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Integration of Production Scheduling and Group Maintenance Planning in Multi-unit System employing TLBO algorithm

Aseem K. Mishra[a,*], Divya Shrivastava[b]

[a]*Mechanical Engineering Department, ITS Engineering College, Knowledge Park 3, Greater Noida U.P.- 201308, India*
[b]*Mechanical Engineering Depratment , Shiv Nadar University, NH-91, Tehsil Dadri, U.P.-201314, India*

* Corresponding author. Tel.: +91-995-372-2180; *E-mail address:* aseem.me.engg@its.edu.in

Abstract

This paper deals with joint optimization of production scheduling and group maintenance planning in single machine system with multi units arranged in series. The objective is to achieve optimum production sequence, preventive maintenance (PM) intervals and grouping of units which minimize the total integrated cost per unit time of the system. Teaching-Learning Based Optimization (TLBO) algorithm is applied to optimize the objective function. The peculiarity of TLBO as against other algorithms is that it is independent of algorithm specific parameters. The largest order value rule is utilized to retrieve the permutation vector while grouping of units is performed under PM intervals. Computational results reveal the effectiveness of the proposed approach.

Keywords: Production Scheduling; Group Maintenance Planning; Integration; TLBO algorithm

1. Introduction

Production scheduling, inventory control, and maintenance planning are the key operational policies, which govern the effectiveness of any shop floor manufacturing system. For shop floor operations to be efficient, it is important to have proper maintenance planning decisions and sound production scheduling methodologies. However, these aspects of operations planning also have an interaction effect on each other and hence a joint optimization of scheduling and maintenance provides improvisation that is even more significant over conventional approaches [1].

For instance, most production scheduling models, do not consider the effect of machine unavailability due to failure or maintenance activity. Similarly, maintenance planning models seldom consider the impact of maintenance on due dates to meet customer requirements. However, maintenance effectiveness cannot be measured in a meaningful way without taking into account whether the maintenance function is meeting the production requirements. On the other hand, delaying the maintenance to meet production requirement may increase the probability of machine failure, which results in higher rejections or downtime losses. Consequently, a large number of integrated models have been proposed in the literature, which provides better-compromised solution with improved efficiency of the shop floor system. The literature in the integrated optimization of scheduling and maintenance planning is extensive and beyond the scope of this article to include all contributions. Rather, we refer the readers to some important review papers [1]–[3] for the comprehensive study of pioneer works in this area.

Despite the awareness about interdependence of scheduling and maintenance, many industries fail to utilize the integrated approaches effectively and efficiently in order to maximize their performance. This may be due to the reason that the present approaches of joint optimization planning is still at

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exploratory stage as most of the integrated models ponder several unrealistic assumptions such as single machine-single unit system, fixed or individual maintenance interval, computational complexities, etc.

With motivation to further improve the performance of manufacturing system, the present paper proposes an integrated model of production scheduling and group maintenance planning in single machine system having multi-units arranged in series. Grouping of units is performed under preventive maintenance (PM) intervals, which leads to direct reduction of set up costs and downtime losses. The objective is to obtain optimum production sequence, optimum (PM) intervals and optimum grouping of units, which minimize the total integrated cost of the system. The total cost include tardiness costs, inventory holding cost, corrective maintenance (CM) and PM costs. In order to optimize the objective function, a novel and efficient algorithm namely teaching-learning based optimization (TLBO) is applied [4]. The specialty of TLBO as compared to other well-established algorithms such as GA, SA and PSO is that it is independent of algorithm specific parameters which reduces computational complexities to great extent. To the best of our knowledge, this is perhaps the first attempt to apply TLBO for integrated optimization of production scheduling and group maintenance planning decisions.

