare parts shortage may arise. This problem makes technicians to be idle when they are supposed to be working and decreases the capacity of an organisation to meet customers' demands. By adopting the expression for cost of an item in Gupta and Hira (2008), the total spare parts cost is expressed as Equation (7).

$$\text{Min } G_4 = \sum_{l=1}^{L}\sum_{c=1}^{C}\left(C_{cl}^{1}\sum_{t=1}^{T} Q_{clt} + \sqrt{C_{cl}^{1}C_{cl}^{2}C_{cl}^{3}\sum_{t=1}^{T} q_{clt}} \right) \qquad (7)$$

where C is total number of spare parts, C_{cl}^{1} is the unit cost for spare part c used in line l, C_{cl}^{2} is the spare part c inventory carrying rate on line l, C_{cl}^{3} is the total acquisition cost for spare c used on line l, and q_{clt} is amount of spare part c ordered for production line l at period t.

2.2 Model Constraints

The model constraints considered technicians' and spare parts budgets, production volume, preventive maintenance schedule, workload and change in technicians' size for flow-shop (Figure 1) manufacturing systems.

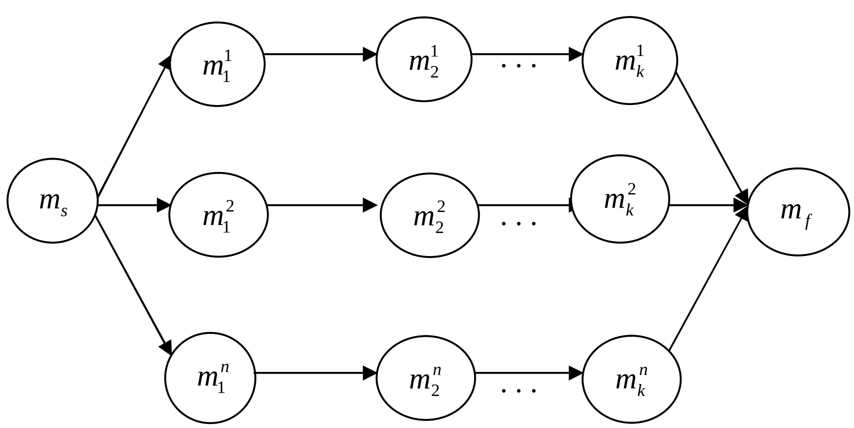


Figure 1: An m-line production system (flow-shop)

where m_s is the first machine in a flow-shop, m_k^1 is machine k on production line 1, m_k^2 is machine k on production line 2, m_k^n is machine k on production n, and m_f is the last machine in a flow-shop.

2.2.1 Preventive maintenance schedule

By using set covering constraint modelling approach (Radin, 1998), the schedule of preventive maintenance on production lines at different periods is modelled using Equations (8) and (9). The set covering constraints ensures that at least one of the production lines is maintained at each maintenance schedule. Equation (8) addressed the problem of the total number of times a production line will be subjected to preventive maintenance at different periods. Equation (9) ensures that at least one maintenance routine takes place in every maintenance schedule.

$$\sum_{s=1}^{S} R_{lts} \geq 1 \qquad \forall (l,t) \tag{8}$$

$$\sum_{l=1}^{L} R_{lts} \geq 1 \qquad \forall (s,t) \tag{9}$$

where R_{lts} is the schedule number for production line *l* at period *t* for maintenance schedule *s*.

2.2.2 Production volume

The interrelationships among average production rates, production times and preventive maintenance schedules that affect productive activities are used in expressing the expected production volume (Equation 10).

$$PV_{lt} = PR_l (PT_{lt} - \sum_{s=1}^{S} \text{¡}_{lts} R_{lts}) \quad \forall (l,t) \tag{10}$$

where PT_{lt} is the amount of production time for production line *l* at period *t*, PV_{lt} is quantity of products produced from production *l* at period *t*, and PR_l is the production rate of production line *l*.

Several investigations on the interrelationships between production and demand levels have been considered in literature (Belmokaddem *et al.*, 2008). This interrelationship is expressed as Equation (11). Two drawbacks of Equation (11) are the lack of out-sourcing of production activities ($\P_t$) and the consideration of demand as a deterministic parameter (d_t). Equation (11) is then modified to account for these drawbacks (Equation 12). The interrelationships between the expected and actual closing finished goods inventory is expressed as Equation (13).

$$\sum_{l=1}^{L} PV_{lt} + I_{t-1} - I_t - d_t = 0 \qquad \forall t \tag{11}$$

$$\sum_{l=1}^{L} PV_{lt} + I_{t-1} + \P_t - I_t - (1 \pm r) d_t = 0 \qquad \forall t \tag{12}$$

$$I_T \le I_{\max} \quad (13)$$

where $I_{\max}$ is the expected maximum quantity of the finished goods at period *T*, and *r* is a random number which lies between 0 and 1.

