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Optimal management of vegetation maintenance and the associated costs of its implementation in overhead power distribution systems

Gestión óptima del mantenimiento de la vegetación y los costos asociados de implementación en sistemas aéreos de distribución

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Abstract

Network operators work constantly to maintain an appropriate level of reliability in their power supply and to preserve the integrity of the vegetation growing underneath overhead power distribution systems. Accordingly, this article proposes and adopts different approaches to optimally manage vegetation maintenance in such field. Mathematical modeling is used to represent the problem in terms of several aspects involved in vegetation management, based on the technical capacity of the utility company and the reliability goals established by governmental regulatory entities. The solution is a vegetation maintenance schedule in terms of when, where, and which crews must perform the pruning activities along the distribution network. As a result, the Non-Served Energy Level NSEL is minimized and the financial resources earmarked for this type of maintenance tasks are optimized.

Keywords

Distribution system, failure rate, growth rate, Non-Served Energy Level, vegetation maintenance.

Resumen

Los operadores de red están constantemente trabajando en mantener un nivel de confiabilidad apropiado en el suministro de energía y preservar la integridad de la vegetación que crece bajo las redes aéreas de distribución de energía. Por tal razón, en este artículo se proponen e implementan diferentes alternativas para gestionar de manera óptima el mantenimiento de la vegetación. El problema se representa a través de modelamiento matemático, en función de varios aspectos enmarcados en el manejo de la flora, basados en la capacidad técnica de la empresa y las metas de confiabilidad estipuladas por los organismos gubernamentales. En la solución del problema, se obtiene un programa de mantenimiento de la vegetación en términos de cuándo y dónde se debe realizar éste, además de la asignación de los grupos de trabajo destinados para las labores de poda a lo largo del sistema de distribución. De esta manera, se minimiza el nivel de energía no servida y se optimizan los recursos financieros necesarios para este tipo de tareas.

Palabras clave

Sistema de distribución, tasa de falla, tasa de crecimiento, nivel de energía no servida, mantenimiento de la vegetación.

NOMENCLATURE

$NSEL$	Non-Served Energy Level.
T	Planning period to perform the vegetation maintenance. In this case, 4 subperiods are used for $T = 1$ year.
NS	Total number of network segments to be considered in the vegetation maintenance schedule.
$U(i,t)$	Unavailability during subperiod t in network segment i.
$AD(i,t)$	Average demand in network segment i of subperiod t.
$\gamma(i,t)$	Binary decision variable that takes a value of *"1"* when a maintenance activity has to be performed in network segment i of subperiod t, and *"0"* otherwise.
ΩDS	Set of network segments downstream network segment i.
$C_{main}(i,j,t)$	Vegetation maintenance cost in network segment i, of crew j, in subperiod t [\$COP/m].
$l(i)$	Length of network segment i [m].
$L_{max}(t)$	Maximum length of pruning allowed in subperiod t [m]
$\lambda_{failure}(i,t)$	Failure rate in network segment i of subperiod t [failures/year].
$NC(i)$	Number of customers connected to the end node of network segment i.
TNC	Total number of customers in the network.
$SAIFI_{max}$	Maximum allowed quantity of power supply outages [failures/customer].
NP	Maximum number of pruning allowed in planning period T in a network segment.
$T_o(i,t)$	Time from the last vegetation pruning in network segment i of subperiod t [years].
$\lambda_{growth}(i,t)$	Vegetation growth rate in network segment i of subperiod t [m/year].
D_{min}	Minimum distance allowed between the overhead power lines and the vegetation [m].
IAP	Introduction average percentage of the vegetation to the security zone [%].
$NCrew$	Number of crews to perform the pruning works.
$\chi(i,c,t)$	Binary decision variable that takes a value of *"1"* if crew c performs the maintenance in network segment i in subperiod t, and *"0"* otherwise.
K	Proportion factor between the cost of $NSEL$ and pruning implementation costs [\$].
C_E	Cost of energy [\$COP/kWh].

1. INTRODUCCIÓN

The emergence of utility services such as water supply, sewage, electricity, and telecommunications has brought to the cities a complex system of wires and pipelines that must live together with the urban vegetation. The latter provides relief to the environment of metropolitan centers, which are often immersed in visual, noise and air pollution.

From the point of view of power energy supply, utility companies have had to face different difficulties related with preserving a suitable level of reliability in the power network and performing vegetation maintenance without compromising the physical integrity of the vegetal species [1].

Due to their low cost in comparison to other configurations, power distribution networks are, in most cases, of the overhead type. However, because of external factors related with the weather, animals, and vegetation, their reliability indices are lower than those of underground networks. The contact of a plant with the energized wires can cause short circuits (in the worst cases, broken wires) and an imminent activation of the protection systems. This event represents one of the main causes of power supply interruptions [2] [3].