Nomenclature

n	number of jobs
i	index of job, $i \in \{1,2,\dots,n\}$
m	number of units/components
j	index of unit, $j \in \{1,2,\dots,m\}$
N_j^{pm}	number of PM intervals of unit j in planning horizon
k	index of PM interval, , $k \in \{1,2,\dots,N_j^{pm}\}$
p_i	processing time of i^{th} job (in minutes)
s_i	set up time of i^{th} batch (in hours)
tp_i	total processing time of i^{th} batch including set up time (in hours)
bs_i	batch size of i^{th} job
ct_i	completion time of i^{th} job (in hours)
dd_i	due date of i^{th} job (in hours)
icc	inventory carrying cost per job per hour
tc_i	tardiness cost of i^{th} job
FC_j^{pm}	fixed cost of unit j for preventive maintenance (PM)
FC_j^{cm}	fixed cost of unit j for corrective maintenance (CM)
TR_j^{pm}	time to repair for PM for unit j
TR_j^{cm}	time to repair for CM for unit j
β	Weibull shape parameter
η	Weibull scale parameter
r_f	restoration factor
γ_j^{pm}	individual optimum PM interval of unit j
γ_j^{g}	optimum PM interval of unit j for group maintenance approach
μ_j	integer multiplier of PM interval for j^{th} unit
θ_{ij}	binary variable, 1 if PM of j^{th} unit is performed prior to processing of i^{th} job, 0 otherwise.

1.1. System structure

We consider a single machine system with m units arranged in series. Each job i ∈ {1,2,…,n} is to be processed on machine while a machine can process only one job at a time i.e. permutation sequence is followed. Meanwhile, each unit j ∈ {1,2,…,m} undergoes two types of maintenance: corrective upon failure and preventive to avoid failure. The imperfect PM based on restoration factor is considered [5] whereas CM is assumed to be minimally repaired. The expected number of failures are estimated based on the well-known theory that the number of minimal repairs between two consecutive PM follows a Non-Homogenous Poisson Process (NHPP) [6]. It can be represented by a cumulative intensity function $\int_{k_j \times \gamma_j^{pm}}^{(k_j+1)\times\gamma_j^{pm}} \lambda_j(t)dt$, where k_j is the k^{th} PM interval of unit j and $\lambda_j(t)$ is the hazard rate function.

In the integration approach, it is assumed that once the batch processing start, it cannot be interrupted. However, PM intervals can be shifted before the start or after the finishing time of job depending on net savings in the downtime costs. The methodology for grouping of units under PM intervals is referred from Mishra *et al.* [7] which states that the optimum PM interval of each unit is assumed to be integer multiples of the minimum optimum PM interval of units amongst them. Therefore, those units are grouped whose PM intervals are equal or closer to each other bearing same integer multiples. Since integer multiples cannot be estimated with accuracy, they are also considered as decision variables along with permutation sequence and PM intervals.

2. Mathematical Formulation

This section provides the mathematical model for integrated approach of production scheduling and maintenance planning in multi-unit system. Moreover, the methodology for grouping of units under PM intervals is also explained.

2.1. Group maintenance approach

In this approach, initially the optimum PM intervals of each unit is obtained individually by traditional trade-off method that minimizes the sum of corrective and preventive maintenance costs over the mission time [8], [9] which can formulated as:

$$TMC_j = \frac{\frac{T_m}{\gamma_j^{pm}}\times\left(TR_j^{pm}\times C_d + FC_j^{pm}\right) + NF_j\times\left(TR_j^{cm}\times C_d + FC_j^{cm}\right)}{T_m} \quad (1)$$

where, TMC_j is the total maintenance cost of the unit j, NF_j are the total number of expected failures, $\frac{T_m}{\gamma_j^{pm}} = N_j^{pm}$ are the number of PM intervals and T_m is the mission time. C_d is the downtime cost which can be expressed as:

$$C_d = PR \times CLP + LC \quad (2)$$

where, PR is the production rate in jobs/hour, CLP is the cost of lost production in Rs./job and LC is the labor cost in Rs./hour. Thus, the optimal PM intervals obtained from equation (1) serve as basis for group maintenance approach.

