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Using Genetic Algorithm to Robust Multi Objective Optimization of Maintenance Scheduling Considering Engineering Insurance

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Abstract. Efficient and on-time maintenance plays a crucial role in reducing cost and increasing the market share of an industrial unit. Preventive maintenance is a broad term that encompasses a set of activities aimed at improving the overall reliability and availability of a system before machinery breakdown. The previous studies have addressed the scheduling of preventive maintenance. These studies have computed the time and the type of preventive maintenance by modeling the total cost related to it. Todays the engineering insurance is an appropriate and durable protection for reducing the risks related to the industrial machinery. This kind of insurance covers a part of maintenance costs. Previous researches did not consider the effect of engineering insurance on maintenance scheduling while it affects the total cost function of

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maintenance scheduling seriously. Given the above-mentioned remarks, this paper introduces for the first time a new scheduling of preventive maintenance with considering total cost and total reliability of the system in which the effect of engineering insurance has been taken into account. Due to the uncertainty in the input parameters, which are very common in application, the paper proposed the application of robust design approaches. To solve this multi objective model, first it has been transformed into a single objective model by using global criterion and the resultant model is solved through genetic algorithm. The results show the magnitude effect of engineering insurance on maintenance scheduling. Therefore, neglecting the importance of engineering insurance leads to an inefficient scheduling maintenance.

Keywords: Preventive maintenance; engineering insurance; robust optimization; global criterion method; genetic algorithm; Pareto set solutions.

1. Introduction

In the current competitive environment managers of manufacturing and service organizations try to make their organizations competitive by providing timely delivery of high quality products. For this purpose, maintenance plays a key role in reducing cost, minimizing equipment downtime, improving quality, increasing productivity, providing reliable equipment, and as a result achieving organizational goals and aims [1]. Despite playing such an important role, the maintenance costs are a major part of the total operating costs of all manufacturing or production plants. Depending on the specific industry, these costs may represent between 15 and 60 percent of the costs of goods produced [2]. Recent surveys of maintenance management effectiveness indicate that one-third of all maintenance costs is wasted because of unnecessary or improperly carried out maintenance. The result of ineffective maintenance management represents a loss of more than 60$ billion each year [3].

Therefore, using an efficient maintenance strategy can reduces the total costs of production in manufacturing or production plants. Industrial and process plants typically use two types of maintenance management, run-to-failure or preventive maintenance [4]. Run-to-failure or corrective maintenance is a reactive management technique that waits for machine or equipment failure before any maintenance action is taken. It is also the most expensive method of maintenance management. While the Preventive maintenance encompasses a set of activities aimed at improving the overall reliability and availability of a system before fault occurs. Preventive maintenance is further divided into periodic maintenance and predictive maintenance. Periodic maintenance is a time-based maintenance consists of periodically inspecting, servicing and cleaning equipment and replacing parts to prevent sudden failure and process problems. Predictive maintenance is a method in which the service life of important part is predicted based on inspection or diagnosis, in order to use the parts to the limit of their service life. Compared with periodic maintenance, predictive maintenance is condition-based maintenance. In general, preventive maintenance activities are categorized in one of two ways, component maintenance or component replacement. It is clear that preventive maintenance involves a basic trade-off between the costs of conducting maintenance and replacement activities and the cost savings achieved by reducing the overall rate of occurrence of system failures. Designers of preventive maintenance schedules must prioritize these individual costs to reduce the overall cost of system operation. They may also be interested in maximizing the system reliability, subject to some sort of budget constraint. In periodic maintenance the optimum scheduling is very necessary.

