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A NEW MODEL FOR PRODUCTION, INSPECTION, AND MAINTENANCE: MODEL VALIDATION AND CASE STUDY

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ABSTRACT

A model is developed to integrate production planning, preventive maintenance, and process/product quality inspection decisions. The integrated model objective is to minimize the total costs of the three decisions that are subjected to constraints of production availability, preventive maintenance economical limitations, and system reliability constraints. Genetic Algorithms and Mixed Integer Linear Program are utilized to solve such complicated problems with constraints considered. An extensive literature review has been presented. The integration of the production, preventive maintenance, and quality decisions in one integrated model is rare so that further investigations and real case study applications in the industry fields are needed. The proposed model and solution method are compared and validated with four models and methodologies from literature. A case study demonstrates the significant improvements of the model results on a real practical industrial application, which also validates the proposed model.

KEYWORDS: Reliability, Preventive maintenance, Production planning, Integrated systems.

1. INTRODUCTION

In modern industrial systems with high competition between firms, growth of market demand and diversity of product designs enforce the necessity of designing more efficient, integrated, flexible, and qualified production systems. The competitors have to reduce expenses to meet customer satisfaction. The key points in any industrial firms are the production, maintenance, and quality inspection systems because of interdependencies influence and resources share [1]. The key success is to integrate

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these systems and find the optimal plan of interrelated decisions. The proposed model is presented to integrate and find the optimum interrelated production, maintenance, and quality decisions with economical and reliability constraints to minimize the total cost. The proposed model is compared and validated with previous models and methodologies. A case study is presented to demonstrate the significant impact of the model results on a real practical industry, which also validates the proposed model.

2. LITERATURE REVIEW

In production environments, maintenance plans are increasingly involved to improve the availability of systems and reliability of machines, as they play a significant role in system performance, overall manufacturing system success, and economic impact. Unexpected failures reduce the system availability and productivity that make the production plan invalid. These failures lead to customer complaints of delivering delays and undesired product quality. Therefore, it is essential to integrate production planning with maintenance planning to avoid undesirable failure consequences [2, 3]. Several studies deal with maintenance models and tackle the effects on the system in several ways. They introduced maintenance policies such as preventive and corrective maintenance, which both are adopted in the proposed work. The previous studies presented preventive maintenance (PM) as a general policy that can be classified into many sub-policies such as time-based, age-based, condition-based maintenance models [2-4]. The policy used in the proposed study is the age-based policy that is widely used and suitable for all kinds of failure modes and deteriorated models [4]. Modeling of production and maintenance were studied earlier as separate models and did not take into account the impact of each model on the other. Researchers recently discerned the importance of integrating the maintenance with production and quality models. An exhaustive literature survey on the integrated models revealed that they can be categorized into three parts as shown in Tables 1-3. The first category is the previous work that integrates PM model with quality model as shown in Table 1. The second category is the previous work that integrates PM model with production system model as shown in Table 2. The integration of PM with both quality and production systems is shown in Table 3.

Table 1. Summarized literature of integration of PM and quality models.

References	Integrated Models: Quality	PM	Production	Model	Methodology	Objective
[5]	√	√		Markov deteriorated model	Simulation model	Minimum defects
[6,7]	√	√		Markov deteriorated model	Conventional optimization methods	Minimum cost
[8]	√	√		Age-perfect PM model with quality state variable	Exact solution algorithm	Optimum PM time interval
[9]	√	√		SPC* with imperfect PM Markov model	Solution algorithm	Minimum cost
[10]	√	√		Hazard failure rate, SPC with age PM Models	Simulation-optimization approach	Minimum cost

*SPC: Statistical Process Control.

Table 2. Summarized literature of integration of PM and production models.

References	Integrated Models: Quality	PM	Production	Model	Methodology	Objective
[11]		√	√	Random failure models, lot-sizing	Solution algorithm	Optimal lot-sizing with Min. cost
[12]		√	√	Virtual age PM model, lot-sizing	Proposed procedures	Optimal lot-sizing with Min. cost
[13]		√	√	Random failure & equal PM intervals, EPQ*	Approximation algorithms	Minimum cost
[14]		√	√	Imperfect PM, age failure model, lot-sizing	Solution algorithm	Optimal PM schedule and Production Runs with Minimum cost

Table 2. Summarized literature of integration of PM and Production models, (Cont.).