The ideology in grouping of units is such that at scheduled PM interval of any unit j, a decision has to be made to perform PM on a certain group of units. Units belonging to this group can be identified based on the individual optimal PM interval of each unit. Let $\gamma = min\{\gamma_j^{pm}\}_{j\in(1,\dots,m)}$ be the minimum PM interval of unit j among all units obtained from equation (1). The PM interval of other units can now be eventually expressed as an integer multiple of γ. Thus, $\gamma_j^g = \mu_j \times \gamma$, where μ_j are integer multipliers. Thus, the decision variables are γ and μ_j which minimize total maintenance cost of the system under group maintenance approach (TMC_g). Hence, the mathematical model can be expressed as:

$$Minimize\ TMC_g = \left[\frac{T_m}{\gamma} \times \left(max\{TR_j^{pm}\}_{j\in G_j} \times C_d\right) + \sum_{j=1}^{m} \frac{T_m}{(\mu_j \times \gamma)} \times FC_j^{pm} + \sum_{j=1}^{m} NF_j \times \left(TR_j^{cm} \times C_d + FC_j^{cm}\right)\right] / T_m \quad (3)$$

Where, $max\{TR_j^{pm}\}$ is the maximum repair time between grouped units.

2.2. Integrated model

The proposed integrated approach involves simultaneous optimization of group PM intervals (obtained from above model) and production sequence in order to minimize the total integrated cost per unit time of the system including tardiness cost, inventory carrying cost and maintenance (PM and CM) costs. Thus, the completion time of job i is a discrete random variable that depends on processing time of job i (p_i), PM time (TR_j^{pm}) and CM time (TR_j^{cm}) of unit j.

Let a_{j0} be the initial age of the unit j at the starting of production. Let, $\bar{a}_{j,i-1}$ is the age of unit j prior to processing of i^{th} job in a sequence and let a_{ji} is the age after the i^{th} job is processed. The effective age of the unit after performing PM action can be defined as:

$$\bar{a}_{j,i-1} = a_{j,i-1} \times (1 - \Delta_{ij} \times r_f) \quad (4)$$

$$a_{ji} = \bar{a}_{j,i-1} + p_i \quad (5)$$

where,

$$\Delta_{ij} = \begin{cases} 1, \text{ if PM is performed on unit } j \text{ prior to } i^{th} \text{ job} \\ 0, \text{ Otherwise} \end{cases}$$

Assuming the Weibull time-to-failure distribution, the probability of failure of unit j while the i^{th} job is processed can be determined as follows:

$$F_{ji} = F(p_i + \bar{a}_{j,i-1} | \bar{a}_{j,i-1}) = 1\text{-}exp\left[-\left(\frac{p_i + \bar{a}_{j,i-1}}{\eta}\right)^{\beta} + \left(\frac{\bar{a}_{j,i-1}}{\eta}\right)^{\beta}\right] \quad (6)$$

Therefore, the expression for the completion time of batch i can be formulated as follows:

$$ct_i = \sum_{i=1}^{i} tp_i + \sum_{i=1}^{i} max\{\Delta_{ji} \times TR_{ji}^{pm}\}_{j\in G_j} + \Phi_i,\ i \in \{1,2,\dots,n\} \quad (7)$$

where, G_j represents the group of units on which PM is performed simultaneously. tp_j is the total processing time of batch including the set up time s_i which can be written as:

$$tp_i = \frac{(bs_i \times p_i)}{60} + s_i \quad (8)$$

Φ_i is a discrete random variable having probability mass function as given in equation (9). It calculates the time to minimal repair of machine while the i^{th} job is processing.

$$\pi_{i,r} = Pr\{\Phi_i = r * TR_j^{cm}\} = \sum_{N_i} \prod_{l\in N_{ji}} \bar{F}_{i,l} * \prod_{l\notin N_{i,k}} F_{i,l} \quad \forall\ r = 1,2,\dots,i,\ \ \forall i \in (1,2,\dots,n\} \quad (9)$$