2.2.3 Changes in technicians' sizes and budgets

To address the problem of technicians' size and budget, the works by Belmokaddem *et al*., (2008), Mansour, (2011) as well as Ighravwe and Oke (2014) are considered. Belmokaddem *et al*. (2008) expressed workforce balancing as Equation (14), while Ighravwe *et al*. (2015) introduced workforce turnover rate into Equation (14) and obtained Equation (15).

$$x_{ijt} - x_{ijt-1} + f_{ijt} - h_{ijt} = 0 \qquad \forall i, j, t \quad (14)$$

$$x_{ijt} + f_{ijt} = (1 - TR_{ij})x_{ijt-1} + h_{ijt} \qquad \forall i, j, t \quad (15)$$

where TR_{ij} is turnover rate of technicians in section *i* belonging to technician category *j*.

For technicians' planning, provision can be made separately for technicians' salaries (Equation 16), hiring (Equation 17) and firing expenses (Equation 18). This serves as a means for proper distributions of available funds for technicians' expenses (Ighravwe et al., 2015). To further enhance technicians' cost management, consideration is given to the ratio (λ) of a particular technician category to another category (Equation 19).

$$\sum_{i=1}^{M}\sum_{j=1}^{N} c_{ijt} x_{ijt} \le B_t \qquad \forall t \quad (16)$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} ¢_{ijt}^{1} h_{ijt} \le \hat{B}_t \qquad \forall t \quad (17)$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} ¢_{ijt}^{2} f_{ijt} \le \overline{B}_t \qquad \forall t \quad (18)$$

$$\lambda \sum_{i=1}^{M} x_{i1t} \ge \sum_{i=1}^{M} x_{i2t} \qquad \forall t \quad (19)$$

where B_t is the amounts of budgeted funds for technicians' salaries, $\hat{B}_t$ is the amounts of budgeted funds for technicians' hiring cost, and $\overline{B}_t$ is the amounts of budgeted funds for technicians' firing cost.

2.2.4 Technician's workload

The amount of time spent for carrying out preventive maintenance activities is expected to reduce as technicians undergo training programmes. The reduction in maintenance time is assumed to follow an arithmetic progression. The relationship between the amounts of workloads at $t = 0$ and $t \ge 1$ is expressed as Equations (20) and (21).

$$w_{ijlt} = w_{ijl0} - (t-1)d_{ijl} \qquad \forall(i, j, l, s, t) \tag{20}$$

$$\mu_{ijlst} = \frac{R_{lts} w_{ijlt}}{x_{ijt}} \qquad \forall(i, j, l, s, t) \tag{21}$$

where d_{ij} is the constant rate of reduction in maintenance time of workers in section i belonging to technician category j.

In flexible automated production systems, the amount of workloads for mechanical section is usually equal or more than the amount of workloads for electrical section (Equation 22). For fixed automation systems, the inequality sign in Equation (22) may change to less than or equal inequality sign.

$$\sum_{j=1}^{N}\sum_{s=0}^{S}\mu_{1jlst} \geq \sum_{j=1}^{N}\sum_{s=0}^{S}\mu_{2jlst} \tag{22}$$

2.2.5 Spare parts inventory

First, the issue of spare parts inventory is considered as the initial step for spare parts modelling. To manage spare parts inventory, two basic tasks need to be considered for the optimal spare parts management to be attainable. First, the task of dealing with spare parts inventory holding cost. The expected average amounts of spare parts inventory (Equation 23) in a production system are influenced by the budgeted funds (Equation 24).

$$\frac{1}{T}\sum_{t=1}^{T} INV_{clt} \leq Aq_{cl} \qquad \forall(c, l) \tag{23}$$

$$\sum_{t=1}^{T} INV_{clt} C_{cl}^{1} C_{cl}^{2} \leq Bq_{cl} \qquad \forall(c, l) \tag{24}$$

where INV_{clt} is the spare parts c inventory for production line l at period t, Aq_{cl} is the expected volume of spare part c for production line l, and Bq_{cl} is the budgeted fund for spare part c for production line l.

The second task is the establishment of the interrelationship among spare parts inventory level, spare parts replenishment size (q_{ilt}) and spare parts usage at each period. To derive an expression for this interrelationship, the time-phased balancing constraint is considered (Equation 25).

$$INV_{il(t-1)} + q_{ilt} = SU_{ilt} + INV_{ilt} \tag{25}$$

where q_{ilt} is the amount of spare part i inventory for production line l order at period t, and is the amount of spare part i inventory for production line l used at period t.

Two fundamental spare parts management issues which affect the optimal values of the decision variables in Equation (25) are as follows: The first problem deals with the interrelationship between the spare part usage rate and the maintenance time for the production lines (Equation 26).

$$SU_{ilt} = \frac{TOT_{lt} - \sum_{s=0}^{S} \mathrm{i}_{lst}}{MTTF_{il}} \tag{26}$$

where *MTTF* is the mean time to failure, *TMT* is the total maintenance time, and *TOT* is the total time of the equipment used.