In general, the network operator in charge of the system performs vegetation maintenance. Traditionally, a group of workers carries out a visual inspection along the power network to determine which network segments are susceptible to vegetation contact. Subsequently, vegetal species are pruned considering the most suitable method to preserve the physical integrity of the plant [4]. These procedures can have satisfactory results from the point of view of the compliance with reliability goals; furthermore, better results can be obtained if the methodologies are derived from mathematical modeling, considering different objectives, reliability indices, and technical constraints.

In the specialized literature, few works deal with vegetation maintenance underneath overhead power distribution lines. Generally, they present the following aspects for an efficient pruning schedule: historical failures, evolution of a failure caused by vegetation, duration of a maintenance cycle, reliability indices, time from the last vegetation pruning, network operator budget, Markov chains, etc. [5] [6] [7]. A criticality analysis of overhead power lines' assets based on decision support systems and risk management is proposed in [8] to improve preventive pruning programs. Additionally, the study in [9] presents the characteristics of leakage current of different vegetation flames and the effect of flame conductivity on wire-plate gap breakdown characteristics.

Other works are focused on developing ways to monitor how close the trees are to the power distribution lines, considering inspections from the air and the ground with thermal cameras and satellite images [10] [11] [12]. An overview of modern remote sensing methods in power line corridor surveys is presented in [13], including synthetic aperture radar images, optical satellite and aerial images, thermal images, airborne laser scanner data, and unmanned aerial vehicles. The latter is particularly important in [14], as multi-rotor solutions are a viable technology option that should be incorporated into both preventive maintenance and damage assessment. From the perspective of satellite imagery, the authors of [15] establish some of the benefits of this technology for power line maintenance in forested areas: identifying individual trees growing near power lines, evaluating the height of vegetation in high voltage power line corridors, and detecting changes in corridors and surrounding areas. Some publications point out the relevance of smart methods, such as neural networks, for predicting the failure rate of distribution feeders caused by vegetation contact [16] [17]. Novel approaches in the framework of image processing were developed in [18], with a conceptual model of a computer vision system capable of identifying overhead urban lines and their three dimensional positioning to aid a teleoperated robot in pruning vegetation. Although their results are accurate and novel alternative solutions are developed, these methods require, in most cases, a high computational cost as well as expensive devices and software for image processing.

In turn, mathematical models have also been used to represent the vegetation maintenance problem through objective functions and a set of constraints, thus obtaining a result in terms of pruning schedules, where the maintenance cost is minimized or the reliability of the distribution network is maximized [19] [20]. Along the same line of research, the work proposed by [21] presents a methodology for long term maintenance scheduling of overhead lines considering feeders ranking for high accuracy investment. Such ranking is defined by the type of costumers, loads, length, and failure rates.

Compared with the works mentioned above, this paper proposes a feasible option that can be implemented, since the input data correspond to historical failures due to vegetation contact and/or vegetation growth rates, most often available in the database of the utility company. This work proposes four solution approaches, as an extension of the works developed by [19] and [20] for the optimal management of vegetation maintenance in overhead power lines, by using mathematical modeling. Each approach aims at minimizing the following aspects:

-Non served Energy Level (NSEL);

-Cost of implementation (CI) of the maintenance plan, in conjunction with the NSEL, using proportion factors;

-Cost of implementation of the maintenance plan; and

-NSEL with investment constraint. In this proposal, a set of solutions is obtained for pruning plans under a multi-objective context.

The solution to this problem is given in terms of a schedule of vegetation pruning activities and the moment at which each activity must be performed over planning period T. The effectiveness of the mathematical model is assessed by simulating, in a real system, what has been studied by other authors.

This article is organized as follows. Section 3 formulates the problem mathematically within the framework of four solution approaches. Afterward, Section 4 presents the real test system used in the computational implementations. Section 5 introduces the results to the problem based on the construction of a non-dominated solutions front and an improvement strategy to obtain better quality solutions.

2. MATHEMATICAL FORMULATION OF THE PROBLEM

Scheduling vegetation maintenance for distribution systems can be represented through a non-convex non-linear integer mathematical model, considering reliability metrics, implementation costs of activity scheduling, vegetation failure rates and growth rates, and the technical and financial capacity of the utility company, among others.

Such problem is formulated adopting four different approaches, thus obtaining four mathematical models, which are similar regarding constraints but different in terms of objective functions.

2.1 Model 1

In this model, the NSEL of the distribution system is minimized, considering the activity schedule obtained from the solution of the mathematical model, which is described in equations (1) to (6).