Let δ_i denotes the tardiness of the i^{th} considering PM and failure times. It is to be noted that δ_i has $i+1$ possible values. The expression for the expected tardiness of the i^{th} job can be written as:

$$E(\delta_i) = \sum_{r=0}^{i} max(ct_{i,r} - dd_i, 0) \times \pi_{i,r} \quad (10)$$

Thus, the total tardiness cost of all the jobs due to schedule and maintenance delay can be given as:

$$TC_{smd} = \sum_{i=1}^{n} tc_i \times E(\delta_i) \quad (11)$$

The approach for the calculation of inventory carrying cost is referred from Mishra and Shrivastava [10]. Accordingly, the inventory carrying cost is calculated for both the batches in queue and those, which are currently in process. Since the inventory of batches being processed depletes at a constant rate, therefore the average inventory level is considered. Note that the inventory cost of only tardy jobs are considered. The expression for the calculation of inventory carrying cost is expressed as:

$$ICC_{smd} = icc \times \left\{\sum_{i=1}^{n} \theta_i * (bs_i \times wtb_i) + \sum_{i=1}^{n} \theta_i * \frac{bs_i}{2} * tp_i\right\} \quad (12)$$

where, wtb_i is the waiting time of i^{th} batch in queue and

$$\theta_i = \begin{cases} 1, \text{ if the job is delayed beyond its due date} \\ 0, \text{ otherwise} \end{cases} \quad (13)$$

Thus, the total integrated cost per unit time of the system due to schedule and maintenance delay including tardiness and inventory carrying cost can be written as:

$$TC_{sys} = \frac{TC_{smd} + ICC_{smd}}{CT_n} + TMC_{g,shift} \quad (14)$$

where, CT_n is the completion time of n^{th} job scheduled at last position. TMC_{gshift} refers to the marginal maintenance cost difference for the units shifted from their optimum value. Thus, the equation (14) is minimized subject to equations/constraints (4)-(13) to achieve optimum sequence and optimum group PM intervals.

3. Solution Procedure: TLBO algorithm

It is evident that most of the scheduling problems are itself NP-hard in nature. In addition to PM decisions, the problem becomes even more complex. Furthermore, in group maintenance approach, while optimum PM intervals can be identified by classical methods, the implications to integer multiples lead to large number of possible combinations. To overcome this complexity, a recently proposed, novel and efficient meta-heuristic named teaching-learning based optimization (TLBO) is applied to optimize the present objective function. TLBO is an iterative search method, which mimics the teaching-learning process of human beings. The optimization progresses in two phases: teacher phase and learner phase. While teacher phase provides the initial solutions, learner phase improvise them by mutual interactions between the candidates in the population. TLBO appears as a rising star in the optimization world as it has received wide variety of successful applications in engineering and sciences [11]. Interested readers can refer to [11], [12] for detailed procedure and applications of TLBO.

In the present problem, the generation of permutation sequences and optimization mechanism of TLBO is explained by means of flowchart as depicted in figure 1. Note that the optimum grouping of units is also optimized by TLBO, which is embedded in the integrated approach. The initial random job permutation sequence is generated by means of largest order value (LOV) rule as depicted in figure 2. Moreover, TLBO is coded in Matlab 8.6.0 and computational results are analyzed on a 3.25 GHz i5-4570 processor.

4. Computational Results

To demonstrate the effectiveness of the proposed approach, we consider a numerical example of a system with 5 units connected in series and 4 jobs to be processed on it. The scheduling and maintenance input parameters are given in table 1 and table 2 respectively. The other input parameters include production rate is 20 jobs/hour, cost of lost production is 50 Rs./job, labor cost is 500 Rs./hour, batch size (bs_i) of 500 units and inventory carrying cost is 1.5 Rs./hour [9].