Spare parts damage may occur during replacement of faulty machine parts. This problem affects the number of spare parts required in a period. Equation (26) is modified to accommodate spares damage and usage (Equation 27). The time-phase expression in Equation (25) becomes Equation (28).

$$SU_{clt} = (1+FSP)\frac{TOT_{clt} - \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{s=0}^{S} \mu_{ijlst} \Big/ MNS}{MTTF_{cl}} \tag{27}$$

$$INV_{cl(t-1)} + q_{clt} - (1+FSP)\left(TOT_{lt} - \sum_{i=1}^{M}\sum_{j=1}^{N}\sum_{s=0}^{S} \mu_{ijlst} \Big/ MN \right) \Big/ MTTF_{cl} = INV_{clt} \quad \forall (c,l,t) \tag{28}$$

$$q_{\min,cl} \le q_{clt} \le q_{\max,cl} \qquad \forall (c,l,t) \tag{29}$$

where *FSP* is the expected amounts of the fraction of spare parts that will be damaged out of *x* units that are successfully used during maintenance activities, $q_{min,cl}$ is the minimum ordering quantity of spare parts *c* used for the maintenance activity on production line *l*, and $q_{max,cl}$ is the maximum ordering quantity of spare parts *c* used for the maintenance activity on production line *l*.

The second problem deals with space allocation for maintenance spare parts during (Gupta and Hira, 2008). A maintenance system with a high level of space utilisation will experience reduction in human and non-human traffic as well as reduction in material handling costs. Given that there is space restriction for spare parts, the required storage area for category of spare parts inventory is expressed as Equation (30).

$$\sum_{c=1}^{C} a_c INV_{clt} \le \Psi_{lt} \qquad \forall (l,t) \tag{30}$$

where a_c is the unit area of spare parts *c*.

2.2.6 Total technicians' and spare parts cost

During maintenance budgets planning, spare parts costs (SPC) and technicians' expenses (*TE*) constitute large proportions of the maintenance budget. Policies are often made that restrain the amounts of funds assigned to spare parts cost and technicians' expenses. Given that the total amounts of funds for technicians' expenses and spare parts cost is stochastic, the interrelationships between spare parts cost and technicians' expense is expressed as Equation (31).

$$TE_t + SPC_t \leq (Mb - Ma)(1 - \text{~}_{2t}) + Ma \qquad \forall t \tag{31}$$

$$TE_t = \sum_{i=1}^{M}\sum_{j=1}^{N}\left(\text{¢}_{ijt}^{1} h_{ijt} + \text{¢}_{ijt}^{2} f_{ijt}\right) + \sum_{l=1}^{L}\sum_{s=1}^{S} {}_{lst}R_{lts}\left(\min\left(\text{¡}_{lst} - \frac{\text{¡}_{\min,lst} + \text{¡}_{\max,lst}}{2}\right),0\right)\sum_{i=1}^{M}\sum_{j=1}^{N} x_{ijt}$$

$$+ \sum_{l=1}^{L}\sum_{t=1}^{T}\sum_{s=1}^{S} \hat{}_{l}R_{lts}\left(\max\left(\text{¡}_{lst} - \frac{\text{¡}_{\min,lst} + \text{¡}_{\max,lst}}{2}\right),0\right)\sum_{i=1}^{M}\sum_{j=1}^{N} x_{ijt} + \sum_{i=1}^{M}\sum_{j=1}^{N} c_{ijt}x_{ijt} + \sum_{i=1}^{M}\sum_{j=1}^{N} T_{ijt}x_{ijt} \tag{32}$$

$$SPC_t = \sum_{l=1}^{L}\sum_{c=1}^{C}\left(C_{cl}^{1} q_{clt} + \sqrt{C_{cl}^{1} C_{cl}^{2} C_{il}^{3} q_{clt}}\right) + SOC_t \tag{33}$$

where SOC_t is spare parts stores overhead cost at period *t*.

The multi-objective model presented is converted into a single-objective model using fuzzy goal programming approach (Belmokaddem *et al.*, 2009). This entails defining the minimum desirable level (ª_i) for each goal and the determination of membership functions for the minimisation (Figure 2) and maximisation (Figure 3) of goals. The weight (©_i) for each goal is also required. The proposed fuzzy goal programming maintenance tasks balancing model is presented as follows:

$$\text{Max} = \sum_{y=4}^{n} \text{©}_y \text{«}_y$$

Subject to :

$$\text{«}_y \geq \text{«}_{Gy} \qquad i = 1,2,3,4$$

$$\sum_{s=1}^{S} R_{lst} \geq 1 \qquad \forall(l,t)$$

$$\sum_{l=1}^{L} R_{lst} \geq 1 \qquad \forall(s,t)$$

$$\sum_{l=1}^{L} PV_{lt} + I_{t-1} + \text{¶}_t - I_t - (1 \pm r)d_t = 0 \qquad \forall t$$

