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An Opportunistic Maintenance Decision of A Multi-Component System Considering the Effect of Failures on Quality

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***Abstract*- Preventive maintenance is a planned activity to keep the manufacturing facilities in good condition. However, because of limited time and resources, not all the system components can be repaired/replaced during the planned opportunity. When the system is under maintenance, it is very conservative to take the maintenance decision on the components because of limited available time and resources, hence the decision is selective. In this paper, an approach for opportunistic maintenance of a multi-component system is presented. The objective is to obtain a minimum cost solution with required availability and which can be accomplished within the allowable maintenance time. The optimization of the proposed model in this paper results into maintenance decision in terms of maintenance actions namely, repair, replace or do-nothing for the system components. A genetic algorithm approach is used for getting the optimal solution. The application of the model is demonstrated through a case study of a high pressure die casting machine.**

***Keywords*-Opportunistic maintenance, Multi-component system, Genetic algorithm, Rejection cost**

Nomenclature

A_{Req}	:	Required system availability
Β	:	Weibull shape parameter for component
η	:	Weibull scale parameter for component
CC	:	Cost of component (Rs.)
C_f	:	Failure cost per incident for component (Rs.)
C_{LP}	:	Cost of lost production (Rs.)
C_{LM}	:	Labour cost of maintenance (Rs./hr)
C_{sp}	:	Cost of sub-components and consumables (Rs.)
C_R	:	Replacement cost for component (Rs.)
C_r	:	Repair cost for component (Rs.)
CRL	:	Cost of loss of residual life (Rs.)
$E[DT]_{TPMS}$	:	Expected downtime in next operating period (hr.)
ML	:	Mean life (hr.)
MRL	:	Mean residual life (hr.)
MTTrA	:	Mean time to repair for component (hr.)
MTTRA	:	Mean time to replacement for component (hr.)
MTTCA	:	Mean time to corrective action for component (hr.)
PR	:	Production rate (units/hr.)
RF	:	Restoration factor for component
T_{PMS}	:	Time between the current maintenance and next expected opportunity (hr.)
T_{Avl}	:	Time available to carry out maintenance (hr.)
T_{LM}	:	Time elapsed between the last maintenance and opportunity (hr.)
TC_f	:	Total cost of failures (Rs.)
TC_R	:	Total cost of replacement (Rs.)
TC_r	:	Total cost of repair (Rs.)
$(v_i)_O$	:	Effective age at opportunity (hr.)

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I. INTRODUCTION

Maintenance of machine components has a direct impact on the machine performance during actual operation. If equipment is not well maintained, the component failures will increase while on the other hand, excessive maintenance can result in unnecessary costs. The frequency of machine failures affects not only the production but also the machine condition. Hence, selection of efficient maintenance strategy is essential to achieve maximum reliability, availability, minimum downtime and required product quality at lowest possible maintenance cost. Opportunistic maintenance refers to the policy in which preventive maintenance is carried out at opportunities, either by choice or based on the physical condition of the system (Cui and Li [1]). Maintenance of multi-component system is an important area from industry perspective, which is studied by many researchers in the literature. Zheng and Fard [2] proposed an opportunistic maintenance policy for multi type units having an increasing hazard rate and considered hazard rate limits and tolerances as maintenance criteria. They considered the decision of the units to be repaired or replaced depending on the hazard rate at a failure or active replacement of another unit. Tam et al. [3] considered maintenance scheduling of a multi-component system that optimizes both cost and reliability simultaneously. The model is based on the concept of imperfect maintenance and includes factors such as ageing due to the operation rate of the system, downtime for maintenance and lead time for spare parts. Samhouri [4] presented a method to decide whether a particular item requires opportunistic maintenance or not, and if so how cost effective this opportunity based maintenance will be, when compared to a probable future grounding. Zhou et al. [5] proposed an opportunistic PM scheduling algorithm for the multi-unit series system based on dynamic programming. The proposed approach considers a component for PM when it has reached certain threshold and this PM action is considered as an opportunity for the maintenance of other components. Saranga [6] developed a cost model for a complex system consisting expensive items and condition monitoring maintenance strategies to take decision on the need of opportunistic maintenance for a particular item and the cost effectiveness of the opportunistic maintenance. Cassady et al. [7] presented a selective maintenance model to take maintenance decision considering limitation on maintenance time, budget and reliability of the system. Shalaby et al. [8] developed an optimization model for preventive maintenance scheduling of multi-component and multi-state system. They define the sequence of preventive maintenance activities as the decision variables and the summation of preventive maintenance, minimal repair, and downtime costs as the objective functions. Hu et al. [9] proposed an opportunistic predictive maintenance-decision method integrating machinery prognostic and opportunistic maintenance model to indicate the optimal maintenance time with minimal cost and safety constrains.