Integrated Models						
References	Quality	PM	Production	Model	Methodology	Objective
[15]		√	√	Lot-sizing, no backlogging, random failure	Solution algorithm	Satisfy lot demand, Min. cost
[16]		√	√	Multi machines, imperfect PM	Solution algorithm	Maximum availability with economic constraint
[17]		√	√	production and imperfect PM with reliability and MILP model	Fix and optimize procedures	Minimum cost
[18]		√	√	Production and Reliability-maintenance model	Lagrangian relaxation method	Minimum cost
[19]		√	√	Lot-sizing cyclic PM	Solution algorithm	Min cost of shortage delay of demand
[20]		√	√	Fixed demand Production-PM and MILP model	MILP branch and bound	PM and replacement to Minimum cost
[21]		√	√	Production and Maintenance plan	Bee Colony Optimization algorithms	Maintenance time scheduling
[22]		√	√	Production scheduling and Maintenance plan	GA	production schedule and PM plan
[23]		√	√	PM model by MILP with Production	Lagrangian-based heuristic procedure	Production plan and PM
[24]		√	√	Maintenance - periodic PM	Nelder-Mead method	Bi objective of Min. Failure rates and Unavailability
[25]		√	√	Production and maintenance plan	A surrogate-assisted memetic algorithm	Multi-objective of Prod. and PM
[26]		√	√	Lot-sizing delay time PM model	Solution algorithm	Minimum Cost

Table 3. Integration with three models.

References	Integrated Models: Quality	PM	Production	Model	Methodology	Objective
[27]	√	√	√	Quality- prod. Rate and PM plan	Suggested algorithm	Max production rate
[28]	√	√	√	Imperfect PM, Production and product quality inspections	Proposed algorithm solution	Profit Max. with scrap and rework cost
[1]	√	√	√	Quality deviation, PM plan, Prod. Capacity	Proposed optimization procedures	Min. total integrated cost
[3]	√	√	√	Imperfect PM, quality inspection with lot-sizing	Memetic algorithm with population management	Min. total integrated cost
[29]	√	√	√	Imperfect to perfect PM, quality inspection, lot-sizing	Non-integrated method, local Tabu search	Min. total integrated cost
[30]	√	√	√	Imperfect periodic and non-periodic PM, quality inspection, lot-sizing	Proposed exact solution algorithm	Min. total integrated cost
Proposed model	√	√	√	Imperfect to perfect PM, periodic quality inspection, production, under reliability and economical constraints	Genetic Algorithm for PM and quality inspection, MILP for production	Min. total integrated cost

Most references consider two decisions integrations of the three decisions mentioned. Including the decisions of production, maintenance, and quality inspection in one integrated model is rare and further investigations and real case study applications in the industry fields are needed. The main contribution of the paper is to integrate these three decisions under economical and reliability constraints to optimally determine the production lot, inventory, and shortage quantities with optimal different PM plans, and quality inspections assigned to multiple machines in multiple periods. Genetic Algorithms (GA) and Mixed Integer Linear Program (MILP) are utilized to solve such complicated problems with limitations considered [29]. The proposed model is validated with previous integrated models. The real case study output supports the top management establishing the overall planning of the organization with limited resources.

3. PROBLEM DEFINITION

Assuming a manufacturing plant consists of two or more identical machines working in parallel with different failure rates. Each machine can produce two variant designs products. Each product has different processing times and defective rates on each of the machines. Each product is required to be delivered in lots at predetermined due dates with potential delay penalties for shortages and holding costs for overproduction. The machines are deteriorating with time and failures could occur affecting their operating availability. Defective products randomly appear during production affecting the product quality.

The objective of the proposed model is to determine the optimal production lot quantity and assign the products to be produced by any of the machines. An optimal PM plan is required to conserve the machines operating conditions to diminish the risk of failure probability and impact cost consequences. Optimal quality inspection activities must be conducted to rectify the specification of the products by re-adjusting machine configurations and consequently minimize the incurred total cost.

4. MATHEMATICAL MODEL

The production cost model is formulated in section 4.1, the maintenance and reliability cost model is formulated in section 4.2, and the quality cost model is formulated in section 4.3. The objective function and constraints are demonstrated in the end of the current section.

