57º SBPO
SIMPÓSIO BRASILEIRO DE PESQUISA OPERACIONAL
Gramado • RS
DE 5 A 9 DE OUTUBRO DE 2025

MULTI-OBJECTIVE OPTIMIZATION FOR PERIODIC MAINTENANCE PLANNING OF INDUSTRIAL EQUIPMENT IN CONTINUOUS SERVICE

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ABSTRACT

In industrial settings, production planning and machine downtime for maintenance are key factors in the search for more robust, reliable, and economically viable processes, as they reduce unexpected failures, which lead to costly production interruptions for the industry. Mathematical models based on periodic maintenance problems can support operational decisions in which equipment must operate continuously, but preventive maintenance shutdowns must be scheduled. In this sense, balancing maintenance costs and reliability is essential to provide a system for which maintenance should be planned carefully to avoid penalties related to machine shortage. Thus, this study presents a multi-objective mathematical model that minimizes maintenance and penalty costs associated with production interruption due to machine shortage over a 52-week time horizon. Results indicated effective solutions by reducing maintenance costs while eliminating penalties. Therefore, the proposed model is a promising tool to support decisions in planning the periodic maintenance for equipment in continuous service.

KEYWORDS. Industrial maintenance. Periodic maintenance. Preventive maintenance. Multi-objective.

Paper topics. Operations and maintenance planning. Optimization in industrial systems. Multi-objective optimization. Decision support.

DOI: 10.59254/sbpo-2025-212458
https://proceedings.science/p/212458?lang=pt-br

1. Introduction

In today's industrial outlook, where production costs and market competitiveness continuously increase, companies are under constant pressure to optimize their processes to remain viable. Maintenance planning for industrial equipment is a key factor in achieving robust, reliable, and economically efficient operations, as it helps to mitigate equipment degradation and reduce the probability of unexpected failures leading to costly production interruptions [Assis et al., 2022].

In the literature, studies addressing periodic maintenance problems are typically classified based on the nature of their objective function. Reliability-based minimization approaches are concerned with system availability and operational demand. On the other hand, economically driven approaches focus on reducing operational and maintenance costs. Additionally, some studies adopt multi-objective approaches to optimize both system reliability and associated costs simultaneously [Froger et al., 2016].

The balance of costs and system reliability is crucial in operations where equipment must operate continuously to meet factory demand, and maintenance shutdowns must be scheduled carefully to avoid penalties related to production downtime. In this sense, it is essential to identify the best periods for performing preventive maintenance without compromising system reliability while ensuring minimal operating and maintenance costs. Despite the importance of this trade-off, few studies have addressed multi-objective models that minimize conflicting goals such as maintenance costs and system reliability.

Therefore, this study aims to investigate the optimization of periodic maintenance planning for industrial equipment operating under continuous production conditions. A multi-objective mathematical model is designed to minimize maintenance-related costs and penalties associated with equipment downtime that prevents the system from meeting minimum production requirements. The problem was formulated as a mixed-integer programming (MIP) model, implemented in Python, and solved using the Gurobi optimizer, employing the hierarchical approach. The main contributions of this study are the development of a model that supports decisions in operational and maintenance planning, aiming to reduce maintenance costs while increasing system reliability and supporting decision-making in a complex industrial environment.

2. Problem Description

The problem involves the weekly planning of preventive maintenance of industrial machinery over a 52-week time horizon in a factory with dozens of machines operating continuously to meet production demand. Machine shutdowns must respect a minimum number of operational units to avoid reduction in production and consequently penalties for unmet demand. These minimum operational units vary weekly according to the factory demand (Tables 5 and 6). Maintenance activities are limited by the factory's internal capacity, with the option to create additional maintenance positions by outsourcing excess work at a higher cost.

The factory operates with different types of machines, categorized according to size and structure: small, medium, and large. Each type requires distinct maintenance operations, varying in tasks, cost, allowable intervals between maintenance, and execution time. The model considers three maintenance types: routine, intermediate, and deep (Table 2).

Routine maintenance involves simpler maintenance tasks such as minor repairs, cleaning, and lubrication, while intermediate maintenance includes these routine activities with more complex procedures, such as replacing heavier components and conducting more detailed inspections. Finally, deep maintenance requires all activities from routine and intermediate maintenance, in ad-

DOI: 10.59254/sbpo-2025-212458
https://proceedings.science/p/212458?lang=pt-br

dition to more comprehensive procedures such as replacing large or hard-to-access components (Table 2).