From the literature it is observed that, most of the models focus on identifying the criteria for maintenance opportunity and its cost effectiveness. Although, the machine condition affects the product quality, the effect of component failure and its consequence in terms of rejections is not generally considered in maintenance decision and the maintenance decision includes only maintenance related costs.

The objective of this paper is to develop an approach for opportunistic maintenance of a multi-component system to take an optimal maintenance decision by selecting maintenance actions for each component during a planned or an unplanned opportunity. A scheduled maintenance is considered as a planned opportunity, while any machine breakdown or stoppage due to other reason is an unplanned opportunity. The maintenance decision is based on the optimization of the total cost which includes all the direct and indirect costs like maintenance activity costs, residual life costs and future failure costs. The maintenance decision is taken considering the constraint on the available time for the maintenance actions, the system availability requirement in the next interval of system operation. The model also considers the effect of components failure on the quality of the product being manufactured and the cost of rejections is included in the total failure cost along with the maintenance and downtime cost.

In the next section, the system considered in this paper is presented.

II. SYSTEM DESCRIPTION

Consider a multi-component system having ‘n’ components, where each component is subjected to degradation due to continuous operation over a period of time and has an increasing failure rate (IFR). The time to failure distribution of each component is assumed to follow a two parameter Weibull distribution. The problem considered in this paper is shown in Fig. 1.

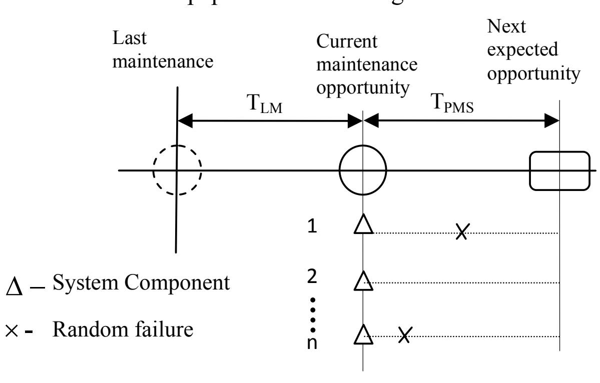

Fig.1. System description

The machine is available for maintenance after a time T_{LM} from the last maintenance action with each component in the system is having a certain age which depends on the last failure time. The next expected planned opportunity duration T_{PMS}, which is the operating period for the machine, is known. The maintenance decision needs to be optimized considering the system availability and the available time for maintenance. Since, all the system components cannot be subjected to maintenance due to limited resources and time, the decision is selective. For every component, one of the three actions namely, repair, replace and do-nothing is to be chosen. Even though the maintenance actions will improve the condition of the system, random failures may occur in the next period of operation. In this paper, we have considered two failure consequences associated with the component failures. The two failure consequences are:

1) Failure will lead to conditions where the detection is immediate and the machine needs to be stopped. This failure consequence is termed as FC1.

2) The failure is in terms of a degraded state where the machine will run, but lead to deterioration of the product quality being manufactured on the machine. This failure consequence is termed as FC2.

The failure consequence FC1 is immediately detectable while, the detection of FC2 is not immediate and occurs after a time lag. The magnitude of the time lag depends on the sensitivity of the quality control scheme. The objective is to obtain the maintenance decision with minimum total cost with required availability in the next period of system operation.

In the next section, model for the expected total cost for opportunistic maintenance is presented.

III. MODEL DEVELOPMENT

In this section, we develop an expected total cost model for opportunistic maintenance. Various aspects associated with the model and different cost components of the total cost are discussed in the following subsections.