4.1 Production Cost Model

The production cost CP_T as shown in Eq. (1) is the summation of all production and setup costs for all machines at time horizon *T*, while Eq. (2) is a constraint that should be added to the model to put $Q_{p,m,t} = 0$, if only $S_{p,m,t} = 0$, and release any integer value greater than zero for $Q_{p,m,t}$, if $S_{p,m,t} = 1$.

$$CP_T = \sum_{t=1}^{T} \sum_{p=1}^{P} \sum_{m=1}^{M} \left(Q_{p,m,t} \cdot Cpr_{p,m} + S_{p,m,t} \cdot Cs_{p,m} \right) \tag{1}$$

$$Q_{p,m,t} \leq S_{p,m,t} \cdot PR_{p,m} \tag{2}$$

Equation (3) represents the backlogging cost CBL_T of the system, that consist of inventory holding cost, and backorder cost of products *p* produced in time horizon T. [30, 31]

$$CBL_T = \sum_{t=1}^{T} \sum_{p=1}^{P} \left(IQ_{p,t} \cdot Ch_p + BQ_{p,t} \cdot Cb_p \right) \tag{3}$$

Equation (4) represents the balanced inventory and backorder quantities with the quantity of product *p* produced subtracted by the demand at period *t* in two consecutive periods. [30].

$$IQ_{p,t} - BQ_{p,t} = \mathrm{IQ_{p,t-1}} - BQ_{p,t-1} + \sum_{m=1}^{M} Q_{p,m,t} - D_{p,t} \tag{4}$$

Equation (5) is the constraint to describe the quantity of product *p* that should be produced within production available time by multiplying production rate $PR_{p,m}$ by production available time $PT_{m,t}$

$$\sum_{p=1}^{P} Q_{p,m,t} \leq PR_{p,m} \cdot PT_{m,t} \tag{5}$$

4.2 Preventive Maintenance and Reliability Model

Equation (6) gives the available production time of the machines at period *t* Where; L is period t length L=1 which is a unit of time. The expected number of failure frequencies of the machine within a period *t* at a given age $a0_{m,t}$and $a1_{m,t}$ is shown in Eq. (7). [3, 29].

$$PT_{m,t} = L - RT_m \cdot FF_{m,t} \tag{6}$$

$$FF_{m,t} = \left(\frac{a1_{m,t}}{\mu_m} \right)^{\gamma_m} - \left(\frac{a0_{m,t}}{\mu_m} \right)^{\gamma_m} \tag{7}$$

The calculation of the new period age $a0_{m,t}$ for machines depends on the preventive maintenance plan K. If K=3, for example, means no PM action has implemented which mean $Cpm_{m,t,k}$=0, then substitute in Eq. (8) to get $a0_{m,t} = a1_{m,t}$, otherwise, if K=0 means a full PM, which mean $Cpm_{m,t,k}$=$Cpm_m(Max)$ then PM plan restore the age $a0_{m,t}$to zero, which is “as-good-as-new” condition [29].

$$a0_{m,t} = a1_{m,t} \cdot \left(1 - \frac{Cpm_{m,t,k}}{Cpm_m(Max)}\right) \tag{8}$$

$$a1_{m,t} = a0_{m,t} + PT_{m,t} \tag{9}$$

$$R_{S,t} = 1 - \prod_m^M \left(1 - e^{-\left[\left(\frac{a1_{m,t}}{\mu_m}\right)^{\gamma m} - \left(\frac{a0_{m,t}}{\mu_m}\right)^{\gamma m}\right]}\right) \tag{10}$$

Equation (10) calculates the reliability system $R_{S,t}$ of machine *m* at period *t*. [1, 4]. Equation (11) is the constraint of system reliability of not exceeding the desired system reliability limit R_{limit} (i.e 90%, 95%, or 98%)

$$R_{S,t} \geq R_{limit} \tag{11}$$

Equations (12 and 13) represent maintenance cost CPM_T, and failure cost CFR_T at time T.

$$CFR_T = \sum_{t=1}^{T} \sum_{m=1}^{M} FF_{m,t} \cdot Cfr_m \tag{12}$$

$$CPM_T = \sum_{t=1}^{T} \sum_{m=1}^{M} Cpm_{m,t,k} \tag{13}$$

Equation (14) is the PM cost constraint. The PM activity cost for all machines M at period *t*, must not exceed PM cost budget limit $PMGC_t$ [3].

$$\sum_{m=1}^{M} Cpm_{m,t,k} \leq PMGC_t \tag{14}$$

4.3 Quality and Inspection Model

Equation (15) represents the conditional probability of process quality deviation occurrence in any of inspection interval *j* assuming the initial age of period *t* is $a0_{m,t}$ [3, 30]. Equation (16) represents the quality checking CC_T at time horizon T. [3, 16, 29], while Eq. (17) gives the inspection cost CIN_T of the time horizon *T*.