Many researches have been optimized maintenance scheduling economically. Reference [5] determined optimal cost of maintenance policies by defining the average cost rate of system operation, in this study it is assumed that an increasing failure rate is based on the Weibull distribution function. Reference [6] developed a model to minimize the total costs related to preventive maintenance schedules. Exact algorithms reach exact optimal solutions of mathematical models, while approximation algorithms seek an approximation that is close to the true optimal solutions. Reference [7] presented a model that optimizes the preventive maintenance scheduling in semiconductor manufacturing operations. They optimized this model via a mixed-integer linear programming model. Reference [8] presented a preventive maintenance optimization model in order to minimize the total maintenance costs in a production system. Reference [9] determined an optimal preventive maintenance schedule by considering the time value of money in all future costs. Reference [10] defined the summation of maintenance activities cost along with cost of unsupplied demand due to failures of components in the objective function to optimize maintenance strategy. Reference [11] presented a model in order to optimize the maintenance policy for a component with random failure rate. Reference [12] presented an optimization model to schedule a preventive maintenance. He considered the total cost relating to operations as the objective function and solved the model using Bender's decomposition. Reference [13] presented two mixed-integer linear programming models for preventive maintenance scheduling problems and use CPLEX to implement the optimization models for a case study of railway maintenance scheduling. Reference [14] developed an age based nonlinear optimization model to determine the optimal preventive maintenance schedule for a single component system. Reference [15] developed three nonlinear optimization models: one that minimizes total cost subject to satisfying a required reliability, one that maximizes reliability at a given budget, and one that minimizes the expected total cost including expected breakdown outages cost and maintenance cost.

Because of complexity of maintenance scheduling, metaheuristic algorithms have been used in several researches [16]. Reference [17] used genetic algorithms with simulated annealing in order to optimize a large-scale and long-term preventive maintenance and replacement scheduling problem. Reference [18] used an ant colony algorithm to optimize the maintenance scheduling. Reference [19] proposed several techniques for representing the decision variables in preventive maintenance scheduling models and used heuristics and metaheuristics optimization algorithms. Reference [20] developed a novel multi-objective genetic algorithm to optimize preventive maintenance schedule problems. Reference [21] presented a production planning model considering preventive maintenance which minimize the completion time of jobs and downtime of machines. Reference [22] solved the previous model using genetic algorithm and simulated annealing algorithm. Reference [23] presented comprehensive research in area of integrating preventive maintenance and production scheduling and computed the Pareto set solution.

Insurance is a financial topic of paramount importance for every industry and is designed to protect the financial well-being in the case of unexpected loss. One of the new types of general insurance products is engineering insurance. This type of insurance is an appropriate and durable protection for reducing the risks related to the industrial machinery. It covers a part of maintenance costs.

Previous researches did not consider the effect of engineering insurance on maintenance scheduling optimization, while it affects the total cost function of maintenance scheduling seriously. So it is necessary to rewrite the cost function considering the cost of maintenance which is compensated by engineering insurance. This paper introduces for the first time a new scheduling of preventive maintenance considering total cost and total reliability of system in which the effect of engineering insurance has been taken into account. Due to the uncertainty in the input parameters, which are very common in application, the paper proposed the application of robust design approaches. Because of the complexity of the proposed model genetic algorithm is used to compute the Pareto set solution. The organization of this paper is as follows. In Section II, machinery breakdown insurance is illustrated; in Section III the preventive maintenance scheduling model is presented. Section IV demonstrates the structure of the robust design. Section V illustrates the multi objective optimization problem. In Section VI the proposed genetic algorithm which is used to solve the optimization problem is explained in details and finally, Section VII concludes the research with future researches

2. Machinery Breckdown Insurance

Engineering insurance refers to the insurance that provides economic safeguard to the risks faced by the ongoing construction project, installation project, and machines and equipment in project operation. Depending on the project, it can be divided into construction project all risks insurance and installation project all risks insurance; depending on the attribute of the object, it can be divided into project all risks insurance, and machinery breakdown insurance. Machinery Breakdown Insurance is designed to provide cover against unforeseen and sudden physical loss or damage to the machinery by any cause subject to excepted risks. Machines are an integral part of all manufacturing and industrial units engaged in production of industrial or household goods. These may be large industrial establishments or small and medium enterprises and any unexpected accident or breakdown to their critical machinery brings it to a standstill adversely affecting business and causing a financial strain towards repair or replacement of the affected machinery. The Machinery Breakdown Insurance offers coverage to organization against these sudden unforeseen accidents or events.