A. Maintenance actions at an opportunity

For each opportunity, the model considers one of the following three types of maintenance actions:

i) Replacement action

In this category, during an opportunity, a component is replaced with a new one and the component starts its working with an age zero i.e. the restoration factor is ‘1’.

ii) Repair action

In this category, during an opportunity, repair is carried out for a component. The maintenance action improves the condition of the component with an improvement factor and effectively its age is reduced. The restoration factor is between 0 and 1 for repair action. In the case of subsystems with a large number of components, repair usually results in replacing only a few of these. For such situations, it may be reasonable to assume minimal repair at the subsystem level i.e. RF=0.

iii) Do-nothing

In this category, no maintenance action is taken and the components are left as they are. For a given component, this could be because of the maintenance time constraint or it

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may be more cost effective to postpone the maintenance action to a future opportunity.

B. Residual life

Residual life is the remaining lifetime of a component which has survived up to certain duration of time (t'). The Mean Residual Life (MRL) of a component 'i', having survived a duration t', can be expressed as (Ebeling, [10]),

$$MRL_i(t') = \frac{1}{R_i(t')}\int_{(t')}^{\infty} R_i(t)dt \quad (1)$$

C. Cost of loss of residual life

When a component is preventively replaced at an opportunity, the effect of the loss of residual life is considered. The cost due to the loss of residual life (CRL) will be proportional to the cost of the component. If we assume that the component cost is uniformly distributed over the lifetime of the component, the cost due to the loss of residual life will be given by,

$$CRL_i = \frac{CC_i}{ML_i} \times MRL_i \quad (2)$$

where, ML_i is the mean life , $ML_i = \int_0^{\infty} R_i(t)\,dt$

D. Cost of replacement

If a component is replaced at an opportunity, the cost of replacement incurred will be given by,

$$(C_R)_i = [MTTRA_i \times (PR \times C_{LP} + C_{LM}) + CC_i + CRL_i] \quad (3)$$

where , MTTRA is the mean time to replacement action.
Therefore, the expected total cost of replacement (TC_R) at an opportunity considering all the candidate components is given by,

$$TC_R = \sum_{i=1}^{n}\left[\Re_i \times (C_R)_i\right] \quad (4)$$

$$\text{where}, \Re_i = \begin{cases} 1, \text{ if } i^{th} \text{ component is replaced.} \\ 0, \text{ otherwise.} \end{cases}$$

E. Cost of repair

If a component is repaired at an opportunity, the cost of repair for the i^{th} component will be given by,

$$(C_r)_i = [\,MTTrA_i \times (PR \times C_{LP} + C_{LM}) + (C_{sp})_i\,] \quad (5)$$

where, $(C_{sp})_i$ is the cost of consumables during the repair of i^{th} component.

Therefore, the expected total cost of repair (TC_r) at an opportunity considering all the candidate components is given by,

$$TC_r = \sum_{i=1}^{n}\left[r_i \times (C_r)_i\right] \quad (6)$$

$$\text{where}, r_i = \begin{cases} 1, \text{ if } i^{th} \text{ component is repaired} \\ 0, \text{ otherwise} \end{cases}$$

F. Total cost of failure

The failure of a component can result into two possible Failure Consequences (FC). It can either immediately bring the machine under breakdown indicating total failure or the machine will operate, but affect the quality of the product being manufactured. The failure consequences are termed as FC1 and FC2 respectively. The detection of FC2 may not be immediate and occur after a time lag with the aid of process monitoring mechanisms like control charts or other sampling procedures. However, from the time of occurrence of the failure till its detection, the process operates in a degraded condition which leads to higher levels of rejection or rework.