$$P_{m,j,t}\left(a1_{m,t} \middle| a1_{m,t} > a0_{m,t}\right) = 1 - e^{-\left[\left(\frac{a1_{m,t}}{\eta_m}\right)^{\beta_m} - \left(\frac{a0_{m,t}}{\eta_m}\right)^{\beta_m}\right] \cdot \left[\frac{1}{IIF_{m,t}}\right]} \tag{15}$$

$$CC_T = \sum_{t=1}^{T} \sum_{m=1}^{M} P_{m,j,t}\left(a1_{m,t} \middle| a1_{m,t} > a0_{m,t}\right) \cdot \sum_{t=1}^{T} \sum_{m=1}^{M} \sum_{p=1}^{P} Q_{p,m,t} \cdot Cc_p \tag{16}$$

$$CIN_T = \sum_{t=1}^{T} \sum_{m=1}^{M} IIF_{m,t} \cdot Cin_m \tag{17}$$

Assuming the process deviation occurs at age u in inspection interval j. From that time (u) to the end of interval j,-at time $a1_{m,t}$,-the machines will work in a quality deviation condition.. Eq. (18) represents the mean time $DT_{m,t}$ of machine m working in a quality deviation condition in period t. [3, 29]. Where $p_m\left(u \middle| u > a0_{m,t}\right)$ is the probability of process deviation occurrence in a time between $a0_{m,t}$ and $a1_{m,t}$. Equation (19) represent the quantity of defected Products p from machine m, and period t that produced in a quality deviation time $DT_{m,t}$ [3, 29, 30]. The defective cost for all Periods T can be obtained by Eq. (20).

$$DT_{m,t} = P_{m,j,t}\left(a1_{m,t} \middle| a1_{m,t} > a0_{m,t}\right) \cdot \int_{a0_{m,t}}^{a1_{m,t}} \left(a1_{m,t} - u\right) . p_m\left(u \middle| u > a0_{m,t}\right) du \tag{18}$$

$$QD_{p,m,t} = \frac{DT_{m,t}}{PT_{m,t}} \cdot DR_{p,m} \cdot Q_{p,m,t} \tag{19}$$

$$CD_T = \sum_{t=1}^{T} \sum_{m=1}^{M} \frac{DT_{m,t}}{PT_{m,t}} \cdot \sum_{p=1}^{P} DR_{p,m} \cdot Q_{p,m,t} \cdot CD_p \tag{20}$$

Equation (21) represent the re-setting of machines configuration cost at time horizon T. Inspection activities $IIF_{m,t}$restore the machines quality condition.

$$CRC_T = \sum_{t=1}^{T} \sum_{m=1}^{M} P_{m,j,t}\left(a1_{m,t} \middle| a1_{m,t} > a0_{m,t}\right) \cdot IIF_{m,t} \cdot Crc_m \tag{21}$$

The Mathematical model: objective function and constraint functions:

$$Min\ TC = CP_T + CBL_T + CFR_T + CPM_T + CC_T + CIN_T + CD_T + CRC_T$$

s.t Constraint are given by Eqs. (2), (4), (5), (11), and (14).

5. SOLUTION METHOD

The integrated model consists of two linked optimization models. The first model is the PM and quality model formulated by GA. GA is widely used for solving integrated models with large potential solutions and finding global optimization solutions, which justify adopting GA in the proposed model [3, 17, 24, 29].

The proposed GA model parameters used are; the population size is estimated by 50 random chromosome, crossover and gene swapping probabilities are 0.5, and mutation probability set as 0.04 to assign new random values of the PM plan range to some genes of the chromosome. The output of the proposed GA model are; the optimum PM plan K, and quality inspection frequencies assigned to each machine *m* in each period *t*. The production time available can be obtained and then linked to the second optimization model to obtain the remaining decision variables of the proposed model. The second optimization model is production and backlogging model formulated as MILP, where the decision variables of the production lot-size and backlogging of $Q_{p,m,t}$, $IQ_{p,t}$, $BQ_{p,t}$ are required to take only integer values and $S_{p,m,t}$ takes binary variables. The MILP model is solved using CPLEX [3, 17, 29]. The flow chart of the solution method is shown in Fig. 1.