3. Preventive Maintenance Scheduling

Variables

N: Number of components

T: Number of periods

J: Number of intervals

λ_i: Scale parameter of component i

β_i: Shape parameter of component i

Z: Fixed cost of system

T_{ri}: Time required to replace component i

T_{Mi}: Time required to maintain component i

$f_i(t)$: Probability distribution function

f_{ij}: Total cost due to failure of component i in period j

Pi: Premium of component i

$Rel_{i,t}$: Reliability of component i at the start of period j

δ_i: Percent of premium which is paid when the component i is replaced

τ_i: Percent of maintenance cost which is compensated by engineering insurance when the component i is maintained.

F_i: Unexpected failure cost of component i

M_i: Maintenance cost of component i

R_i: Replacement cost of component i

x_{ij}: Effective age of component i at the start of period j

y_{ij}: Effective age of component i at the end of period j

N_{ij}: Number of failures of component i in period j
R_{ij}: Cost due to replacement of component i in period j
M_{ij}: Cost due to maintenance of component i in period j
α_i: Improving factor of component i when the preventive maintenance is done.

In this paper it is considered that the system consists of N machines which are organized in series. So, to improve the system's overall performance each of machines must perform efficiently. The number of machinery breakdowns in specific interval follows poison distribution with probability distribution function as in

$$f_i(t) = \lambda_i \beta_i t^{\beta_{i-1}} \quad t \geqslant 0(1)$$

Also, the interval [0, T] is segmented into J discrete intervals, each of length T/J. For example a time horizon of 2 years is equal to 24 segments. At the end of period j, the system is either, maintained, replaced, or no action is taken. Regards to the remarks, the decisions variables are as follow:

$$m_{ij} = 1 \text{ if component i at the start of period j is maintained}$$
$$\text{otherwise } m_{ij} = 0$$

$$r_{ij} = 1 \text{ if component i at the start of period j is replaced}$$
$$\text{Otherwise } r_{ij} = 0$$

If the maintenance activity occurs at the end of the period for component i, the effective age of it at start of next period is as in

$$x_{i,j+1} = \alpha y_{i,j}$$
$$0 < \alpha < 1 \tag{2}$$

If the replacement activity occurs at the end of segment j for component i, the failure rate of the component will tend to zero. If nor of the replacement or repairment activity occurs the failure rate will increase.

To option the cost function of maintenance scheduling, costs are categorized as follow:

3.2.1. Unexpected failure cost: due to unplanned component failures the inevitable costs must be taken into account, therefore average cost of failures of component i in period j is computed as in

$$F_{ij} = F_i E(N_{i,j})$$

$$E(N_{i,j}) = \int_{x_{i,j}}^{y_{i,j}} f_i(t)dt \tag{3}$$

3.2.2. Maintenance cost: if component i is maintained in period j, engineering insurance compensate a part of related cost, therefore maintenance cost is as follow:

$$M_{ij} = m_{ij} M_i (1 - \tau_i) \tag{4}$$

3.2.3. Replacement cost: the replacement of component i in period j have an additional insurance premium cost, therefore the total replacement cost is as follow:

$$R_{ij} = r_{ij} R_i + \delta_i P_i \tag{5}$$

3.2.4. Fixed cost: a fixed cost of downtime equal to Z can be charged in period j, if any component (one or more) is maintained or replaced in that period.
Summation the previous costs results the final cost function as in

$$C = \textstyle\sum_{i=1}^{N} \sum_{j=1}^{T} [F_{ij} + R_{ij} + M_{ij}] + \sum_{j=1}^{N} [Z(1 - \prod_{i=1}^{N} (1 - m_{ij} - r_{ij})]$$

$$C = \textstyle\sum_{i=1}^{N} \sum_{j=1}^{T} [(F_i \int_{x(i,j)}^{y_{i,j}} \lambda_i \beta_i t^{\beta_{i-1} dt)} + r_{ij} R_i + \delta_i P_i + m_{ij} M_i]$$
$$+ \textstyle\sum_{j=1}^{N} [Z(1 - \prod_{i=1}^{N} (1 - m_{ij} - r_{ij}))] \tag{6}$$