In this paper, the cost of failure is considered as the cost associated with the repair/replace actions, downtime cost and the cost of rejection on account of quality. In other words, the cost of failure is a consequence of the maintenance actions chosen at an opportunity over the next period of operation i.e. till the next expected scheduled opportunity. In the present study, the expected downtime, E(DT) over a given period is determined through a failure simulation approach using the time to failure distribution of the component (Yanez et al. [11]) and the corresponding corrective action time.

$$TC_f = \sum_{i=1}^{n}(C_f)_i \times \left[1 - R_i(t/T)\right] \quad (7)$$

where, $(C_f)_i$ is the cost of failure of the i^{th} component and is given by,

$$(C_f)_i = [MTTCA_i \times (PR \times C_{LP} + C_{LM}) + \Re_i \times CC_i + r_i \times C_{sp\,i}] + (PR \times IRR \times TTD_{FC2} \times C_{Rej}) \times QF_i \quad (8)$$

where,

$$MTTCA_i = \begin{cases} MTTRA_i, \text{ if } i^{th} \text{ component is replaced.} \\ MTTrA_i, \text{ if } i^{th} \text{ component is repaired.} \end{cases}$$

$$QF_i = \begin{cases} 1, \text{ if failure of } i^{th} \text{ component affect product quality.} \\ 0, \text{ otherwise.} \end{cases}$$

The expected time to detect the occurrence of failure consequence FC2 is calculated from the average run length parameter of the quality control scheme.

$$TTD_{FC2} = \frac{1}{1 - \beta_S} \times \text{sampling interval} \quad (9)$$

where, β_S = Type 2 error of quality control scheme.

G. Total maintenance cost

The total cost incurred due to an opportunistic maintenance decision is the sum of maintenance cost and total failure cost which is given as,

$$TC = TC_M + TC_f \quad (10)$$

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$$TC = \sum_{i=1}^{n}\left[\Re_i \times (C_R)_i\right] + \sum_{i=1}^{n}\left[r_i \times (C_r)_i\right] + \left\{\sum_{i=1}^{n}(C_f)_i \times \left[1 - R_i(t/T)\right]\right\} \tag{11}$$

H. Optimization of model

For the maintenance optimization of a multi-component system, efficient maintenance decisions should be taken whenever opportunity arises. The objective of the optimization is to generate a set of maintenance decisions that will lead to a minimum total cost while meeting all the constraints. The objective function considered in the present study for the optimization of the maintenance decision is as follows:

$$\text{Minimize, } TC = \sum_{i=1}^{n}\left[\Re_i \times (C_R)_i\right] + \sum_{i=1}^{n}\left[r_i \times (C_r)_i\right] + \left\{\sum_{i=1}^{n}(C_f)_i \times \left[1 - R_i(t/T)\right]\right\} \tag{12}$$

Subject to:

i) $$\sum_{i=1}^{n}\left[\Re_i \times (MTTRA)_i\right] + \sum_{i=1}^{n}\left[r_i \times (MTTrA)_i\right] \le T_{Avl} \tag{13}$$

ii)

$$1 - \frac{\left[\sum_{i=1}^{n}\left[\Re_i \times (MTTRA)_i\right] + \sum_{i=1}^{n}\left[r_i \times (MTTrA)_i\right] + \left[E(DT)_{T_{PMS}}\right]\right]}{T_{PMS}} \ge A_{Req} \tag{14}$$

iii) $$\Re_i + r_i \le 1 \tag{15}$$

IV. SOLUTION METHODOLOGY: *GENETIC ALGORITHM*

Genetic Algorithms (GAs) are adaptive search techniques based on the evolutionary ideas of natural selection and genetics (Goldberg [12]). GA has been used in a wide variety of applications, particularly for finding the global optimum solution for an optimization problem. A Genetic algorithm works on the principle of survival of the fittest by progressively accepting better solutions to the problems. It operates on the population of potential solutions to the problem and iterates towards the optimum solution. As the search iterates, the population includes fitter solutions converging towards the near-optimality. The basic elements of genetic algorithm are solution representation, population, evaluation (Fitness), selection, crossover and mutation. The crossover and mutation are considered to be the main operators of GA. The algorithm starts with a randomly generated initial set of population consisting of chromosomes, which represent the solution of the problem. The chromosomes are evaluated for the fitness function or the objective function and selected according to their fitness value. The selected chromosomes then undergo crossover and mutation operation with a certain probability to form new generations. The general mechanism of a genetic algorithm is shown in Fig. 2.

```
Begin GA
  Create Initial population (Chromosomes)
  Select Fitness function.
  Evaluate each chromosome.
    while (termination criteria)
      Selection- of the stronger chromosomes as parents.
      Crossover -mate the chromosomes to form
                 offsprings with a probability of
                 crossover.
      Mutation- mutate the offsprings with a probability of
                mutation.
      Evaluate the fitness of new population.
    end
End (GA)
```