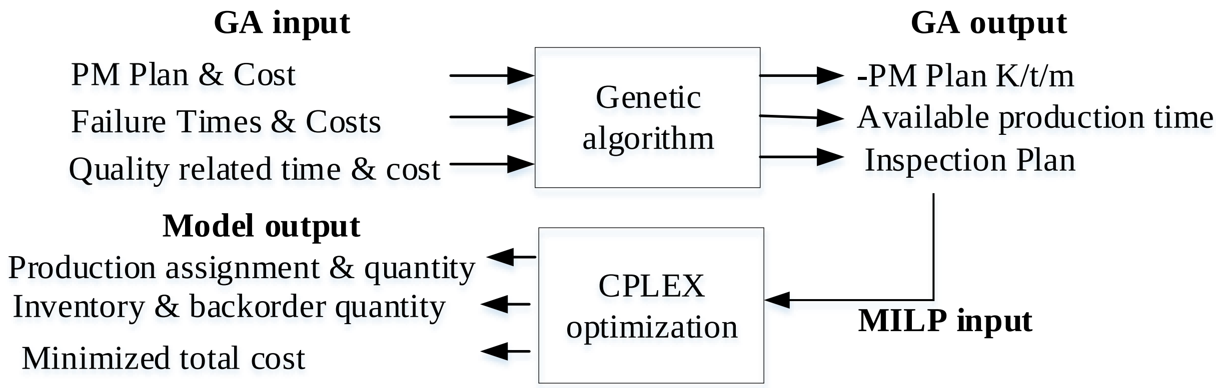

Fig. 1. Solution methodology flow chart.

6. VALIDATION WITH PREVIOUS WORK

Imperfect PM all the time without consideration of the system reliability was previously assumed [3]. The results of this policy generate unacceptable system reliability at each period t. The proposed model applied the investigation of the two policies; the one adopted in [3] without reliability constraint and the policy of implementing imperfect PM by considering two reliability limits 0.9, and 0.95. The results of the proposed model show the significant enhancement of the system reliability and system cost components when applying reliability constraint. Table 4 shows the system reliability, total cost, production cost, PM cost, and quality inspection cost using the approach adopted by [3] and compared with the proposed model using reliability limits of 90% and 95%.

Table 4. System reliability and cost comparison with [3].

	$R_{S,t}$ for six periods	TC, \$	CP$_T$, CBL$_T$ \$	CPM$_T$, CFR$_T$\$	Total quality cost, \$
No Rs [3]	0.63,0.42,0.29,0.2,0.12,0.09	462,832	311,384	77,075	74,373
Rs≥0.9	0.96, 0.94,0.95,0.96,0.94,0.94	401,398	285,818	67,690	47,889
Rs≥0.95	0.95, 0.95,0.96,0.95,0.96,0.95	463,101	317,238	90,164	55,699

The results of the proposed model are compared with the results obtained by [29] with the same data inputs to validate the optimization method. The total cost of the proposed model and solution method is \$321,558, compared with \$331,335 using Tabu search hybrid GA [29]. This result obtained, not only the lower total cost, but also did not violate PM cost constraint of not exceeding \$1500 per period. In addition, the results obtained satisfy the reliability constraint for each period of not exceeding 98% reliability. The results are presented in Table 5.

The results of the proposed model are also compared to the results obtained by [30]. They used an exact solution algorithm for the solution of the problem. They proposed an inspection-maintenance model with intervals of 0.2 months and 0.3 months. Two PM plans can be implemented each inspection time, the plan with 100% PM plan, and the plan with 50% of PM plan. They concluded that the inspection interval of 0.3 months with 100% PM plan obtains the lowest cost of \$107,930 for the model while the same decision obtained by the proposed model, but with a lower cost of \$107,382, with the same fulfillment of production and inventory decisions obtained by the proposed MILP method as indicated in Table 5.

The proposed model was compared with different approaches presented by [26]. They used the time delay concept to describe failures, PM, and defect inspection and presented an exact solution algorithm to obtain the optimum results. The proposed model results obtained an inspection and PM activities must be implemented every month to generate a lowest total cost of \$11,980,354, while the results obtained by [26] were implementing inspection and PM every two months generating a total cost of \$11,934,000.

Table 5. Validation comparison.