Reliability engineering is engineering that emphasizes dependability in the lifecycle management of a product. Reliability, describes the ability of a system or component to function under stated conditions for a specified period of time [24]. The aim of reliability engineering is to improve the overall reliability of the system. For this purpose there are different ways such as focusing on preventive maintenance, reducing the complexity of the systems, increasing reliability of components, and using back up components [25]. So the reliability of component i'th in segment t is computed as in

$$f(t) = P[t < T < t + dt] = -\frac{dRel(t)}{dt}$$

$$Rel(t) = exp[-\int_0^t f(t)dt]$$

$$Rel_{i,t} = exp[-\int_{x_{it}}^{y_{it}} f(t)dt] \tag{7}$$

The reliability function:

$$Rel = \prod_{i=1}^{N}\prod_{t=1}^{T} Rel_{i,t} = \prod_{i=1}^{N}\prod_{t=1}^{T} exp[-\int_{x_{it}}^{y_{it}} f(t)dt] \tag{8}$$

4. Robust Optimization

Imprecision in the input parameters is one of the reasons for lack of confidence in the economically designed of maintenance variables. This shows the necessity of robust design procedures for maintenance scheduling. For example the cost of operating is minimized when the impreciseness is considered in estimating the parameters of the operation. Also the maintenance and replacement costs are not deterministic; the premium and other parameters of engineering insurance are different under scenarios. Robust economic design is aimed at reducing the monetary losses which occurs as a result of departure of the model from basic assumptions. The non-availability of precise estimates of cost and process parameters for use in the cost function indicates the need for robust designs in maintenance scheduling. Some robust optimization methods such as simple weighting method considering the probability of occurrence, regret value and min-max regret model are the most significant among others. One of the robust optimization approaches is scenario-based approach in which the cost parameters are defined by different scenarios. The scenario is defined as a set of model parameters that can be realized in the production environment. When there is more than one scenario, the maintenance scheduling which is designed for only one particular scenario is not appropriate, while it may result in higher costs when the other scenarios are realized. The optimum maintenance scheduling should be minimized the cost of operating the process according to all possible scenarios. Reference [26] proposed a framework for robust discrete optimization, which seeks to find a solution that minimizes the worst case performance under a set of scenarios for the data.

Three different designs have been suggested based on the following discrete optimization measures as below:

a. Absolute robustness: The absolute robustness criterion is explained as a measure that selects the design that minimizes the objective across all scenarios

b. b. Robust deviation: The robust deviation is explained as a measure that selects the design that has the smallest deviation from the best possible performance for each scenario

c. Relative robustness: Relative robustness is explained as a measure that selects the design that has the smallest percentage deviation from the best possible performance for each scenario

Robust optimization approach:

$$Minimize\ C = \sum_{i=1}^{N} \sum_{j=1}^{T} [(F_i \int_{x_{i,j}}^{y_{i,j}} \lambda_i \beta_i t^{\beta_i - 1} dt) + r_{ij} R_i + \delta_i P_i + m_{ij} M_i] + \sum_{j=1}^{N} [Z(1 - \prod_{i=1}^{N} (1 - m_{ij} - r_{ij}))]$$

$$Maximize\, Rel = \prod_{i=1}^{N} \prod_{t=1}^{T} exp[- \int_{x_{it}}^{y_{it}} f(t) dt]$$

Subject to:

$$x_{i1} = 1$$

$$x_{i,j+1} = \alpha_i y_{i,j} = x_{i,j} + r_{ij} T_{r,i} + m_{ij} T_{m,i} + \frac{T}{J}$$

$m_{ij} + r_{ij} \leqslant 1$

x_{ij} and y_{ij} must be positive and r_{ij} and m_{ij} must be binomial

$\lambda_i \beta_i \alpha_i \tau_i \delta_i$ are belong to different scenario (9)

5. The Multi Objective Optimization Problem

The purpose in the multi objective optimization problem is to compute the vector of decision variables in a manner that it optimizes the objectives considering feasible state.

$$Minf(x) = \{f_1(x), f_2(x), , f_m(x)\}$$
$$Subjectto: \quad x \in X$$

Vector $x(x_1, x_2, ..., x_n), X, f_i$ represent the vector of variables, feasible state and i the objective function respectively.