The objective function in (1) describes the *NSEL* that the distribution system will have over the planning period of vegetation pruning activities. The software NEPLAN was used to compute, offline, the energy not served downstream network segment i. Equations (2) and (3) are operating constraints that represent the available resources of the utility company to implement the maintenance plan of vegetation pruning. Such resources are limited by the number of crews, which have a determined capacity of linear meters of network that can be attended for vegetation pruning. The multiplication of the terms $l(i).\gamma(i,t)$ implies an increase in the pruned length when the binary variable $\gamma(i,t)=1$ (maintenance on the network segment). Otherwise, if $\gamma(i,t)=0$, no linear meters are added to the expression. The term $L_{max}(t)$ limits the allowed quantity of linear meters subject to pruning for each subperiod t. This resource can vary depending on the time of the year and availability of economic resources. Equation (3) limits the number of pruning activities that can be performed on a network segment over the planning period.

Equation (4) is a regulatory constraint that determines the quality indices of the utility company regarding power supply continuity. This index must be monitored and controlled to avoid economic penalties.

Equation (5) is the constraint that controls the Introduction Average Percentage (IAP) of vegetation in regards with the security zone, as shown in Fig. 1.

This value is determined via the product $T_o(i,t)\,.\lambda_{growth}(i,t)$, which is normalized by dividing by D_{min}, thus obtaining a percentage [%]. The variable $T_o(i,t)$, computed in (6), is controlled by $\gamma(i,t)$, and it determines the time elapsed since the last vegetation pruning on each network segment. Such time duration is accumulated every time that $\gamma(i,t)=0$. When $\gamma(i,t)=1$, $T_o(i,t)$ is reset. Table 1 proposes an example of the result of $T_o(i,t)$ according to the value of $\gamma(i,t)$.

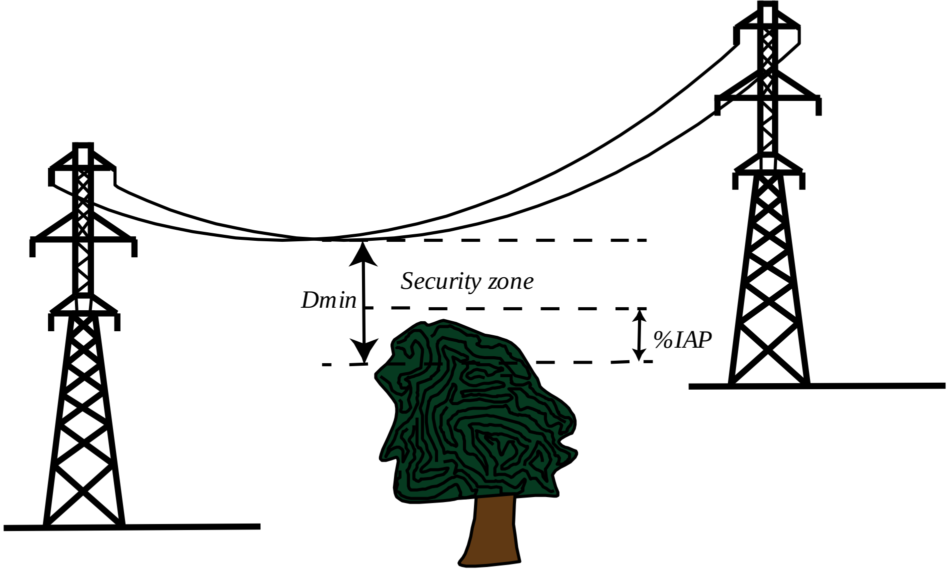

Fig. 1. Graphical description of the security zone.
Source: Authors' own work.

Table 1. Example of maintenance proposal on a network segment to calculate $T_o(i,t)$.
Source: Authors' own work.

Last pruning before the planning period	0.5	This value implies that, before the planning period, the time elapsed since the last pruning was 2 quarters, that is, 0.5 years.
$T_o(i,t_1)$	0	Due to that time, in this subperiod, there will not be pruning activity, that is, $\gamma(i,t_1)=0$. At this point, the time since the last pruning is 0.5+0.25=0.75 years.
$T_o(i,t_2)$	0	Because $\gamma(i,t_2)=0$, the time since the last pruning is 0.5+0.25+0.25 = 1 year.
$T_o(i,t_3)$	1	In this subperiod, the network segment will be pruned. This means that $\gamma(i,t_3)=1$, and the introduction percentage into the security zone is zero.
$T_o(i,t_4)$	0	In this case, $\gamma(i,t_4)=0$, the time since the last pruning is 0.25 years.

After the pruning schedule is obtained with the mathematical model described in (1) to (6), a mathematical programming problem, known as "assignment problem", is solved. Such problem delegates the activities to work teams (maintenance crews, workgroups, etc.) so that the cost of implementing these activities can be minimized (see (7)).

