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Optimizing Affordably Tree Seeding to Enhance Mexico City's Air Quality

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Abstract. High levels of air pollutants represent a problem in many cities worldwide. Reforesting urban areas is a straightforward but challenging solution since different factors, such as pollen release and optimal location, should be considered. In this work, we propose a model to improve air quality in Mexico City via urban reforestation. A specific genetic algorithm was designed to obtain an optimal tree distribution over Mexico City counties. We provide an affordable solution to the problem, assuming a limited number of available seeding trees. A prediction model is also proposed for the solutions using publicly available data on the city's air quality and meteorological aspects. This work shows these numerical tools' potential to implement solutions to increase life quality based on publicly available data.

Keywords: Evolutionary algorithms, air quality, optimization.

1 Introduction

Unacceptable air quality is a significant issue in many cities all over the world [11]. Identified causes of bad air quality are urban extension and the population growth in developing countries [9]. In response, cities have launched numerous projects, including monitoring, reforestation, clean energies, awareness, etc [16]. Some of these ideas have worked, and much pollution has been reduced [21]. Over the years some evidence emerged that vegetation is important in reducing pollution concentrations [9].

Air pollution in Mexico City is conformed by several elements, i.e., Carbon Dioxide (CO_2), Ozone (O_3), Nitrogen Dioxide (NO_2), particles smaller than 10 micron (PM_{10}) and particles smaller than 2.5 micron ($PM_{2.5}$). Various human-related processes cause polluting emissions into the air; for example, industry, electricity generation, commerce, domestic sources of energy, and motorized vehicles [19].

Air-suspended particles are a complex mix of liquid and solid materials [14]; depending on their origin, they can vary in size, shape, and composition. The size of pollutant particles can vary in diameter from 0.005 to 100 microns [25]; their sources are diverse, such as pollen, plant emissions, and plastic burning, among others [4, 20]. Epidemiology studies have shown a correlation in urban areas between air-suspended particles, such as $PM_{2.5}$ and PM_{10}, in daily deaths and hospital entrees for cardio and respiratory diseases [3, 12, 25].

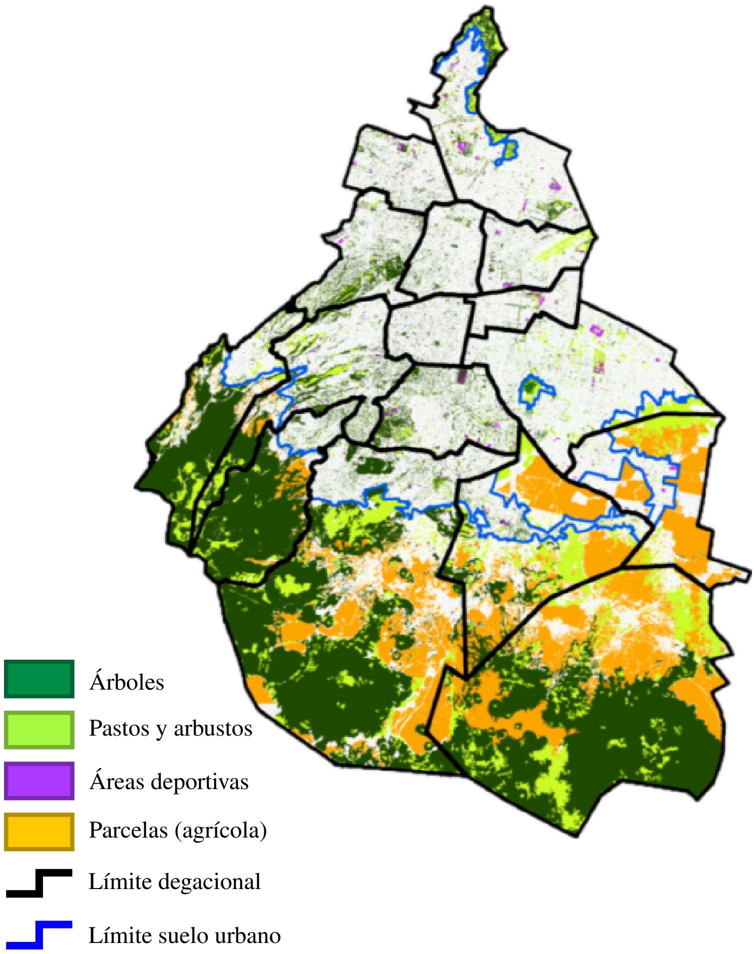


Fig. 1. Inventory of urban green areas in Mexico City, estimated total area of 128 km^2. Source PAOT 2002.

Short-term exposure to these particles is also related [24] to severe or mild cardiovascular diseases like arrhythmia, heart attack, and thrombosis. In the meanwhile, large-time exposure is associated with arterosclerosis [29] and significant health consequences in children [17]. City trees are a crucial component of the urban ecosystem. It is clear that residential trees bring benefits to society by improving the physical and mental health of its members, its economy [32], noise control, and in general the community well-being [1, 22].

From an environmental point of view, trees contribute to energy savings and influence the local weather [10]. However, the most important for this work is that the presence of urban trees is strongly related to the cities' air quality improvement. Since they are not only capable of removing air pollutants [33, 8] but also contribute to local temperature control [26], which lessens the adverse effects of pollutants.

Table 1. Percentage of urban trees by county, the data was obtained from the Environmental Attorney's Office and the Territorial Planning of México City.