4.1. Group maintenance results

Initially the optimal PM intervals of each unit is obtained individually as per equation 1. Table 3 shows the optimum

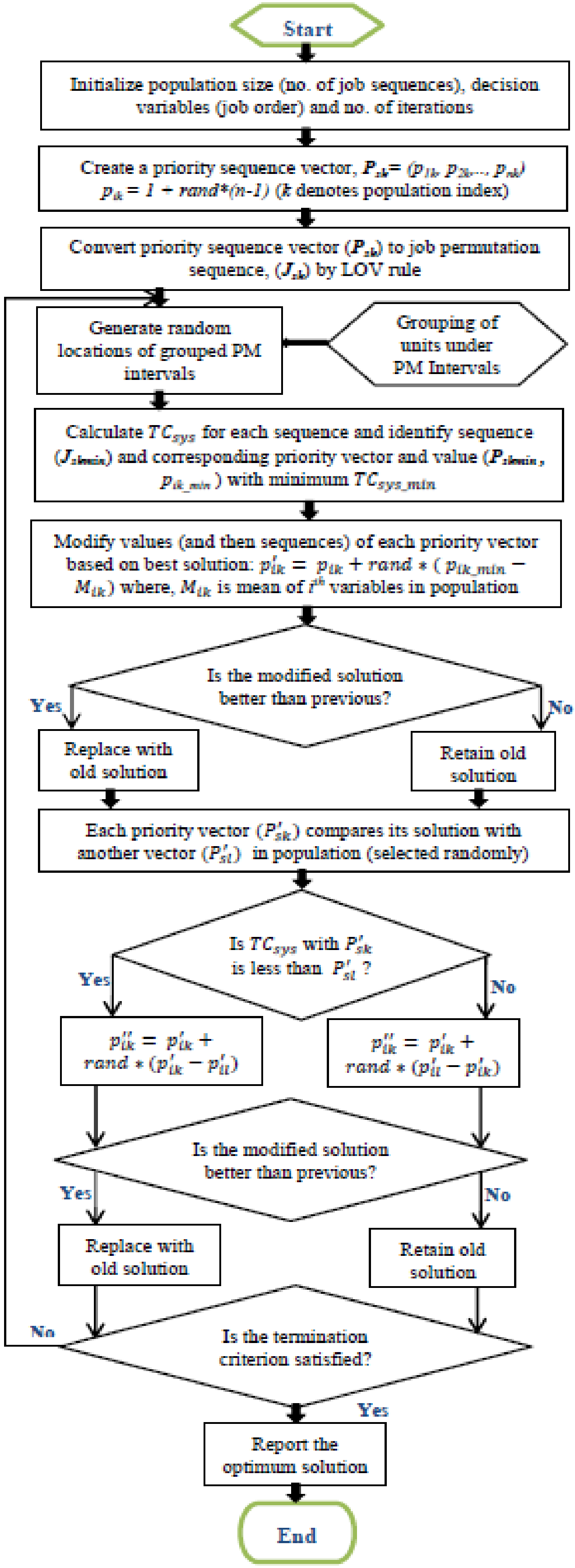


Fig. 1 Integrated optimization procedure by TLBO algorithm

PM intervals with minimum maintenance cost of each unit in the system. It is seen that U5 has minimum PM interval of 126 hrs.

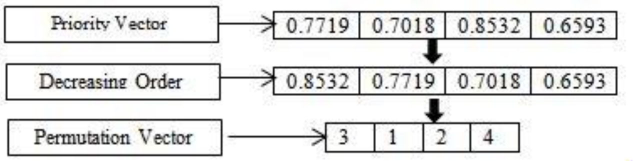


Fig. 2 Generation of permutation vector by LOV rule

Table 1: Input scheduling parameters

Jobs	Processing Time (pi) (minutes)	Set up Time (s_i) (hours)	Total Processing Time (tp_i) (hours)	Due Date (dd_i) (hours)	Tardiness Cost (tc_i) (Rs./ hour)
J1	6	3	53	60	20
J2	5	5	45	50	15
J3	7	2	61	70	11
J4	9	4	78	100	25