		Proposed Model and solution results	
Reference	Reference Total Cost, $	Model Type	Total Cost$
[29]	331,335	Reliability constraint of 98%	321,558
[30]	108,490	Model 1 (5 inspections, 100% PM)	108,490
	115,500	Model 2 (5 inspections, 50%PM)	115,483
	107,930	Model 3 (3inspections, 100% PM)	107,382
	123,200	Model 4(3 inspections, 50% PM)	123,168
[26]	11,934,000		11,980,354

7. CASE STUDY

7.1 Multi-Purpose Machining Factory

To show the applicability of the proposed model, the case study was applied to machining factory. The factory consists of many milling, drilling, turning, machines. The factory can produce many designs, spares, and parts that could be assembled in final products such as dies and appliances. The methodology of this study was to gather the data of the on-going plan and then apply the proposed model policies on the real factory. The results of both the proposed model and the real outputs are compared for validating the proposed model with real field application. The readings were gathered during operation for the same produced products with one week as the unit of time. Plans of production and deliveries, maintenance and quality inspections are updated weekly for a total cost estimate. The factory operating hours are 7 hours daily with one shift for six days a week. At the time of the case study, there was a project of producing two designs products that needed to be operated on two milling machines M1/1050, and M2/850.

The production data will be as follow: Two products lot are demanded for six weeks with 500 piece/week/lot for each product. The management estimated the operation hourly cost at EGP 200 per hour. Based on this data, all related data and costs are calculated. The time required to operate product (P1) on Machine 1 (M1), and Machine 2 (M2) is 7 min. and 10 min. respectively and the time required to operate product 2 (P2) on M1, and M2 is 3 min and 5 min. respectively. The machines related cost, times, and rates are shown in Table 6. The factory management is leasing storage area for storing the overproduction products. The leasing cost is EGP5000 for an area of 150 m^2, knowing previously the product dimensions, and the cost of storing one product can be estimated in Table 7. The shortage costs are the unfulfilled due date products and estimated as the over-time working hours cost required to overcome the delaying problem. The main problem of this factory is delivering weekly products on contracted due dates and with desired specification and quality.

Table 6. Machine 1 and machine 2 related costs in EGP.

	Production		Production Cost		Set-up Cost, EGP	Inspection Cost, EGP	Adjustment Cost, EGP	Repair Cost, EGP/ repair
Product	P1/ week	P2/ week	EGP/ P1	EGP/ P2				
Machine 1	360	840	23	10	200	16.6	33.3	1800
Machine 2	252	504	33	17	200	16.6	33.3	1800

Table 7. Product 1 and product 2 related costs in EGP per product.

Product	Storage Cost, EGP	Shortage Cost, EGP	Rework Cost, EGP	Quality Check Cost, EGP
P1	1.33	57	61.33	0.6
P2	0.9	27	46.33	0.42

The factory does not adopt a particular quality inspection policy or procedure. They depend on the experience of the worker. The main cause of non-adequate product dimensions and defected products are the machines setting deviations. The main course of action of re-setting the machines are tool replacement, tool holder fixing, and tool coolant refilling. The defective rate of machines M1 and M2 while they work in the deviated settings are 0.7 and 0.6. Process inspection activity time estimated 5 minutes per machines, and the machines re-setting time required is twice the time required to inspect. Inspection cost could be calculated in terms of inspection time required and hour cost operation as indicated in Table 6. Rework cost and quality check cost per product is shown in Table 7. The time to defect is the elapsed time to next defect appearance in the process. Time to defect Weibull distribution parameters for M1 and M2 are (0.2857, 2.5) and (0.4, 2.5) respectively.

The factory on-going maintenance policy adopted was monthly, weekly, and daily with a granted cost for each maintenance activity of EGP 400, EGP 300, and EGP 100 respectively. The preventive maintenance policy of the proposed model is the weekly maintenance activities from minor maintenance, to major maintenance with a cost range from 100 to EGP 400, PM plan K={0, 1, 2, 3}, and PM cost={400, 300, 300, 100} with weekly PM cost limit of EGP 400 according to factory's financial restrictions. Time to failure is the elapsed time to next failure occurrence. The time to failure Weibull distribution parameters for M1 and M2 are (0.142, 3.5) and (0.2, 3.5) respectively. The system reliability limit is set to be 90%.

7.2 Results Implementations and Comparisons

The GA solution method was used to solve and extract the optimum decision variables of production, maintenance, and quality inspection using the same algorithm parameters and conditions stated in solution method section. The GA run settings set were 40 runs with 30 minutes each to figure out that the results convergence occurred. Fig. 2 shows the best results among the 40 runs revealing the results convergence.

The results of the proposed model are implemented in the real factory for six weeks with system reliability of 90% to reveal the significant improvements by the proposed model recommendations. The results of the real readings validate the proposed model with real application.

The proposed model plan was implemented in the real factory showing significant enhancement in total cost, production capacities, shortage levels, failure frequencies, and quality of the products compared with the old on-going plan, which validates the proposed model in real practical industries as shown in Table 8.