Fig. 2. General mechanism of GA

V. ABOUT CASE STUDY

A real life case study of High Pressure Die Casting (PDC) machine is considered for demonstrating the opportunistic maintenance methodology proposed in this paper. The company being considered is a first tier supplier of pressure die cast (PDC) components to automobile OEMs in India and abroad. The company has a large PDC section containing 35 machines of different capacities. The data of one of the machines has been used to demonstrate the proposed methodology. The machine under consideration operates for 7 hours per shift and 3 shifts per day. The details of the components which are considered for maintenance are given in Table I. (NA in Table I indicates 'not applicable')

The production rate is 72 units per hour and the profit is Rs. 8 per piece. The labor cost for maintenance is Rs. 100 per hour. The minimum required availability in the next operating period is 0.95. In the present case study, the same sampling plan, which is used by the company for quality control purpose is considered, where the sample size is 1, the time between samples is 1 hour and the acceptance number is 0. From the shop floor records it was observed that, failure of five machine components (Sr. no 22-26 in Table I) leads to increase in the defective rate. The normal defective percentage is 8% while in the case of failure of these five components, the defective rate increases to 20 %. If the sample size is 1 with an acceptance number of 0, the probability of not detecting a failed state at any given sample is 0.8, which is the type 2 error and hence, it will take 5 samples on an average to get an indication of a process failure. Since the time between samples is 1 hour, the time to detect the occurrence of failure consequence (FC2) will be 5 hours in the present case. From this, the increase in the rejection cost is calculated. The details of the components whose failure affect the product quality and results into an increase in the defective rate are given in Table I (Sr. no. 22-26). In the present case, whenever any of these components fail, it results into blow holes and non-filling in the castings. However, it should be noted that the given increase in the defective rate is specific to the machine under consideration.

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TABLE I
MAINTENANCE DATA FOR MACHINE COMPONENTS

Sr. No	Component	β	η (hr.)	Component cost during replacement (Rs.)	Failure cost (Rs.)	Sub-component/ consumables cost during repair (Rs.)	MTTrA (hr.)	MTTRA (hr.)
1	Electrodes	1.61	2388	1100	776	100	1	0.33
2	Electrode Insulator	1.07	3458	100	776	NA	NA	1
3	Electric wire	1.06	7877	300	976	NA	NA	1
4	Arm Bearings	2.83	1837	6200	6538	200	1	0.5
5	limit switch	3.33	14027	20000	20676	NA	NA	1
6	Chain	6.04	1623	5000	2352	800	2	3
7	Chain lock	4.14	3368	150	826	NA	NA	1
8	Bearing (cup side)	2.83	1837	2500	5028	200	1	3
9	Pneumatic Cylinder	3.33	14027	30000	31402	NA	NA	2
10	Seal	4.40	6680	7000	8352	NA	NA	2
11	Dia. Valve	5.56	3265	8000	9352	NA	NA	2
12	connector	2.49	7738	250	473.08	NA	NA	0.33
13	Shock Absorber	3.33	14027	10000	10676	NA	NA	1
14	Valve screw	2.59	22803	100000	12028	10000	3	4
15	Gear box	3.93	20364	100000	18760	12000	10	4
16	Servo valve	3.33	14027	200000	200676	200	4	1
17	Inj. Unit piston	3.93	20364	160000	192448	20000	8	48
18	Shot sensor	3.76	6840	100000	105338	NA	NA	0.5
19	Teflon seal	5.94	1624	150	319	NA	NA	0.25
20	Extractor Bearings	2.69	14027	12200	17608	NA	NA	8
21	length adjustor	4.64	9958	250	926	50	1	1
22	Acc. Piston	2.69	3744	120000	60292	50000	5	6
23	Acc. seal	2.83	1837	50000	59616	NA	NA	4
24	safety valve	3.01	36023	10000	8088	500	1	1
25	O'ring Set	3.33	14027	40000	55700	NA	NA	13
26	Couplings	2.49	7738	16200	11492	1000	5	1