Equation (8) is an operating constraint, similar to (2), which limits the linear meters that each crew can prune. The multiplication of the terms $l(i).\chi(i,c,t)$ indicates an increase in pruned length, when $\chi(i,c,t)=1$; otherwise, when $\chi(i,c,t)=0$, there is no addition of linear meters, as this variable shows the network segments that will be pruned and the crew assigned to perform the task. The term $L_{max}(t)$ limits the allowed quantity of linear meters to be pruned in each subperiod t, which can vary depending on the time of the year and the availability of economic resources.

In (9), the models are combined when the binary variables $\chi(i,c,t)$ and $\gamma(i,t)$ take equal values for each network segment i of subperiod t, thus guaranteeing that the assignment of tasks is completed in accordance with the pruning plan and maintenance can only be assigned when required by the network segment.

2.2 Model 2

In this mathematical model, the costs associated with $NSEL$ and the implementation of pruning activities are minimized, focusing on a mono-objective function, which is expressed in (10). The implementation costs consider the work teams in charge of the activities.

Note that (10) has two conflicting objectives. In general, if the $NSEL$ cost is high, the cost of pruning implementation is low, and vice versa. The value of k represents the level of significance of the terms in the equation, which depends on the particular interests of the decision maker.

2.3 Model 3

In Model 3, only implementation costs of the pruning activities are minimized, subject to the same constraints in Model 2.

$$min\ (7)$$

Subject to:

Equations (2) to (6), (8), and (9).

$$\min NSEL = \sum_{t=1}^{T}\left[\sum_{i=1}^{NS}[U(i,t)]\left(\sum_{i\,\epsilon\,\Omega DS} AD(i,t)\right)\right]\left(1-\gamma(i,t)\right) \tag{1}$$

Subject to:

$$\sum_{t=1}^{T}\sum_{i=1}^{NS} l(i).\gamma(i,t) - L_{max}(t) \le 0 \tag{2}$$

$$\sum_{t=1}^{T}\gamma(i,t) \le NP \qquad i = 1,\ldots,NS \tag{3}$$

$$\left(\frac{1}{TNC}.\sum_{t=1}^{T}\sum_{i=1}^{NS}\lambda_{failure}(i,t).\left(1-\gamma(i,t)\right).NC(i)\right) \le SAIFI_{max} \tag{4}$$

$$\frac{\left(T_o(i,t)\,.\,\lambda_{growth}(i,t).100\right)}{D_{min}} \le IAP \quad i = 1,\ldots,NS \quad t = 1,\ldots,T \tag{5}$$

$$T_o(i,t) = \left(1-\gamma(i,t)\right).\left(T_o(i,t-1)+\left(\frac{1}{t}.\left(1-\gamma(i,t)\right)\right)\right) \tag{6}$$

$$min\sum_{t=1}^{T}\sum_{c=1}^{NCrew}\sum_{i=1}^{NS} C_{main}(i,c,t)\, l(i).\chi(i,c,t) \tag{7}$$

Subject to:

$$\sum_{i=1}^{NS}\chi(i,c,t).l(i) - L_{max}(t) \le 0 \quad c = 1,\ldots,NC \quad t = 1,\ldots,T \tag{8}$$

$$\sum_{c=1}^{NCrew}\chi(i,c,t) = \gamma(i,t) \quad i = 1,\ldots,NS \;\; y \;\; t = 1,\ldots T \tag{9}$$

$$min\left((1-K).C_E.\sum_{t=1}^{T}\left[\sum_{i=1}^{NS}[U(i,t)]\left(\sum_{i\,\epsilon\,\Omega DS} AD(i,t)\right)\right]\left(1-\gamma(i,t)\right)\right)\left(K.\sum_{t=1}^{T}\sum_{c=1}^{NCrew}\sum_{i=1}^{NS}[C_{main}(i,c,t).l(i).\chi(i,c,t)]\right) \tag{10}$$

Subject to:

Equations (2) to (6), (8), and (9).

After the solution is obtained under the conditions of this model, the *NSEL* is calculated in accordance with (1).

2.4 Model 4

In this case, the *NSEL* is minimized considering the operation constraints in all the models above. In summary, this model is represented as follows:

$$min\ (1)$$

Subject to:

Equations (2) to (6), (8), and (9).