$$I_T \leq I_{\max}$$

$$x_{ijt} + f_{ijt} = (1 - TR_{ij})x_{ijt-1} + h_{ijt} \qquad \forall i, j, t$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} c_{ijt}x_{ijt} \leq B_t \qquad \forall t$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} \text{¢}_{ijt}^{1} h_{ijt} \leq \hat{B}_t \qquad \forall t$$

$$\sum_{i=1}^{M}\sum_{j=1}^{N} \text{¢}_{ijt}^{2} f_{ijt} \leq \overline{B}_t \qquad \forall t$$

$$\lambda \sum_{i=1}^{M} x_{i1t} \geq \sum_{i=1}^{M} x_{i2t} \qquad \forall t$$

$$\sum_{t=1}^{T} INV_{clt} C_{cl}^{1} C_{cl}^{2} \leq Bq_{cl} \qquad \forall (c,l)$$

$$\frac{1}{T} \sum_{t=1}^{T} INV_{clt} \leq Aq_{cl} \qquad \forall (c,l)$$

$$INV_{cl(t-1)} + q_{clt} - (1+FSP)\left(TOT_{lt} - \sum_{i=1}^{M} \sum_{j=1}^{N} \sum_{s=0}^{S} \mu_{ijlst} \Big/ MN \right) \Big/ MTTF_{cl} = INV_{clt} \qquad \forall (c,l,t)$$

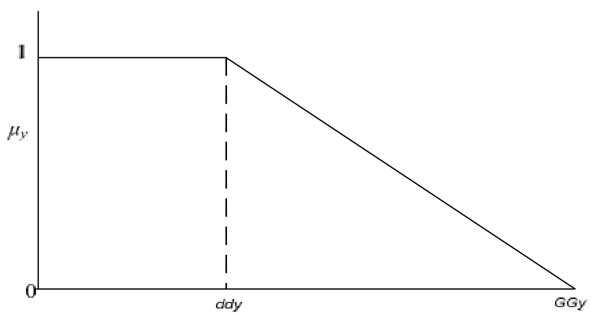
$$\sum_{j=1}^{N} \sum_{s=0}^{S} \mu_{1jlst} \geq \sum_{j=1}^{N} \sum_{s=0}^{S} \mu_{2jlst} \qquad \forall (l,t)$$

$$q_{\min,cl} \leq q_{clt} \leq q_{\max,cl} \qquad \forall (c,l,t)$$

$$\sum_{c=1}^{C} a_c INV_{clt} \leq \Psi_{lt} \qquad \forall (l,t)$$

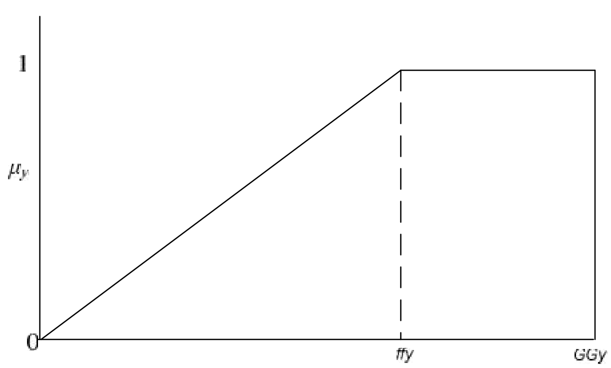
$$\mathrm{MWE}_t + \mathrm{SPC}_t \leq (Mb - Ma)(1 - \sim_{2t}) + Ma \qquad \forall t$$

$$\text{«}_y \geq \bar{a}_y \qquad i = 1,2,3,4$$



$$\text{«}_y = \begin{cases} 1 & \mathrm{G}_y \leq dd_y \\ 1 - \dfrac{\mathrm{G}_y}{GG_y} & \mathrm{G}_y > dd_y \end{cases}$$

Figure 2: Membership function for the minimisation objective



$$\text{«}_y = \begin{cases} \dfrac{\mathrm{GG_y}}{ff_y} & \mathrm{G_y} \leq ff_y \\ 1 & \mathrm{G_y} > ff_y \end{cases}$$

Figure 3: Membership function for the maximisation objective

where dd_y is the boundary between partial and complete memberships functions for the minimisation objective functions, and ff_y is the boundary between partial and complete memberships functions for the maximisation objective functions.

The quality of solution from the proposed model can be improved using population-based solution methods. This study selects BB-BC algorithm as a solution method for the proposed model. Some benefits of BB-BC algorithm are its low computation time and high quality solution (Sakthivel and Mary, 2012). The fuzzy BB-BC algorithm is described as follows (Erol-Osman and Ibrahim, 2006; Engelbrecht, 2007; Sakthivel and Mary, 2012):

Step 1: Define the attainment level for each of the fuzzy goals

Step 2: Formulate a single fuzzy goal programming model by defining the relative importance of each goal

Step 3: Select a population size and stoppage criterion for the BB-BC algorithm

Step 4: Create an initial solution for the decision variables (y_{ijg})

Step 5: Evaluate the quality of each particle ($f_{\bar{j}g}$) in the population

Step 6: Determine the centre of mass of each decision variables (y_{ijg}) using Equation (34). The center of mass for each decision variable can also be taken as the best particle solution.

$$y_{\bar{i}g}^{\bar{c}} = \frac{\sum_{\bar{j}=1}^{\bar{N}} y_{\bar{i}\bar{j}g} / f_{\bar{j}g}}{\sum_{\bar{j}=1}^{\bar{N}} 1 / f_{\bar{j}g}} \tag{34}$$

where $f_{\bar{j}g}$ is the fitness value of particle $\bar{j}$ at generation *g*, and $y_{\bar{i}\bar{j}g}$ is decision variable $\bar{i}$ from particle $\bar{j}$ at generation *g*.