In multi objective problems we can rarely find a vector which optimizes all of objectives at a time, therefore in this type of problem, we deal with efficient solutions. For two points in 2-dimensional space, point (x_i, y_i) dominates (x_i, y_i) if $x_i > x_j$ and $y_i > y_j$. Given a set of points, a maximum is a point that is not dominated by any other point in the set. These points are sometimes called Pareto optimal (assuming larger values are better), and the set of maxima called the Pareto set. A design vector x* is a Pareto optimum if and only if, for any x and i,

$$f_j(x) \leqslant f_j(x^*), \quad j = 1, ..., m; \quad j \neq i \rightarrow f_i(x) \geqslant f_i(x^*)$$

Global criterion method is a common method in multi objective problem to calculate the Pareto solution. This technique minimizes the sum weighted distance from the each objective to an ideal solution to find the optimal solution as in 10. Clearly this method transforms the multi objective problem to a single objective problem and solves it using common method in this type of problem.

$$Min\ D = \sum_{i=1}^{m} u_i \left(\frac{f_i^* - f_i}{f_i^*}\right)^p$$
$$\text{Subject to:} \quad x \in X \tag{10}$$

f_i^* And u_i represent the optimum value and the weight of $i'th$ objective respectively. in this paper $p = 2$ and $u_1 = u_2 = 0.5$, therefore equation 11 is obtained.

$$Min\ D = \frac{1}{2}(\frac{c^* - c}{c^*})^2 + \frac{1}{2}(\frac{Rel^* - Rel}{Rel^*})^2$$

Subject to:

$$x_{i1} = 1$$

$$x_{i,j} + 1 = \alpha_i y_{i,j} = x_{i,j} + r_{ij} T_{r,i} + m_{ij} T_{m,i} + \frac{T}{J}$$

$$m_{ij} + r_{ij} \leqslant 1$$

x_{ij} and y_{ij} must be positive and r_{ij} and m_{ij} must be binomial

$\lambda_i \beta_i \alpha_i \tau_i \delta_i$ are belong to different scenario (11)

6. Numerical Example

In an industrial unit in order to avoid sudden failures of production systems and improve availability of system, manager of maintenance department proposed a preventive maintenance scheduling program. In this industry the machines are covered by engineering insurance. Due to uncertainty in the input parameters, the parameters are chosen from three scenarios, which are illustrated in tables 1, 2 and 3. To solve the scheduling problem a genetic algorithm is developed and the results are shown in tables 4, 5, 6 and 7. Details of proposed genetic algorithm are illustrated in the next section. The steps of the proposed genetic algorithm are as follows 1. The decision variables in this paper are shown in a matrix with 4 rows and 24 columns. Number of rows shows the number of machines and number of columns shows the number of segments in each time interval. 1.1. Generate 10 chromosomes in which the value of each gen is chosen randomly considering the constraints as in 11 2. Compute fitness function as in 11 3. After the selection the chromosomes with best fitness function, the crossover operator is performed as follow: 3.1. A random crossover point is selected between 1 and 24. The first part of the first parents is hooked up with the second part of the second parent to make the first offspring. The second offspring is built from the first part of the second parent and the second part of the first parent. 4. Mutation operator with rate of 0.1 and type of non-uniform is performed. 5. After 100 iteration the algorithm is stopped.

In order to illustrate the effect of engineering insurance on preventive maintenance scheduling, this scheduling is performed under third scenarios considering and ignorance the effect of engineering insurance in objective functions. Results are shown in tables 8 and 9.

Table 1. Input parameters under first scenario

component	λ_i	β_i	α_i	τ_i	δ_i
I	0.000348	2.4	0.787401	0.8	0.1
II	0.000387	2	0.761577	0.8	0.1
III	0.000395	2.1	0.74162	0.8	0.1
IV	0.000384	1.8	0.707107	0.8	0.1

Table 2. Input parameters under second scenario

component	λ_i	β_i	α_i	τ_i	δ_i
I	0.000274	2.6	0.687356	0.7	0.15
II	0.000294	2	0.672684	0.7	0.15
III	0.000297	2.15	0.661174	0.7	0.15
IV	0.000292	1.7	0.640896	0.7	0.15