In addition to its constraints, this model considers the implementation cost, limited by the availability of a resource, as shown in (11).

$$\sum_{t=1}^{T}\sum_{c=1}^{NCrew}\sum_{i=1}^{NS} C_{main}(i,c,t)\, l(i).\chi(i,c,t) \le CI_{disp} \qquad (11)$$

Where CI_{disp} is the implementation resources the utility company has available to perform the pruning activities in the planning period. In this case, Model 4 is fed the solutions provided by Models 1 and 3. In Model 1, a minimum value of *NSEL* and a high value of *CI* are obtained. Conversely, in Model 3, the value of *CI* is minimum and that of *NSEL* is high. That way, the maximum and minimum values of *NSEL* and *CI* are obtained. Afterward, Model 4 is executed for different values of *CI*, which are within the range of maximum and minimum values provided by Models 1 and 3. Therefore, Model 4 represents a multi-objective approach through an iterative process that provides a set of non-dominated solutions that consider a conflict of interests between *NSEL* and *CI*. Such process is depicted in Fig. 2.

Subsequently, based on the non-dominated solution front of this model, it is possible to improve most solutions obtained in the front. Thus, better quality maintenance schedules can be obtained by reducing both implementation costs and *NSEL* or one of them.

The improvement stage takes each solution in the front obtained in Model 4, and it evaluates them in the model of equations (7), (8), and (9).

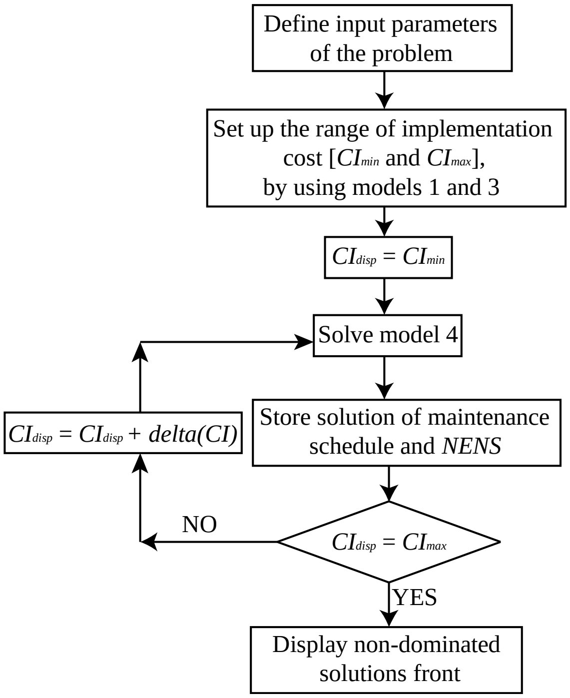

Fig. 2. Iterative process to form the non-dominated solution front. Source: Authors' own work.

3. TEST SYSTEM

In order to evaluate the mathematical models explained above, a real 34.5-kV distribution system, which can be requested from the authors, was used. Tables 2 to 5 were considered for the implementation of the mathematical approach.

Vegetation maintenance is planned over a period of one year, divided into 4 quarters, being $t = 1,..,4$. Table 2 presents failure rates associated with vegetation in each network segment of the distribution system, which have a growing behavior overtime. This trend represents a nonhomogeneous Poisson process; nevertheless, the statistical procedure to find the failure rates is out of the scope of this work. In this case, the reliability analysis module of NEPLAN [22] was used to find both the failure rates and the average demand of each network segment. The latter is based on the N-1 contingency criterion. Additionally, the network segment lengths and number of customers connected to the end node are presented in Table 2.

Unavailability $U(i,t)$ is computed from the failure rates using (12) to find the *NSEL*, given a maintenance proposal.

$$(i,t) = \frac{\lambda_{failure}(i,t).\overline{T_r}}{8760} \qquad (12)$$

Where $\overline{T_r}$ is the mean repair time of a failure, assumed to be 1.5 hours in accordance with [23]. Furthermore, it is necessary to include the average demand of each network segment (see Table 3) in the input data of the mathematical models.

Moreover, Table 4 lists the vegetation growth rates [24] with variations depending on the time of the year, due to environment factors that significantly influence this parameter.

The maintenance costs detailed in Table 5 correspond to the cost of vegetation pruning by a maintenance crew, considering the length of each network segment. A maximum number of three crews $c = 1, 2, 3$ and an invariant maintenance cost for each network segment over the planning period were assumed.

The following are other parameters considered in the development of the models:

$TNC = 70$ customers
$SAIFI_{max} = 7$ failures
$NP = 1$ pruning
$L_{max}(t) = 10000$ m
$IAP = 75\%$
$D_{min} = 1.5$ m
$C_E = 320$ COP/kWh

Table 2. Failure rates of each network segment. Source: Authors' own work.