Table 2: Input maintenance parameters

Units	Scale Parameter (η)	Shape Parameter (β)	PM Repair Time (TR_j^{pm}) (hours)	CM Repair Time (TR_j^{cm}) (hours)	Fixed PM Costs (FC_j^{pm}) (Rs./unit)	Fixed CM Costs (FC_j^{pm}) (Rs./unit)
U1	898	2.53	4	11	4320	28900
U2	905	2.14	9	20	6700	36600
U3	486	1.73	5	12	1820	7460
U4	736	3.55	10	25	7060	23320
U5	507	1.88	3	8	2720	19600

The estimated integer multiples of other units are also given which states that units U1 and U2 form one group with PM of 252 hours, U3 and U5 with 128 hours and U4 with 378 hours. However, this may not be the optimum combination. Thus, the optimum solution is obtained by TLBO algorithm. The population size and iterations for TLBO are set as 50 and 500 respectively. Furthermore, the range of integer multiples are varied within $\mu_j \pm 1$ as our initial testing revealed that the solution becomes worse beyond this range, however without eliminating the potential optimum solutions Table 4 shows some of the combinations integer multiples and corresponding PM intervals of units with total group maintenance cost per unit time. It is seen that the optimum solution is the third combination (marked in bold italics) with minimum PM of 142 hours and integer multiples as 2/2/1/2/1 having maintenance cost of 324 Rs/hour. Therefore, U1, U2 and U4 are grouped with PM interval of 284 hours whereas U3 and U5 form another group with 142 hours of PM time. These groups with common PM intervals of 142 and 284 hours are referred as G_1 and G_2 respectively. This shows cost savings of 27% from the estimated solution and 33% from the single unit model (sum of individual cost of units).The other combinations are far from being optimal. This grouping of units is utilized in the integrated model.

4.2. Integrated scheduling and group maintenance results

Having being identified the optimum grouping of units, the integrated approach in the present problem with 4 jobs and two maintenance groups will have $4!*2^4$ possible solutions.

Table 3: Individual Optimal PM intervals of units

Units	Optimum PM Interval (hours) (γ_j^{pm})	Estimated Number of Failures (NF_j)	Minimum Maintenance Cost (Rs./hour) (TMC_j)	Estimated Integer Multiples (μ_j)
U1	275	3.30	61	2.18 ≃ 2
U2	303	2.68	88	2.41 ≃ 2
U3	192	16.38	102	1.52 ≃ 1
U4	361	2.68	87	2.87≃ 3
U5	***126***	***10.65***	***97***	***1***

Table 4: Optimum Solutions of group maintenance model

S. No.	Minimum PM Interval (γ) (hours)	Integer Multiples (μ_j)	Optimum PM intervals (γ_j^{pm})	Minimum Group Maintenance Cost (TMC_g) (Rs./hour)
1.	135	3/1/2/3/1	405/135/270/405/135	421
2.	***142***	***2/2/1/2/1***	***284/284/142/284/142***	***324***
3.	148	2/2/1/3/1	296/296/148/444/148	412
4.	144	1/2/1/2/1	144/288/144/288/144	429
5.	161	2/3/2/4/2	322/483/322/644/322	426

Thus, a full factorial analysis is performed by TLBO to achieve the optimum results. Table 5 shows some of the explicit solutions with total integrated cost per unit time of the system. It is identified that fourth alternative (marked in bold italics) with job sequence 2-1-3-4 yields the optimum solution with minimum integrated cost per unit time of the system. G_1 is performed after job 1 while G_2 after last job. Figure 3 depicts the completion time of each job and PM action for the optimum solution.