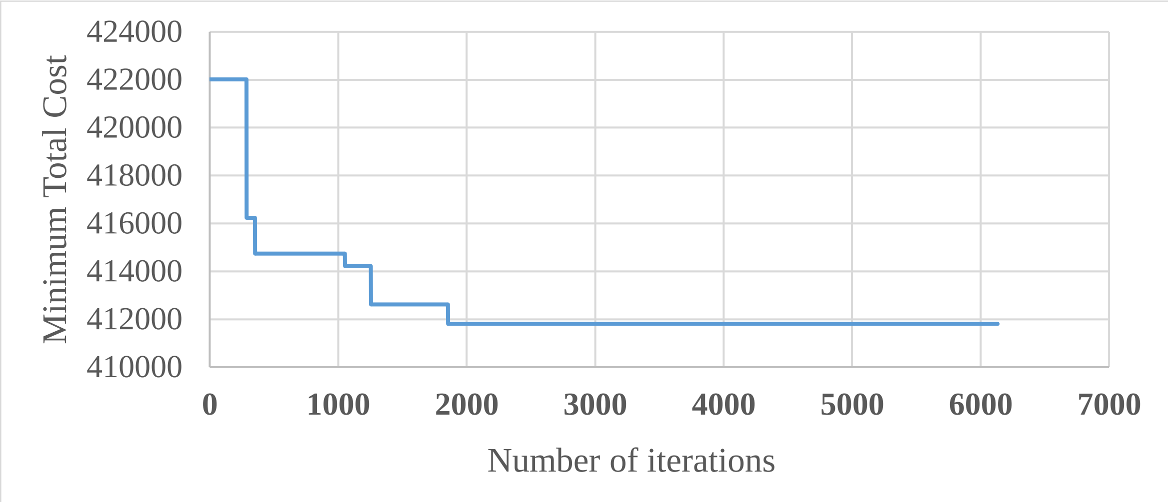

Fig. 2. Results convergence of 40 runs with 30 minutes.

Table 8. Model results Vs. real implementation results.

<table>
<tr><th colspan="2"></th><th>Factory Old Plans Output</th><th>Factory Proposed Plan Output</th><th>Model Results</th></tr>
<tr><td colspan="2">Average P1 quantity on M1</td><td>77</td><td>94</td><td>99</td></tr>
<tr><td colspan="2">Average P1 quantity on M2</td><td>154</td><td>221</td><td>224</td></tr>
<tr><td colspan="2">Average P2 Quantity on M1</td><td>230</td><td>486</td><td>500</td></tr>
<tr><td colspan="2">Average P2 Quantity on M2</td><td>122</td><td>6</td><td>0</td></tr>
<tr><td rowspan="2">Average Backorder Quantities</td><td>P1</td><td>800</td><td>640</td><td>618</td></tr>
<tr><td>P2</td><td>200</td><td>10</td><td>4</td></tr>
<tr><td rowspan="2">Average % Defected Products</td><td>P1</td><td>8%</td><td>6.1%</td><td>5.81%</td></tr>
<tr><td>P2</td><td>6%</td><td>5.1%</td><td>4.71%</td></tr>
<tr><td>Average Failure Frequencies/week</td><td>M1/M2</td><td>1.7</td><td>1.25</td><td>1.25</td></tr>
<tr><td colspan="2">Production Cost (EGP)</td><td>380,000</td><td>315,000</td><td>304,438</td></tr>
<tr><td colspan="2">Quality Cost (EGP)</td><td>100,000</td><td>75,000</td><td>74,127</td></tr>
<tr><td colspan="2">PM, Failure Cost (EGP)</td><td>35,000</td><td>34,000</td><td>33,241</td></tr>
<tr><td colspan="2">Total Cost (EGP)</td><td>515,000</td><td>424,000</td><td>411,806</td></tr>
</table>

8. CONCLUSIONS

An integrated production, maintenance, and inspection mathematical model is proposed that showed significant interdependencies between production, maintenance, and quality inspection decisions. The model objective minimizes total costs subject to constraints of machine availability and PM cost limitations with a desirable reliability limit. GA are utilized to find the optimum PM plan and inspection decisions, while a MILP model is used to find the production decisions. The proposed model and solution methodology are compared to four related references for validated. The proposed model is compared to [3]. The proposed model significantly enhanced system reliability from 20% as resulted by [3] to the desired reliability limit of 90% and 95%., with enhanced total cost incurred. The solution methods and proposed model are compared with various solution methods and integrated models presented by [26, 29], and [30] and showed close or even enhanced total cost.