Step 7: Create new values for the decision variables using Equation (35)

$$y_{\bar{i}\bar{j}g} = y_{\bar{i}g}^{\bar{c}} + r\hat{\sim} \frac{\left(y_{\bar{i},\max} - y_{\bar{i},\min}\right)}{g} \tag{35}$$

where *r* is a uniform random number that lies between -1and 1, and $\hat{\sim}$ is a constant value which regulates the limit of search for optimal values of decision variables.

Step 8: Evaluate the quality of each particle.

Step 9: Check the stoppage criterion. The stoppage criterion is taken as the maximum generation.

3. Model Application and Results

The proposed model is implemented in a powdered detergent manufacturing company that operates two shifts. Our interest is to design the maintenance schedule based on quarterly technicians plan as a short plan strategy. The demand for the first period was 19,510,177 kg, for the second period it was 19,033,786 kg. For the third period, demand was 19,888,404 kg, while the fourth period demand was 20,060,249 kg. During the model implementation, the cost of hiring and firing of technicians were 0.85 and 3 times the cost of existing technicians.

The available production time for each production line per quarter was the same (1,152 hr). The average production rate for the first production line was 4,000 kg/hr, while the second production line has an average production rate of 3,500 kg/hr. The average production rate of the third production line was 4,000 kg/hr. The time amount of maintenance task for the electrical section was between 6,798 - 7,167 hr, while that of mechanical section was between 4,521- 4,776 hr. Each technician is expected to give 8 hr services per day. The amount of maintenance tasks on each machine is considered to be proportional to its production rate. It is expected that at least 65% of the total number of full-time technicians at any period *t* should be greater than the total number of part-time (casual) technicians at any period *t*.

The above information was complemented with simulated information in Table 2. The quantity of maximum spare parts inventory at the end of each period is taken as 50% of spare parts order quantity. The benchmark for technicians to restore a production line back to the functional state for repair that affects production activities was 135 min. The minimum membership function for goal 1 was 0.75, while for goal 2 the minimum membership function was 0.80. Goal 3 has the minimum membership function of 0.75, while goal 4 has the minimum membership function of 0.80.

Table 1: Basic information for the case study

Items	Values
Electrical casual	6 – 9 technicians
Electrical full-time	5 – 8 technicians
Mechanical casual	4 – 8 technicians
Mechanical full-time	3 – 7 technicians
Maximum inventory (kg)	4,000,000
Budgeted total salaries of technicians (₦)	1,300,000
Budgeted total firing cost of technicians (₦)	350,000
Budgeted total hiring cost of technicians (₦)	300,000

Table 2: Simulated information for the case study

S/n	Items	Line 1	Line 2	Line 3
1	Spare part unit cost (₦)	500	600	550
2	Spare part holding cost (₦)	100	220	200
3	Spare part carrying rate	0.40	0.30	0.35
5	MTTF (min)	720	700	650
6	Unit area of batch spare ($m^{2)}$	52	35	20
7	Locate area	400	300	250
8	Ordering range	0 - 50	0 - 40	0-35
9	Spare parts inventory cost (₦)	500,000	800,000	600,000
10	Benefits	1000	1000	1000
11	Penalty	1500	1500	1500

₦ 340 = $1

From the BB-BC algorithm implementation, a near-optimal value of 0.9275 was obtained for goal 1 (production line availability), while goal 2 (technicians cost) near-optimal solution was ₦ 13,650,994. For goal 3 (penalty and bonus expenses) ₦ 3,009,418.78 was obtained as near-optimal solution. A value of ₦ 206,284.50 was obtained as the near-optimal solution for goal 4 (inventory expenses). The near-optimal values for the decision variables in the proposed model are presented in Tables 3 to 7.

4. Discussion of Results

Technicians' logistic planning (size, cost, time and training) influences the implementation production plan. Based on the near-optimal values of the technicians (Table 3), the minimum and maximum technicians' size that is required for smooth running of the system production plan was between 23 and 25 technicians. The cost analysis of the system showed that the cost for penalty and incentives was ₦ 752354.70. The average cost for spare parts inventory per planning period was ₦ 51571.10. The higher the service rate of a maintenance department, the higher the release date of equipment that is undergoing maintenance. The model presented therein has been able to allocate the available maintenance time for each schedule at the different periods that are considered (Table 4).