Table 5: Optimal solutions of integrated scheduling and group maintenance approach

S. No.	Integrated Job Sequence and Group PM actions	TC_{sys} (Rs/hour)
1	2 1 G_1 4 G_2 3	713
2	2 G_1 3 G_2 1 4	742
3	1 2 G_1 3 4 G_2	645
4	2 1 G_1 3 4 G_2	***626***
5	3 G_1 1 G_2 2 4	771
6	4 1 G_1 2 G_2 3	813
7	4 G_1 2 G_2 3 1	784
8	2 1 G_1 3 G_2 4	629
9	2 G_1 1 G_2 3 4	672
10	1 2 3 G_1 4 G_2	638

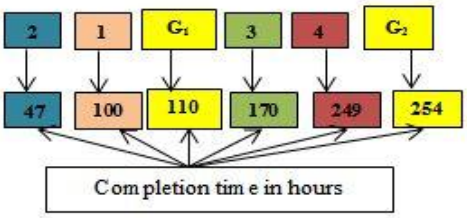
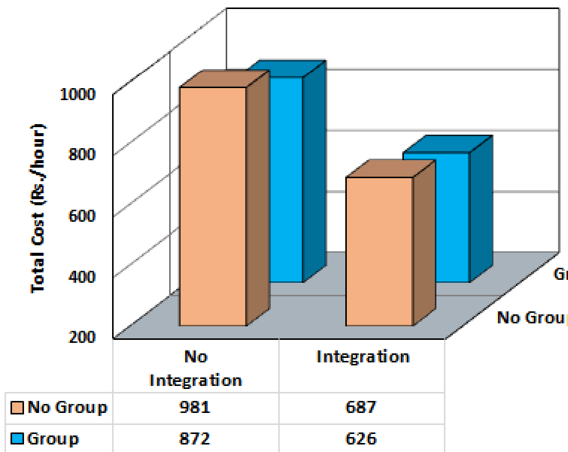


Fig. 3: Completion time of jobs and PM action for optimum solution

In order to analyze the effectiveness of the proposed integrated methodology and group maintenance approach, the obtained total integrated cost is compared with no integration and no group approach. For instance while considering the only scheduling model (by excluding the maintenance decisions in equation 7) the optimum production sequence is 2-1-4-3 with total cost per unit time of scheduling as 548 Rs./hour. Thus, the algebraic sum of scheduling cost and maintenance cost (group/no group) yields total cost with no integration. Figure 4 shows the comparison of total cost with integration and no integration as well as with no group and group maintenance approach. It is seen that integrated cost along with group maintenance approach shows 9.7% cost savings when compared to individual maintenance approach. Moreover, as compared to no integration the proposed model show substantial cost savings of approximate 39% and 57% for group and no group respectively. This justifies that the proposed integrated methodology is effective and efficient over other traditional policies. Moreover, in the optimization process, the main advantage of TLBO algorithm is that being a parameter less algorithm, it substantially reduces both numerical and computational complexities specially when dealing with problems, which are themselves complex.

Fig. 4 Cost comparison of different approaches



Above all, it can be concluded that the proposed integrated model of production scheduling and group maintenance planning show better economic performance, which can be applicable to real industrial systems. In addition, the TLBO algorithm has considerable potential in dealing with such integrated optimization problems.

5. Conclusions

In the present study, we proposed an integrated model of production scheduling and group maintenance planning in multi-unit series system. The objective was to obtain optimum production sequence, optimum grouping of units, which minimize the total integrated cost per unit time of the system. A novel and efficient meta-heuristic named TLBO algorithm is proposed to optimize the objective function. Computational results show the better economic performance of the proposed methodology when compared from the traditional practices.

As a scope for future research, the proposed approach can be applied to multi-machine systems along with multi-objectives such as improving quality, minimizing time etc. Furthermore, the new proposed TLBO algorithm can be applied to large size problems and to other integrated scheduling and maintenance optimization including job shop scheduling, condition based maintenance, reliability based maintenance etc.

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