Finally, the objective is to minimize total maintenance costs while ensuring a minimum operational level of machines to meet production demands. The optimization model is intended to support the industry's weekly planning decisions, which include determining the number of machines in operation and under maintenance, and assessing whether additional maintenance capacity is needed to meet the required maintenance schedule.

3. Mathematical model

The mathematical model proposed by Grigoriev et al. [2006] is the inspiration for the formulation developed in this study to address the Periodic Maintenance Problem (PMP). The linearized version of the model from Grigoriev et al. [2006] is presented as follows.

Sets
I: machines in the system operation, $i \in I = \{1, 2, ..., I\}$.
T: time periods of the planning horizon (weeks), $t \in T = \{1, 2, ..., T\}$.

Parameters
α: maintenance delayed costs.
b_i: cost of maintenance i.

Variables
$X_{i,t}$: number of periods t since last maintenance of the machine i.
$Y_{i,t}$: binary that takes value 1 if maintenance is performed on machine i in period t, and 0 otherwise.

$$Minimize: \sum_{i}^{I}\sum_{t}^{T}(\alpha\, X_{i,t} \;+\; b_i\, Y_{i,t}) \tag{1}$$

$$X_{i,t+1} \geq X_{i,t} + 1 - N(Y_{i,t+1}) \quad \forall\, i \in I,\; t \in T \setminus |T| \tag{2}$$

$$X_{i,1} \geq X_{i,|T|} + 1 - N(Y_{i,1}) \quad \forall\, i \in I \tag{3}$$

$$\sum_{i}^{I} Y_{i,t} \leq 1 \quad \forall\, t \in T \tag{4}$$

$$X_{i,t} \in \mathbb{Z}^{+} \quad \forall\, i \in I,\; t \in T \tag{5}$$

$$Y_{i,t} \in \{0, 1\} \quad \forall\, i \in I,\; t \in T \tag{6}$$

Expression (1) defines the objective function, which minimizes both the deterioration costs due to lack of maintenance and the direct costs associated with performing maintenance activities. Expressions (2) and (3) establish the cyclic maintenance scheduling for the variables $Y_{i,t}$, where N is a sufficiently large number. Finally, Expression (4) imposes a capacity constraint on the execution of maintenance activities.

DOI: 10.59254/sbpo-2025-212458
https://proceedings.science/p/212458?lang=pt-br

While the original formulation by Grigoriev et al. [2006] addresses machine delays and maintenance costs, this research builds upon that foundation by introducing additional objectives: penalty costs associated with the allocation of extra maintenance resources and penalty costs arising from machine shortages. Furthermore, new constraints are incorporated, including the maximum allowable interval between maintenance actions, weekly maintenance maximum capacity, and minimum machine availability requirements to ensure system reliability. Unlike Gregoriev's model, the proposed formulation also distinguishes between different types of maintenance activities.

A multi-objective mathematical model was considered since the model consists of conflicting objectives. The first term (f_1) of the objective function (OF) refers to **maintenance delay costs** [Equation (7)]. The second term (f_2) corresponds to the **direct maintenance costs** of the machines [Equation (8)]. The third term (f_3) and the fourth one (f_4) of the OF account for the **penalty costs associated with additional maintenance positions** [Equation (9)] and **penalty costs due to machine shortages** in system operation [Equation (10)], respectively.

Sets

M: type of maintenance, $m \in M = \{1, 2, ..., M\}$.
I: machines in the system operation, $i \in I = \{1, 2, ..., I\}$.
T: time periods of the planning horizon (weeks), $t \in T = \{1, 2, ..., T\}$.
V_i: subset of type of machines (machine group), $v \in V_i = \{1, 2, ..., V_i\}$.

Parameters

α: maintenance delayed costs.
b_m: cost of maintenance m, regardless of machine type.
c_m: penalty cost for opening additional positions of maintenance m.
ϵ: penalty cost for machine shortage in system operation.

Variables

$X_{m,i,t}$: number of periods t since last maintenance m of the machine i.
$Y_{m,i,t}$: binary variable takes the value 1 if maintenance m is performed on machine i in period t, and 0 otherwise.
$Q_{m,t}$: number of additional positions opened for maintenance m in the period t, regardless of the machine type.
$W_{m,v,t}$: number of additional positions opened for maintenance m in the period t for each type of machine v.
R_t: number of machine shortages in system operation during the period t, regardless of the machine type.
$S_{v,t}$: number of machine shortages in system operation during the period t for each type of machine v.