During maintenance activities, the production line with the highest preventive maintenance time was production line 1 (35,695.99 hr), while production line 2 requires the least preventive maintenance time of 27,737.48 hr. The preventive maintenance time for production line was 3, 5313.05 hr. The minimum preventive maintenance time required for the production system per annual was 68,746.52 hr (Table 5). Based on the technicians' and workloads structures (Tables 3 and 4), the expected amounts of unplanned maintenance tasks that affect production activities were computed (Table 6). The annual production time losses for production line 1 was 37.79 hr, while for production line 2 it was 40.18 hr. The annual production time loss for production line 3 was 40.51 hr.

The issues of manufacturing time management between the production and the maintenance departments can be properly managed based on optimal maintenance schedules knowledge (Table 7). It was observed that periods 2 and 4 have the highest frequencies that production lines are released for maintenance activities (6 schedules), while period 3 has the least frequency (4 schedules). It was observed that the only schedule in which technicians will be busy throughout was schedule 1 on production line 3 (Table 7). Schedule 2 (production line 2) and schedule 3 (production line 1) have the same number of idle periods for the technicians (75%).

With the aid of optimal schedule for a production line, the volume of expected demand for an organisation product will be managed properly. With the combination of finished goods inventory and the volume of finished goods expected from outsourced production, a buffer can be generated to cater for variations in an organisation's products. The principle of establishing buffer in a production system minimises the effect of penalty cost for failure to meeting customers' demands. At period 1, 829,699 kg was generated as buffer for demand, while period 2 had a buffer of 3,233,929 kg. In period 3, the buffer was 1,753,365 kg, while a buffer of 3,040,890 kg was obtained for period 4 (Table 8). These values complement the optimal values of product produced (Table 8). The optimal value of finished goods inventory showed that at period 2, there were no shortages of finished goods (Table 8).

To solve the problem of shortages, business owners adopt different strategies. First, the amount of time allocated for production activities can be increased. This strategy comes with increase in the cost of factors of production (technicians, spares and raw-material costs). The second strategy is to increase the amounts of production activities that can be outsourced to their business partners. Also, there is the possible of changing old production lines (defender) with a new production line (challenger) which has a higher production rate. This hinges on the concept of replacement analysis, which is beyond the scope of this study. Interested readers can pick-up a textbook on engineering economy on this subject matter.

By applying the concept of stock-on-hand (SOH), the rates of annual consumption of spare parts for the production lines were determined (Table 9). The value of SOH for production line 1 was 14 units. The values of SOH for production lines 2 and 3 were the same (9 units). At the end of period 4, the spare part shortage for production line 1 was 29 units, while for production line 2, the spare part shortage was 1 unit. Production line 3 had spare part surplus of 13 units (Table 9). Since there is surplus spare parts in the maintenance system, decision makers can combine intuition and the model results in re-scheduling of maintenance tasks. When dealing with spare parts which are critical to maintenance tasks, the shortage experience for production lines 1 and 2 will affect the availability of these production lines significantly. However, a reversal effect will be experienced for less critical spare parts.

Table 3: Maintenance technician's distribution for the different maintenance technician categories

Periods	x_{11t}	X_{12t}	x_{21t}	x_{22t}	f_{11t}	f_{12t}	f_{21t}	f_{22t}	h_{11t}	h_{12t}	h_{21t}	h_{22t}
$t = 1$	8	6	4	5	3	1	0	1	2	2	1	0
$t = 2$	7	5	8	6	2	1	2	1	3	1	1	0
$t = 3$	6	6	7	3	1	2	1	1	3	1	1	0
$t = 4$	7	6	4	5	0	2	0	2	2	2	0	1
Total	28	23	23	19	6	6	3	5	10	6	3	1

Table 4: Workloads distribution for the different technician categories

		Workloads (hr)											
		$l = 1$				$l = 2$				$l = 3$			
Schedules	Periods	w_{11lst}	w_{12lst}	w_{21lst}	w_{22lst}	w_{11lst}	w_{12lst}	w_{21lst}	w_{22lst}	w_{11lst}	w_{12lst}	w_{21lst}	w_{22lst}
	$t = 1$	110.75	120.83	332.25	217.60	110.75	120.83	332.25	217.60	0.00	0.00	0.00	0.00
	$t = 2$	125.14	143.20	164.25	179.17	125.4	143.20	164.25	179.17	0.00	0.00	0.00	0.00
$s = 1$	$t = 3$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	$t = 4$	122.14	116.50	321.00	210.00	122.4	116.5	321.00	210.00	122.14	116.50	321.00	210.00
	$t = 1$	110.88	121.00	332.75	217.80	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$s = 2$	$t = 2$	0.00	0.00	0.00	0.00	125.14	143.20	164.25	179.17	125.14	143.20	164.25	179.17
	$t = 3$	144.00	117.83	185.29	353.67	0.00	0.00	0.00	0.00	144.00	117.83	185.29	353.67
	$t = 4$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	$t = 1$	110.75	120.83	332.00	217.40	110.75	120.83	332.00	217.40	0.00	0.00	0.00	0.00
	$t = 2$	125.14	143.20	164.25	179.17	0.00	0.00	0.00	0.00	125.14	143.2	164.25	179.17
$s = 3$	$t = 3$	144.33	118.00	185.71	354.33	144.33	118.00	185.71	354.30	0.00	0.00	0.00	0.00
	$t = 4$	122.29	116.67	321.25	210.40	122.29	116.67	321.25	210.40	122.29	116.67	321.25	210.40