Network segment i	Send node	End node	$\lambda_{rate}(i,t)$ [failures/year]				$l(i)$ [m]	$NC(i)$
			t_1	t_2	t_3	t_4		
1	1	2	3.22	3.55	3.93	4.34	3285	2
2	2	3	0.14	0.16	0.18	0.19	134	1
3	3	4	0.40	0.44	0.49	0.54	240	1
4	4	5	0.99	1.09	1.21	1.33	450	2
5	5	6	0.01	0.01	0.01	0.01	389	3
6	6	15	1.77	1.96	2.17	2.39	1768	7
7	2	7	0.19	0.21	0.23	0.25	144	4
8	4	8	0.90	1.00	1.10	1.22	536	2
9	8	9	0.65	0.72	0.79	0.87	778	1
10	8	10	0.29	0.32	0.35	0.39	773	1
11	5	11	1.22	1.35	1.49	1.65	640	2
12	12	12	1.04	1.15	1.27	1.41	497	3
13	6	13	2.71	3.00	3.31	3.66	1405	7
14	6	14	1.34	1.48	1.64	1.81	1889	21
15	15	16	2.60	2.88	3.18	3.51	1902	9
16	16	17	1.11	1.23	1.36	1.50	2514	4

Table 3. Average demand of each network segment. Source: Authors' own work.

Network segment i	$AD(i,t)$ [kWh]			
	t_1	t_2	t_3	t_4
1	878179	922088	851834	977413
2	283114	297270	274621	315106
3	170393	178913	165281	189647
4	862450	905573	836577	959907
5	2340937	2457984	2270709	2605463
6	4527210	4753570	4391393	5038784
7	3379023	3547974	3277653	3760853
8	972551	1021178	943374	1082449
9	254279	266993	246650	283012
10	188743	198180	183081	210071
11	367000	385350	355990	408471
12	1313336	1379003	1273936	1461743
13	4000302	4200317	3880293	4452336
14	4854888	5097633	4709242	5403491
15	4744788	4982028	4602445	5280949
16	3573009	3751660	3465819	3976759

Table 4. Vegetation growth rates of each network segment. Source: Authors' own work.

Network segment i	$\lambda_{growth}(i,t)$ [m/year]				T_o [years]
	t_1	t_2	t_3	t_4	
1	0.8033	1.0277	0.7532	0.9834	0.25
2	0.5776	0.9841	0.6104	1.1759	0.25
3	0.6862	1.0669	0.8905	0.9600	0.50
4	0.6792	1.1213	0.5870	1.1333	0.75
5	0.8262	1.0117	0.6550	0.9043	1.00
6	0.6225	0.9700	0.8891	1.0574	0.25
7	0.8393	1.0977	0.6639	0.9926	1.00
8	0.5940	1.0438	0.5103	1.0073	0.50
9	0.8980	1.2382	0.8142	0.9216	0.25
10	0.6974	1.0641	0.7199	0.9115	0.25
11	0.5694	1.0497	0.6094	1.0240	0.75
12	0.6035	1.1131	0.5410	1.1945	0.75
13	0.6869	0.9710	0.6336	1.2247	0.25
14	0.8080	1.1819	0.5774	1.1690	0.50
15	0.5046	1.2487	0.5941	1.0752	0.50
16	0.5259	0.9401	0.7830	1.1187	0.25

Table 5. Maintenance costs per crew for each network segment. Source: Authors' own work.

Network segment i	$C_{main}(i,c,t)$ [COP$]		
	Crew 1	Crew 2	Crew 3
1	6728022	6391621	8073626
2	274446	260724	329335
3	491545	466968	589854
4	921647	875564	1105976
5	956055	836548	796712
6	4345257	3802100	3621048
7	294927	280181	353912
8	1097784	1042895	1317340
9	1593425	1513754	1912110
10	1583184	1504025	1899821
11	1310787	1245247	1572944
12	1017908	967012	1221489
13	3453103	3021465	2877586
14	4642642	4062312	3868868
15	4674593	4090269	3895494
16	6178720	5406380	5148933

Table 6. Solution alternatives with $NP = 1$. Source: Authors' own work.

Alternative	CI [COP$]	$NSEL$ [kWh/year]
1	16577251	159142
2	26772099	126375
3	26905123	126231
4	28397474	126198
5	28479091	126189
6	31999167	125494
7	32027738	125424
8	32583901	125208
9	34122437	125166
10	35536140	125164
11	35725488	125152

4. RESULTS

The results of the mathematical models are represented by vegetation pruning schedules considering when and where the maintenance activities are performed. In general terms, Model 4 presents a complete procedure that includes Models 1, 2, and 3 and presents the results in a non-dominated solution front. Therefore, it is necessary to run Models 1 and 3 to find the solutions that represent a maximum value of *NSEL* with a low cost of implementation *CI*, and a maximum value of *CI* with a minimum *NSEL*. Such solutions are the extremes of the non-dominated front. Fig. 3 is a graph of the non-dominated solution front after Model 4 is run in the test system described in Section 4. Each solution is described in Table 6.