$$f_1 = \sum_{m}^{M} \sum_{i}^{I} \sum_{t}^{T} \alpha \, X_{m,i,t} \tag{7}$$

$$f_2 = \sum_{m}^{M} \sum_{i}^{I} \sum_{t}^{T} b_m \, Y_{m,i,t} \tag{8}$$

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https://proceedings.science/p/212458?lang=pt-br

$$f_3 = \sum_{m}^{M} \sum_{t}^{T} c_m(Q_{m,t} \ + \ \sum_{v}^{V_i} W_{m,v,t}) \tag{9}$$

$$f_4 = \sum_{t}^{T} \epsilon(R_t \ + \ \sum_{v}^{V_i} S_{v,t}) \tag{10}$$

Expression (11) represents the whole objective function of the problem, where variables $\mathbf{X}$ lie within the feasible region S. Using the Gurobi multi-objective priority function, it was possible to prioritize each objective differently, allowing a sort of hierarchical optimization, from highest to lowest priority. Several scenarios with different priority settings were tested, as shown in Table 4, where higher arguments provide a higher priority order to the objective term. Experiments were conducted on an instance with 16 machines over a 52-week time horizon. The Gurobi v11.0.3 solved the model on hardware with processor Intel(R) Core(TM) i5-7200U CPU at 2.50 GHz with 8 GB of RAM.

$$\begin{aligned} &minimize \ \{f_1(\mathbf{X}), \ f_2(\mathbf{X}), \ f_3(\mathbf{X}), \ f_4(\mathbf{X})\} \\ &subject \ to \ \mathbf{X} \ \in \ S \end{aligned} \tag{11}$$

4. Case study

The instances considered for this study are presented in Table 1 and were collected from a collaborating company with this study. A small instance with 16 machines and a planning period of 52 weeks was considered to evaluate better the results obtained from the optimization.

Table 1: Machine parameters.

	Machines			Total
	Small	Medium	Large	
Number of machines	3	11	2	16
RM capacity	2	1	1	4
IM capacity	2	1	1	2
DM capacity	1	1	1	2

RM: Routine Maintenance;
IM: Intermediate Maintenance;
DM: Deep Maintenance.

The parameters associated with the maintenance area are presented in Table 2, where the tasks corresponding to each type of maintenance are indicated with an 'X'. At the start of the time horizon for this problem ($t = 0$), the machines have a recorded history of the number of weeks since their last maintenance stop (Table 3). This information is incorporated into the mathematical model through fixing values to variable $X_{m,i,t}$ in $t = 0$.

The parameter α associated with maintenance delay cost, also interpreted as equipment degeneration cost, was set to a unit value solely to account for the corresponding term in the objective function, since in practice α varies depending on the machine's model and its age and it is not

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https://proceedings.science/p/212458?lang=pt-br

Table 2: Parameters of maintenance area.

Maintenance type	Maximal Interval (weeks)	Costs	Duration (weeks)	Tasks of Routine maintenance	Tasks of Intermediate maintenance	Tasks of Deep Maintenance
Routine	15	$ 250.00	0.5	X		
Intermediate	50	$ 2000.00	1	X	X	
Deep	90	$ 7500.00	3	X	X	X

Table 3: Historical record at the start of the planning horizon ($t = 0$) for the number of weeks since last maintenance ($X_{m,i,0}$).

Machine #	**Weeks since last deep**	**Weeks since last intermediate**	**Weeks since last routine**
1 - small	75	39	2
2 - small	87	28	10
3 - small	2	2	2
4 - medium	2	2	2
5 - medium	1	1	1
6 - medium	88	29	11
7 - medium	2	2	2
8 - medium	50	1	1
9 - medium	16	16	3
10 - medium	17	17	4
11 - medium	18	18	5
12 - medium	19	19	6
13 - medium	82	41	3
14 - medium	80	40	2
15 - large	1	1	1
16 - large	42	1	1

easy to be measured accurately. Regarding the scenarios presented according to the priority order of each objective function component (Table 4), they were designed from a management perspective, aiming to help decision makers explore which objective terms it is desirable to work with a higher prioritization over others.

5. Results

5.1. Multi-objective approach outputs

The results show that Scenario 5, single objective function without hierarchical prioritization, presented more promising solutions compared to other scenarios (Table 4). Scenario 5 resulted in more coherent solutions from a managerial point of view, as there were no penalties related to machine shortage in operation and the opening of new maintenance positions, in addition to presenting the best balance between direct maintenance costs and maintenance delay costs.

In a 16-machine and 52-week instance, Gurobi solved Scenario 5 in optimality within a resolution time of 240 seconds. On the other hand, the solver had trouble dealing with the scenarios

DOI: 10.59254/sbpo-2025-212458
https://proceedings.science/p/212458?lang=pt-br

where the optimization should follow a prioritization order of the objective function terms, unable to prove the optimal solution after a significant time resolution (Table 4).