Table 5: Summary of total maintenance time for each schedule

Schedules		l = 1 (hr)	l = 2 (hr)	l = 3 (hr)
s = 1	t = 1	4,027.98	4,027.98	0.00
	t = 2	3,981.00	3,982.82	0.00
	t = 3	0.00	0.00	0.00
	t = 4	3,887.98	3,889.80	1,050.00
s = 2	t = 1	4,033.04	0.00	0.00
	t = 2	0.00	3,981.00	1,075.02
	t = 3	3,929.02	0.00	1,061.01
	t = 4	0.00	0.00	0.00
s = 3	t = 1	4,025.98	4,025.98	0.00
	t = 2	3,981.00	0.00	1,075.02
	t = 3	3,936.94	3,936.85	0.00
	t = 4	3,893.05	3,893.05	1,052.00

Table 6: Distribution of the unplanned maintenance time

Periods	Maintenance time (hr)								
	s = 1			s = 2			s = 3		
	R_{1st}	R_{2st}	R_{3st}	R_{1st}	R_{2st}	R_{3st}	R_{1st}	R_{2st}	R_{3st}
t = 1	82.19	88.49	64.16	72.53	44.91	84.34	61.55	116.64	60.80
t = 2	83.88	58.0	71.56	78.25	77.98	123.15	111.02	87.96	87.35
t = 3	88.53	27.05	86.09	69.83	73.45	119.57	119.57	11.61	71.02
t = 4	88.56	99.21	69.42	90.67	68.73	60.95	60.95	91.16	92.49

Table 7: Optimal values for maintenance schedules

	s = 1			s = 2			s = 3		
Periods	R_{1st}	R_{2st}	R_{3st}	R_{1st}	R_{2st}	R_{3st}	R_{1st}	R_{2st}	R_{3st}
t = 1	1	1	1	1	0	1	0	0	0
t = 2	1	0	1	1	1	0	0	1	1
t = 3	0	1	1	0	0	1	0	1	0
t = 4	1	0	1	1	0	1	1	0	1

Table 8: Optimal values for products

Periods	Production volume (kg)			Outsourced goods (kg)	Inventory (kg)
	l = 1	l =1	l = 3		
t = 1	3,925,269	3,778,140	3,895,257	829,699	-1,422,414
t = 2	4,040,410	3,328,046	3,814,491	3,233,929	428,534
t = 3	4,608,000	3,473,279	4,083,263	1,753,365	-2,035,233
t = 4	3,579,228	4,032,000	3,629,538	3,040,890	-1,732,046

Table 9: Optimal values for spare parts

Periods	Spare parts (units)		
	l = 1	*l* =1	*l* = 3
t = 1	48	31	34
t = 2	32	12	41
t = 3	34	35	12
t = 4	51	27	16

5. Conclusions

This study discussed the suitability of a mixed-integer nonlinear optimisation model for the quarterly analysis of technicians and spare parts plan for powdered detergent manufacturing plant. The developed plan is based on Pareto optimal results generated for changes in technicians and training costs, technician's penalty cost and bonuses, spare parts costs and the maximisation of production line availability. The feasibility of BB-BC algorithm as a solution method for the proposed model was considered. The results obtained shows that the optimal workloads balancing will result in the system production lines availability of up-to 92.75%.

The empirical results obtained provided answers to the following maintenance planning questions raised in this study.

- We observed that the average number of electrical technicians required for executing the available electrical maintenance tasks is 5 and 6 casual and full-time technicians, respectively. For the maintenance tasks, 6 and 7 casual and full-time technicians are required.
- The proposed model identified production line 3 at schedule 1 as requiring maintenance activities through out all the planning periods.
- Production line 1 was identified as requiring the highest amount of preventive maintenance time
- Shortages in production line 1 spares was observed while there were excess spares for production lines 2 and 3.
- The average quantity of product that should be out-sourced is approximately 2,214,471 kg.

The performance of the proposed model is subject to the accuracy of data used in its implementation. There may exist difficult in defining the limits which an objective may have as a complete membership. In such a situation, other multi-objective handling may be adopted. One interesting feature of the proposed model is that it can be used to estimate how much time technicians should spend on a production line (maintenance tasks balancing). The contribution of this study is the joint optimisation of maintenance time, spare parts and technicians' costs as well as technicians' incentives. The proposed model can be applied in a company where production lines are either in the same factory or in different factories. Fuzzy inference system could be designed for technicians and spare parts costs analysis using the data generated from the proposed model as a further study.