After the solution front is obtained, the improvement stage is completed by submitting each solution to the mathematical model described by (7), (8), and (9). In that context, the implementation cost of some of the solutions is enhanced, as described in Fig. 4. Each solution is described in Table 7, marking with a double asterisk the solutions that were improved. In Fig. 4, the solutions in the zoom-in correspond to alternative 8 in Table 6, with the same value of *NSEL* but different cost of implementation and a better solution found after the improvement stage. Such alternatives (alternative 8 before and after the improvement stage) have the same activity schedules, as shown in Table 8.

Table 7. Improvement of the solution front. Source: Authors' own work.

Alternative	*CI* [COP$] Initial front	*CI* [COP$] Final front	*NSEL* [kWh/year]
1	16577251	16577251	159142
2	26772099	26772099	126375
**3	26905123	26878805	126231
**4	28397474	28392559	126198
5	28479091	28479091	126189
**6	31999167	31972849	125494
7	32027738	32027738	125424
**8	32583901	32518362	125208
9	34122437	34113425	125166
10	35536140	35536140	125164
**11	35725488	35699886	125152

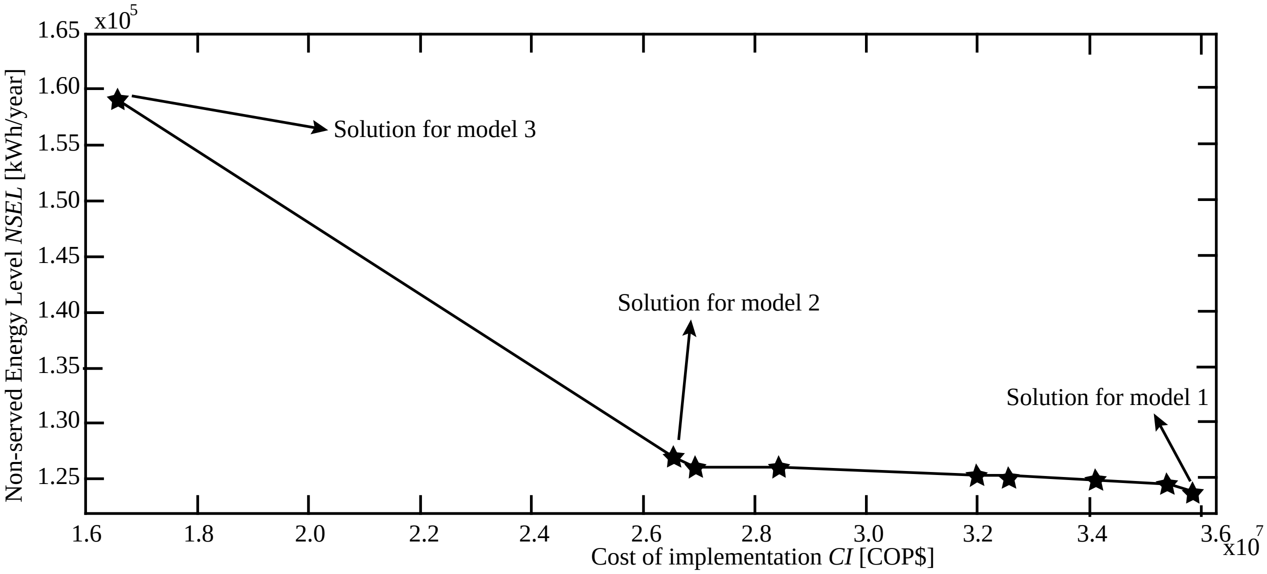

Fig. 3. Non-dominated solution front. Source: Authors' own work.