The proposed model plan was implemented in the real factory case study to show significant enhancement in total cost, production capacities, shortage levels, failure frequencies, and quality of the products compared with the old on-going plan, which validates the proposed model in real practical industries.

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DECLARATION OF CONFLICT OF INTERESTS

The authors have declared no conflict of interests.

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Nomenclature

$a0_{m,t}$	Age of machine *m* at the start of period *t* or after immediate PM
$a1_{m,t}$	Age of machine *m* at the end of processing time period *t*
$BQ_{p,t}$	Backorder quantity of product *p* from shortage at time *t*
Cb_p	Backorder penalty cost per unit of unsatisfied product
CBL_T	Total Backlogging cost for time horizon T
Cc_p	Cost of product *p* quality checking
CC_T	Quality checking total cost for all machine *m* at *T*
CD_p	Cost per unit defected product *p*
CD_T	Defective cost for all Periods *T*
Cfr_m	Cost per failure repair for machine *m*
CFR_T	Total cost of failure repair for all periods *t* of *T*
Ch_p	Holding cost per unit of product *p* stored
Cin_m	Production line *m* per inspection activity cost
CIN_T	Total inspection cost in all production periods *T*
$Cpm_{m,t,k}$	Cost of PM for *m* action activity plan *k* at period *t*
$Cpm_m(Max)$	PM cost at full Preventive Maintenance maximum cost
CPM_T	Total Preventive Maintenance cost of time horizon *T*
$Cpr_{p,m}$	Production cost for product *p* in machine *m*
CP_T	Total Production cost of time horizon *T*
Crc_m	Re-set machines configuration cost for machine *m*
CRC_T	Total re-setting machines configuration cost at time horizon *T*
$Cs_{p,m}$	Set-up cost of machine *m*
$D_{p,t}$	Product *p* demand at period *t*
$DR_{p,m}$	Product *p* specification deviation rate on machine *m*.
$DT_{m,t}$	Mean time of machine *m* working in deviation condition at *t*
$FF_{m,t}$	Expected failure frequencies of *m* within a time *t*
$f_m(y)$	Probability density function of time to failure for *m*
$IIF_{m,t}$	Number of inspection frequencies for machine *m* in period *t*
$IQ_{p,t}$	Inventory quantity of product *p*
L	Period *t* length
$PMGC_t$	Preventive maintenance cost limit at period *t*.
$PR_{p,m}$	production rate per unit of time for product *p* on machine *m*
$PT_{m,t}$	Production time available of machine *m* at period *t*
$Q_{p,m,t}$	Production quantity of product *p* assigned to *m* at period *t*

$QD_{p,m,t}$	Quantity of defected Products *p* from machine *m*, and period *t*
$R_{S,t}$	Reliability of system at period *t*
RT_m	Repair time required for machine *m*
$S_{p,m,t}$	Set-up binary {0, 1} variable of setting product *p* on *m* at period *t*
T	The time horizon of multiple periods *t*
β_m, η_m	Weibull distribution parameters for machine *m* for time to defect
γ_m, μ_m	Weibull distribution parameters for machine *m* for time to failure

نموذج جديد للإنتاج والفحص والصيانة: تحقيق النموذج ودراسة ميدانية

يتناول البحث عمل نموذج رياضي لدمج قرارات كل من تخطيط الإنتاج وتخطيط الصيانات الوقائية وفحص جودة ومواصفات المنتجات والعمليات الصناعية واتخاذ قرارات الخطط المثلى لتقليل التكاليف الكلية للإنتاج والصيانة والاعطال المتوقعة ولضبط العلميات التصنيعية لإنتاج منتج مطابق لمواصفات الجودة وتسليمه في إطار الجدول الزمني المتوقع، وتأتي أهمية البحث لأنه موجها لمتخذي القرار للمنافسة في سوق العمل بأقل تكلفة وأعلى جودة، هذا وقد تم استخدام الخوارزمية الجينية لاستخراج الحلول المثلى ومقارنة النتائج مع نماذج وطرق حل سابقة للتحقق من صحة النموذج وطريقة الحل المقترحة وقد أظهرت المقارنات تقارب وصحة النتائج المقترحة مع النماذج السابقة وتم عمل دراسة حاله في الصناعة المصرية حيث أظهرت النتائج تميز النموذج.