References

Bautista, J. and Pereira, J. (2007). Ant algorithm for time and space constrained assembly line balancing problem. *European Journal of Operational Research*, Vol. 177, pp. 2016-2032.

Bautista, J. and Pereira, J. (2009). A dynamic programming based heuristic for the assembly line balancing problem. *European Journal of Operational Research*, Vol. 194, pp. 787-794.

Bautista, J. and Pereira, J. (2011). Procedures for the time and space constrained assembly line balancing problem. *European Journal of Operational Research*, Vol. 212, pp. 473-481.

Belmokaddem, M., Mekidiche, M. and Sahed, A. (2008). Application of a fuzzy goal programming approach with different importance and priorities to aggregate production planning. *Journal of Applied Quantitative Methods*, Vol. 4, No. 3, pp. 317-331.

Boysen, N., Fliedner, M. and Scholl, A. (2007). Production planning of mixed-model assembly lines: Overview and extensions. *Jene Research papers in Business and Economics*, pp. 1-20.

Chica, M. Cordon, O., Damas, S. and Bautista, J. (2011). Including different kinds of preferences in a multi-objective ant algorithm for time and space assembly line balancing on different Nissan scenarios. *Expert Systems with Applications*. Vol. 38, pp. 709-720.

Engelbrecht, A.P. (2007). *Artificial Intelligence: An Introduction*, John Wiley, England.

Erol-Osman, K. and E. Ibrahim, 2006. New optimisation method: Big-bang big-crunch. *Advance in Engineering Software*, Vol. 37, No. 2, pp. 106-111.

Faira J., Natos, M. and Numes E. (2006). Optimal design of work-in-process buffers. *International Journal of Production Economics*, Vol. 99, pp. 144-155.

Gupta, P.K. and Hira, D.S. (2008). *Operations Research*, S.Chand, New Delhi, India.

Hong, D.S. and Cho, H.S. (2013). Dual criteria assembly line balancing for single-model and deterministic problems using simulated annealing. *Intelligent Automation and Soft Computing*, Vol. 7, No. 1, pp. 63-73.

Ighravwe, D.E. and Oke, S.A. (2014). A nonzero integer non-linear programming model for maintenance workforce sizing. *International Journal of Production Economics*, Vol. 150, pp. 204-214.

Ighravwe, D.E., Oke, S.A. and Adebiyi, K.A. (2015). Maintenance workload optimisation with accident occurrence considerations and absenteeism from work using a genetic algorithm. *International Journal of Management Science and Engineering Management*, DOI: 10.1080/17509653.2015.1065208.

Law A.M. and Kelton D.W. (2000). Simulation Modelling and Analysis. McGraw Hill.

Lawrence S.R. and Buss A.H. (1994). Shifting production bottleneck: Causes, cures and conundrums. *Journal of Production and Operations Management*, Vol. 3, No. 1, pp. 21-37.

Masood, S. (2006). Line balancing and simulation of an automated production transfer line. *Assembly Automation*, Vol. 26, No. 1, pp. 69-74.

Mansour, M.A.A-F. (2011). Solving the periodic maintenance scheduling problem via genetic algorithm to balance workforce levels and maintenance cost. *American Journal of Engineering and Applied Sciences*, Vol. 4, No. 2, pp. 223-234.

McGovern, S.M. and Gupta, S.M. (2007). A balancing method and genetic algorithm for disassembly line balancing. *European Journal of Operational Research*, Vol. 179, pp. 692-708.

Patti A.L., Watson K. and Blackstone J.H. (2008). The shape of protective capacity in unbalanced production systems with unplanned downtime. *Production Planning and Control*, Vol. 9, No. 5, pp. 486-494.

Powell S.K. and Pyke D.F. (1998). Buffering unbalanced assembly systems. *IEE Transactions*, Vol. 30, pp. 55-65.

Rardin, R.L. (1998). *Optimisation in Operations Research*. USA: Prentice-Hill, Incorporation.

Rana, R.S. and Purohit, R. (2012). Balancing of maintenance task during preventive maintenance of four wheeler. *International Journal of Engineering Research and Applications*, Vol. 2, No. 3, pp. 496-504.

Sakthivel, S., Pandiyan S.A., Marikani, S. and Selvi, S.K. (2013). Application of big-bang big-crunch algorithm for optimal power flow problems. *The International Journal of Engineering and Science*, Vol. 2, No. 4, pp. 41-47.

Seyed-Alagheband, S.A., Ghomi, S.M.T.F. and Zandieh, M. (2010). A simulated annealing algorithm for balancing the assembly line type II problem with sequence-dependent setup times between tasks. *International Journal of Production Research*, Vol. 49, No. 3, pp. 805-825.

Shin, D. and Min, H. (1991). Uniform assembly line balancing with stochastic task times in Just-in-time manufacturing. *International Journal of Operations and production Management*, Vol. 11, No. 8, pp. 23-34.

Wu, Z. (2008). Hybrid multi-objective optimisation models for managing pavement assets. Ph.D. thesis, Virginia Polytechnic Institute and State University, USA.