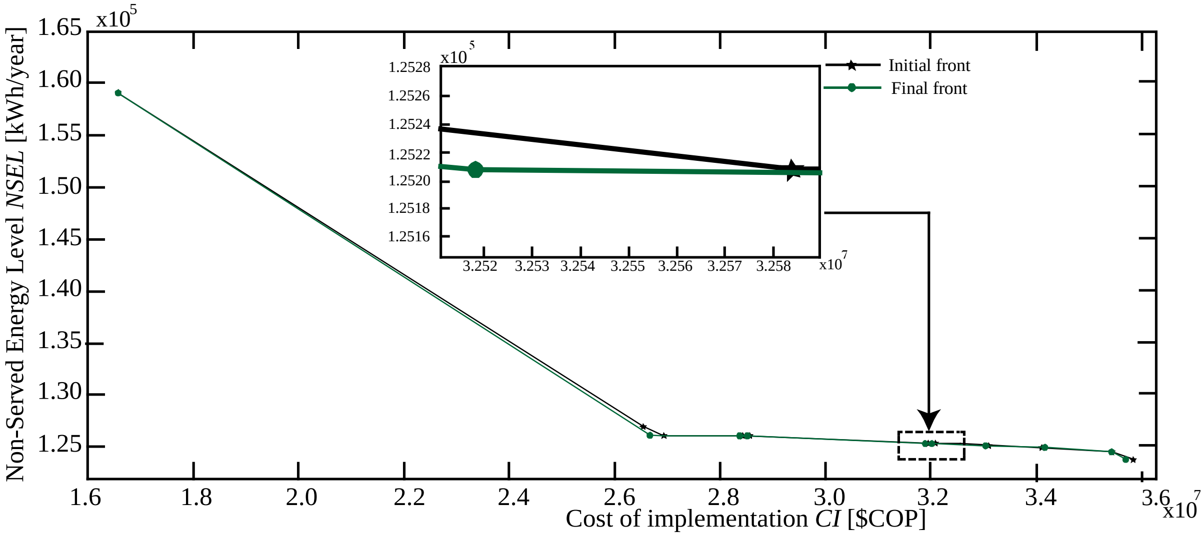

Fig. 4. Improved solution front. Zoom-in on Alternative 8 in Table 7. Source: Authors' own work.

Regarding the information in Table 8, pruning activities are more common in the last quarter. In the second and third quarters, such activities are less frequent, and the first subperiod presents no interventions.This mainly due to the failure rates caused by vegetation, which exhibit an increasing behavior, thus making pruning activities more common in the last quarter of the planning period. With respect to the crews or work teams c_1, c_2, c_3, the execution of the pruning plan is assigned as shown in Tables 9, 10, and 11. Note that the assignment of activities for the fourth subperiod is different in the solution after implementing the improvement. This is demonstrated in Table 7, as the option of improved solution establishes a vegetation maintenance activity in network segment 11 for Crew 2, while in the solution in the first stage (before improvement), the same activity is carried out by Crew 1. The enhancement of the *CI* is performed in accordance with the minimization of the maintenance cost developed by the mathematical approach in (7), (8), and (9). The mathematical models in this work were run using the software GAMS (General Algebraic Modeling System) and the solver DICOPT, specifically designed for the solution of mixed integer non-linear mathematical models. The GAMS codes can be requested from the authors.

Table 8. Activity schedule for alternative 8. Source: Authors' own work.

	Network segment															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
t_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t_2	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
t_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
t_4	1	1	1	1	0	1	0	1	0	0	1	1	1	1	1	0

Table 9. Assignment of activities during the second quarter. Source: Authors' own work.

Network segment	5	7
c_1	0	0
c_2	0	1
c_3	1	0

Table 10. Activity assignment during the fourth quarter (before the improvement stage). Source: Authors' own work.

Network segment	1	2	3	4	6	8	11	12	13	14	15	16
c_1	1	0	0	0	0	1	1	0	0	0	0	0
c_2	0	1	1	1	0	0	0	1	0	1	1	0
c_3	0	0	0	0	1	0	0	0	1	0	0	1

Table 11. Activity assignment during the fourth quarter (after the improvement stage). Source: Authors' own work.

Network segment	1	2	3	4	6	8	11	12	13	14	15	16
c_1	1	0	0	0	0	1	0	0	0	0	0	0
c_2	0	1	1	1	0	0	1	1	0	1	1	0
c_3	0	0	0	0	1	0	0	0	1	0	0	1

Table 12. Results of maintenance proposal 8. Source: Authors' own work.

NSEL benchmark case [kWh/ year]	*NSEL* solution [kWh/year]	*CI* [$COP]
181268	125208	32518362

5. CONCLUSIONS

The vegetation maintenance problem underneath overhead power distribution network has been represented in this work through mathematical programming, encompassing several aspects of power systems reliability, the financial and technical capacity of the utility companies, and the biological characteristics of the vegetation species. Therefore, the results were obtained in terms of where and when the vegetation pruning activities must be performed along the power distribution system, minimizing the *NSEL* and the implementation costs associated with such tasks. Likewise, crews or work teams were also assigned to conduct those activities.

The sensitivity parameters represented by the failure rates caused by vegetation influence the distribution of the pruning activities over the planning period under study. This aspect is reflected in the increased frequency of maintenance works in the last quarters.

The different mathematical modeling approaches adopted in this study to address such problem provide a non-dominated solution front that contains different vegetation maintenance proposals, allowing the decision maker to select the solution that best represents the priorities of the utility company.

Furthermore, an improvement strategy was applied to the solution front to obtain better proposals from the point of view of cost of implementation.

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