Table 4: Multi-objective solutions of scenarios with different priorities assigned to each objective term.

	:: Obj. term 1		:: Obj. term 2		:: Obj. term 3		:: Obj. term 4		::	
Scenarios	Solution	P.O.	Solution	P.O.	Solution	P.O.	Solution	P.O.	Opt.	R. time (s)
Scenario 1	71,188	0	78,500	3	0	2	80,000	1		5,000
Scenario 2	47,200	0	79,000	1	0	1	0	1	✓	3,820
Scenario 3	208	1	1,976,000	0	13,520,000	0	23,120,000	0	✓	162
Scenario 4	46,721	1	78,500	2	280,000	0	550,000	0		5,000
Scenario 5	46,691	0	79,250	0	0	0	0	0	✓	240

Obj. term 1: maintenance delay costs; Obj. term 2: direct maintenance costs; Obj. term 3: penalty costs associated with additional maintenance positions; Obj. term 4: penalty costs due to machine shortages; P.O.: Priority order.; Opt.: Optimality is achieved?; R. time: Solver resolution time

Scenario 3 presented the worst solutions. When the objective function term associated with maintenance delay costs was assigned the highest priority in the optimization hierarchy, its minimum value was obtained (Table 4). Consequently, the model planned maintenance for all machines in all periods. In the subsequent optimization of the objective terms with lower priority levels (objective terms 2, 3, and 4), subject to the solution of the first optimization, it was not possible to converge to a solution with reduced maintenance costs or penalties for machine shortage in operation and the opening of extra maintenance positions.

Although both Scenario 2 and Scenario 5 resulted in effective solutions, their computational performance was lower, as the model required approximately 4,000 seconds to converge to an optimal solution. For scenario 2, the prioritization strategy was to initially optimize objective function terms 2, 3, and 4 jointly, followed by optimization of objective term 1, subject to constraints defined by the solution of the first optimization. The first optimization was easily solved in a few seconds (6 seconds), whereas the second optimization required more time (3,812 seconds) to converge.

Scenarios 1 and 4 did not achieve optimality. For Scenario 1, the optimization of the objective function term 4, constrained by the solutions of objective terms 2 and 3, showed no progress toward a feasible solution. In other words, the optimization of objective term 4 did not reach optimality, and the solver could not initiate the optimization of objective term 1, constrained by the previously obtained solutions for objective terms 2, 3, and 4. Consequently, the solution for objective term 1 resulted in the highest machine deterioration costs ($ 71,188) compared to the other scenarios.

Further analyzing the outputs from Scenarios 1 and 4 (Table 4), it is evident that they achieved the lowest maintenance costs ($78,500); however, they also incurred penalties. From this perspective, it is not advantageous for an industry to minimize maintenance costs if it results in penalties due to outsourced maintenance or insufficient machines in the system to meet factory demand. In contrast, Scenario 5 reached a slightly higher maintenance cost compared to the minimum observed in Scenarios 1 and 4, but it achieved the lowest deterioration-related costs (objective term 1) and incurred no penalties (objective terms 3 and 4).

Therefore, since the authors of this study aim to experiment with instances involving a larger number of machines and a longer time horizon, it is advisable to adopt the approach used in Scenario 5, where a single objective function was considered. This method yielded good results and is simpler to manage.

DOI: 10.59254/sbpo-2025-212458
https://proceedings.science/p/212458?lang=pt-br

5.2. Maintenance planning outputs

The analysis of the equipment maintenance planning over 52 weeks obtained from the solution of Scenario 5 shows promising potential to support effectively the decision making. The maintenance plans present in Tables 5 and 6, were designed to facilitate the visualization by the industry team. This format allows decision-makers to view the entire plan on a single page and more easily extract insights from the proposed solution.

In this study, Tables 5 and 6 represent the maintenance plan from weeks 1 to 26 and from weeks 27 to 52, respectively. Cells labeled with the letter "O" indicate that the machine is in operation ($Y_{m,i,t} = 0$), while cells labeled "RM," "IM," and "DM" indicate that the machine is undergoing routine maintenance ($Y_{1,i,t} = 1$), intermediate maintenance ($Y_{2,i,t} = 1$), and deep maintenance ($Y_{3,i,t} = 1$), respectively. The final row displays the parameter associated with the minimum machine demand required for each period.

Table 5: Maintenance plan output from Scenario 5. To be continued in Table 6.