Table 3. Input parameters under third scenario

component	λ_i	β_i	α_i	τ_i	δ_i
I	0.000316	3.8	0.687356	0.8	0.2
II	0.000339	3	0.672684	0.8	0.2
III	0.000343	3.2	0.661174	0.8	0.2
IV	0.000337	2.6	0.640896	0.8	0.2

Table 4.Optimum preventive maintenance scheduling under scenario1

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
I	-	-	R	-	-	-	R	-	-	-	-	M	-	-	-	-	-	-	M	-	-	-	-	R
II	-	-	-	-	M	-	-	M	-	-	M	-	-	-	-	M	-	-	-	R	-	-	R	-
III	R	-	-	R	-	-	-	-	R	-	-	-	M	-	-	-	-	R	-	-	-	-	-	R
v	-	-	-	R	-	R	-	-	-	-	R	-	-	R	-	-	-	-	-	M	-	-	-	-

Table 5.Optimum preventive maintenance scheduling under scenario2

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
I	-	-	M	-	-	R	-	-	M	-	-	-	-	-	M	-	-	-	R	-	-	-	-	-
II	-	-	-	-	R	-	-	-	-	-	R	-	-	-	-	R	-	-	-	-	-	-	M	-
III	-	-	M		-	-	-	-	-	M	-	-	-	-	-	R	-	-	-	-	M	-	-	R
v	M	-	-	-	-	-	-	R	-	-	R	-	-	R	-	-	-	-	-	R	-	-	-	-

Table 6.Optimum preventive maintenance scheduling under scenario3

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
I	-	-	R	-	-	-	R	-	-	-	-	-	R	-	-	R	-	-		R	-	-	-	R
II	-	-	-	M	-	-	-	R	-	-	-	M	-	-	-	-	-	R	-	R	-	-	M	-
III	-	-	-	R	-	R	-	-	-	-	R	-	-	R	-	-	-	-	-	M	-	-	-	-
v	R	-	-	-	-	-	-	-	M	-	-	-	-	-	-	R	-	-	-	-	-	-	-	R

Table 7. Optimum costs and reliability under the different scenarios

Cost/scenarios	Failure cost	Maintenance cost	Replacement cost	Total reliability
Scenario 1	250	40	330	0.9787
Scenario 2	200	30	400	0.9856
Scenario 3	320	60	480	0.975

Table 8.Optimum maintenance scheduling under scenario3 (ignoring the effect of engineering insurance)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
I	-	-	-	-	-	-	R	-	-	-	-	-	-	R	-	-	-	-	-	-	-	M	-	-
II	-	-	-	R	-	-	-	-	-	-	-	M	-	-	-	-	-	-	-	R	-	-	-	-
III	-	-	-	-	-	R	-	-	-	-	R	-	-	-	-	-	R	-	-	-	-	-	-	M
v	-	R	-	-	-	-	-	-	R	-	-	-	-	-	-	-	-	-	M	-	-	-	-	-

Table 9. Optimum costs and reliability of preventing maintenance considering and ignoring the effect of engineering insurance

Cost/scenarios	Failure cost	Maintenance cost	Replacement cost	Total reliability
Considering the effect of engineering insurance	320	60	480	0.975
Ignoring the effect of engineering insurance	980	750	1500	0.8943

7. Conclusion

Maintenance plays a key role in minimizing equipment downtime, improving quality and increasing productivity. Preventive maintenance is a broad term that encompasses a set of activities aimed at improving the overall reliability and availability of a system. This paper explores an industrial unit which encompasses 4 machines and proposed a maintenance scheduling. The objective functions for this scheduling was total cost and total reliability of system. Despite of previous researches total cost of system is modeled considering engineering insurance. After that, a numerical example is solved in which the cost parameters are considered not deterministic, therefore; a robust model of maintenance is proposed. To compute the optimal results, first the multi objective is transformed to single objective using global criterion method; then the genetic algorithm is used and Pareto optimal solution are computed. Finally the effect of engineering insurance is investigated on the optimal preventive maintenance and replacement scheduling. Results show that engineering insurance affects the optimal maintenance scheduling seriously, therefore ignorance of engineering insurance in maintenance scheduling problem lead to inefficient scheduling plan. In future researches the effect of preventive maintenance on premium of insurance can be investigated.

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