VI. RESULTS OF OPTIMIZATION

In order to demonstrate the applicability of the proposed model, a scheduled maintenance is considered as a maintenance opportunity. The time between last maintenance and current opportunity is taken to be 800 hours and the time till next scheduled opportunity is 1000 hours. It is assumed that 20 hours are available for the maintenance work. The maintenance decision should be taken for the system such that the maintenance actions should be completed within this time and meet the target availability requirements. The effective age values of the components at the opportunity are given in Table II. The age values indicates the deterioration of the system components from the last maintenance and continuous operation till the current opportunity. The opportunistic maintenance approach proposed in this paper is applied and the possible maintenance actions for the system components will be evaluated at this maintenance opportunity, using genetic algorithm (GA) as the solution methodology.

TABLE II
EFFECTIVE AGE OF COMPONENTS AT THE OPPORTUNITY

Component	1	2	3	4	5	6	7
$(v_i)_O$ (hr.)	2274	953	197	400	6134	90	1964
Component	**8**	**9**	**10**	**11**	**12**	**13**	**14**
$(v_i)_O$ (hr.)	1292	6034	5045	2508	6966	7439	4350
Component	**15**	**16**	**17**	**18**	**19**	**20**	**21**
$(v_i)_O$ (hr.)	15481	9696	16494	4452	1391	964	1224
Component	**22**	**23**	**24**	**25**	**26**		
$(v_i)_O$ (hr.)	2401	621	28495	7109	4530		

A genetic algorithm approach is used to get an optimal solution. The first step in using GA is the selection of encoding principle for the chromosomes to represent the solution. In this paper, the numbers 1, 2 and 3 are used to represent the maintenance actions namely repair, replace and do-nothing respectively. The chromosome in the form of a string of numbers 1, 2 and 3 represents the maintenance decision and each chromosome consists of 26 genes. The parameters of the GA are, an initial population of 200

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chromosomes, which is generated randomly, a crossover probability of 0.8, a mutation probability of 0.05 and the total number of generation as 2000. The total cost of the maintenance decision is used as a fitness function for evaluating the relative fitness of each maintenance decision. A roulette wheel selection method is used for the chromosome selection and a two point crossover is used to form new off-springs during the crossover operation. The results of the maintenance decision using the GA are given in Table III and the path taken by the total cost during the generations is shown in Fig. 3.

TABLE III
RESULTS OF MAINTENANCE DECISION USING GA.

Maintenance Action	Repair	Components - Nil
	Replace	Components- 7,8,19
	Do Nothing	Components- 1,2, 3, 4, 5, 6, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20, 21, 22, 23, 24, 25,26
Total Cost (Rs.)	215535	
Maintenance decision Cost(Rs.)	4360	
Future Risk (Rs.)	211175	
Availability	0.9562	
Time taken	592.317 seconds.	

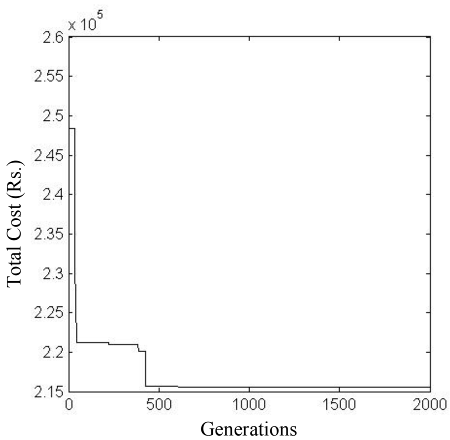

Fig. 3. Total cost progress over generations.

VII. CONCLUSION

This paper has presented an approach for opportunistic maintenance of a multi-component system. A cost model considering the expected total cost of maintenance decision with the constraints of availability and allowable maintenance time is developed. A genetic algorithm approach is used for optimization of the maintenance decision. Optimization of the proposed model results into maintenance decision by taking one of the three maintenance actions namely, repair, replace or do-nothing for the system components. The approach presented in this paper, is practical to implement on the shop floor and will help maintenance managers to effectively evaluate the maintenance actions based on the condition of the system components. It will also aid to effectively manage the resources such as manpower, spares etc. As a future research scope, the other solution methodologies can be applied to obtain the optimal solution and their performance can be compared.

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