	Week																								
Machine #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
1 - Small	O	O	O	O	DM	DM	DM	O	O	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O
2 - Small	DM	DM	DM	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O
3 - Small	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	IM	O
4 - Medium	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	IM	O
5 - Medium	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O
6 - Medium	DM	DM	DM	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O
7 - Medium	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O	IM
8 - Medium	O	O	O	O	O	O	O	O	O	O	O	O	DM	DM	DM	O	O	O	O	O	O	O	O	O	O	O
9 - Medium	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	IM	O	O
10 - Medium	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	IM	O	O	O
11 - Medium	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O	IM	O	O	O	O
12 - Medium	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	IM	O	O	O	O	O
13 - Medium	O	O	O	O	DM	DM	DM	O	O	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O
14 - Medium	O	O	O	O	O	O	O	DM	DM	DM	O	O	O	O	O	O	O	O	O	O	O	O	O	O	RM	O
15 - Large	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O	O
16 - Large	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	DM	DM	DM	O	O	O	O	O	O
Machine demand	8	11	12	16	9	10	12	11	12	11	14	10	9	8	11	12	16	9	10	12	11	12	11	14	10	9

O: In operation; RM: Routine maintenance; IM: Intermediate Maintenance; DM: Deep maintenance.

Table 6: Maintenance plan output from Scenario 5. Continuation of Table 5.

	Week																								
Machine #	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**
1 - Small	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O	O
2 - Small	RM	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O
3 - Small	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O
4 - Medium	O	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O
5 - Medium	IM	O	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O
6 - Medium	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O
7 - Medium	O	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O
8 - Medium	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O
9 - Medium	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O
10 - Medium	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O	O
11 - Medium	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
12 - Medium	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
13 - Medium	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O	O
14 - Medium	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O	O
15 - Large	IM	O	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	O
16 - Large	O	O	O	O	O	RM	O	O	O	O	O	O	O	O	O	O	O	RM	O	O	O	O	O	O	O	O
Machine demand	8	11	12	16	9	10	12	11	12	11	14	10	9	8	11	12	16	9	10	12	11	12	11	14	10	9

O: In operation; RM: Routine maintenance; IM: Intermediate Maintenance; DM: Deep maintenance.

The presented solution shows that the maximum intervals between maintenance are respected. The maintenance quantities that the factory supports were also not violated, and it was not necessary to perform external maintenance, as demonstrated by the solution of objective term 3 (Table 4). The model also respected the minimum demand for machines operating in the system,

DOI: 10.59254/sbpo-2025-212458
https://proceedings.science/p/212458?lang=pt-br

making it more evident for weeks 4, 17, 30, and 43, which did not program the maintenance for any machines once these periods require full operation.

One aspect that should be analyzed in future studies is the absence of maintenance operations during the last weeks (weeks 45 to 52). Another pertinent observation is that deep maintenance for some machines was planned significantly earlier than the maximum allowable interval. For instance, deep maintenance for machine 8 was scheduled only 62 weeks after its previous maintenance, even though the maximum permitted interval was 90 weeks.

From a management perspective, a better distribution of maintenance activities was expected, which would create idleness in the maintenance area toward the end of the analyzed horizon. Regarding deep maintenance, it was also expected that these activities would be postponed to periods closer to the maximum allowable period since the last maintenance. One of the main reasons for these issues is related to the objective term 1, which aims to minimize maintenance delays and may result in maintenance being conducted earlier than the maximum allowable.

Despite the simplifications, the model proposed here for this problem successfully achieved the objective of determining the optimal number of machines operating and undergoing maintenance, aiming to minimize maintenance costs and penalty costs associated with machine shortages.

6. Conclusion

The model developed for planning the periodic maintenance of industrial equipment in continuous operation has shown promise as a decision-support tool for managing machine shutdowns, helping to prevent production interruptions caused by equipment shortages.

Scenario 5, which does not assign any prioritization order to the objective function and no hierarchical optimization is necessary, presented the best results, in addition to being a simpler scenario to handle. Although scenario 5 did not achieve the lowest maintenance cost, its cost was very close to the best solution obtained for other scenarios. Moreover, it eliminated penalty costs related to machine shortage and outsourced maintenance.

After selecting the best approach, the operational and maintenance plan was analyzed. The model helps decision-makers determine the optimal number of machines to stop for maintenance and keep in operation, minimizing both maintenance and shortage penalty costs.

The model can be considered a promising formulation to solve periodic maintenance problems. For future studies, the authors will evaluate the model's limitations and incorporate to solve bigger and more complex instances.

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DOI: 10.59254/sbpo-2025-212458
https://proceedings.science/p/212458?lang=pt-br

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DOI: 10.59254/sbpo-2025-212458
https://proceedings.science/p/212458?lang=pt-br