Counties Key	Counties	Surface area	Percentage of surface
1	Álvaro Obregón	80.94 km^2	28%
2	Azcapotzalco	33.57 km^2	11%
3	Benito Juárez	26.77 km^2	11%
4	Coyoacán	54.02 km^2	21%
5	Cuajimalpa de Morelos	74.55 km^2	57%
6	Cuauhtémoc	32.49 km^2	10%
7	Gustavo A. Madero	87.78 km^2	11%
8	Iztacalco	23.08 km^2	8%
9	Iztapalapa	113.25 km^2	5%
10	Magdalena Contreras	75.57 km^2	68%
11	Miguel Hidalgo	46.99 km^2	26%
12	Milpa Alta	282.72 km^2	48%
13	Tláhuac	85.65 km^2	1%
14	Tlalpan	307.84 km^2	45%
15	Venustiano Carranza	33.89 km^2	8%
16	Xochimilco	126.56 km^2	12%

Nowadays, in Mexico City, the highest density of trees is located in particular reservoir areas [18]; they represent the 41.5% of the total green area of Mexico City this later is approximately 617.7 km^2, see Figure 1. The total area occupied by each county and the corresponding percentage of green areas are mentioned in Table 1. According to PAOT [1], trees, grass, and shrubs form such green areas.

Some counties have a higher percentage of green areas in the form of natural reservoirs like Magdalena Contreras. In this work, we propose a mathematical model to reforest the Mexico City counties to maximize air quality with limited resources. We consider five types of trees that are beneficial for our purposes, and present a way to distribute the limited resources among the considered counties.

In Section 2, we provide information related to the collected data on air quality and meteorological sensors all over the city, also a description of the data cleaning process. The proposed model is presented in Section 3, and its numerical solution is presented in Section 4. Finally, in Section 5, we state our conclusions and future work.

2 Preprocessing Data

Mexico City has a population of 9.3 million people within an area of 1,485 km^2 [13] with a density of 6,163.3 people/km^2. This high density produced, as a consequence, a reduction in green areas to build, instead, habitable and working, i.e. gray areas [31]; producing an increment in temperature.

[1] CDMX Environmental and Territorial Planning Attorney

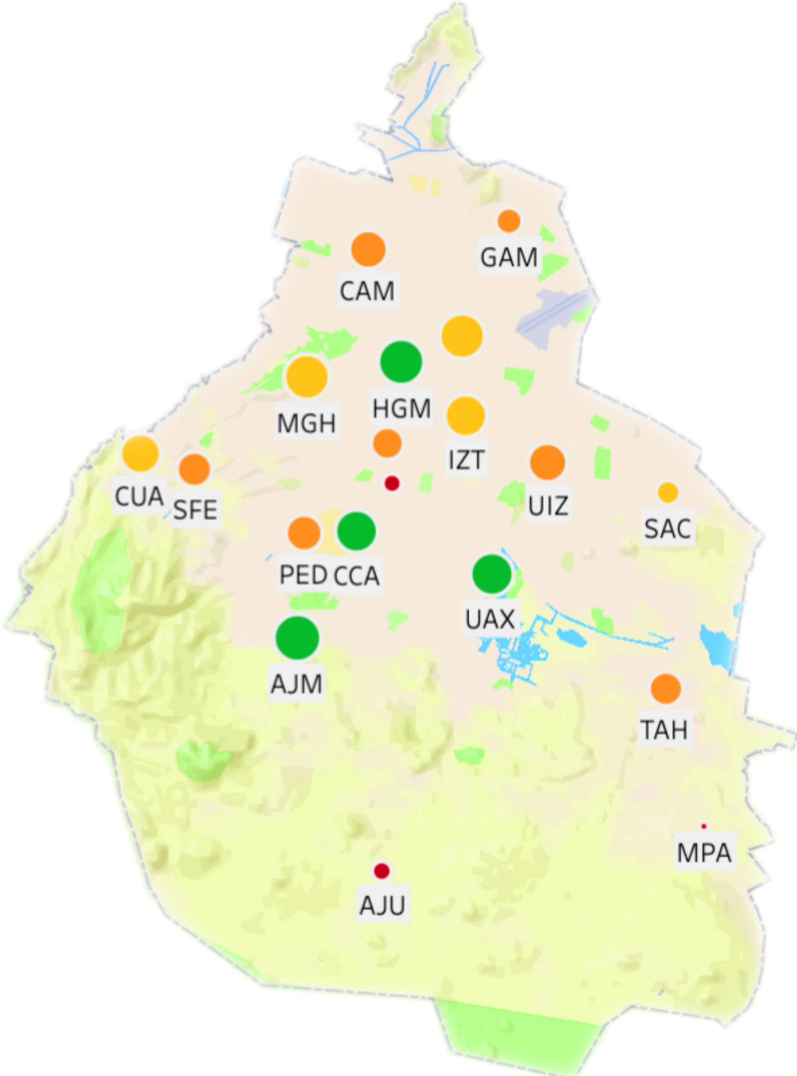


Fig. 2. Air quality monitoring stations located in several Mexico city's counties. The monitoring stations may change their location, depending on the needs of the Directorate of Atmospheric Monitoring of Mexico City.

The high temperatures, lack of wind, and reduced amount of surface water in the city have raised the concentration levels of O_3, PM_{10} and $PM_{2.5}$ [34, 29]. Given the high levels of air pollution, the government of Mexico City created the Dirección de Monitoreo Atmosférico (DMA), to alert the population of the metropolitan area about the high levels of pollution of the different levels of the different pollutants and to carry out research. The DMA has pollution monitoring stations throughout the metropolitan area of Mexico, see Figure 2.

Table 2. Count of null values of Relative Humidity (RH), Wind Speed (WSP), and O_3 from 2017 to 2019 per year of the stations located in Mexico City.

Years	Schedule	O_3	RH	WSP
2018	24 hrs	22023	14448	12423
	6 to 21 hrs	12902	9675	8327

Table 3. Values of the coefficients of each variable, with standard error and the level of significance of each variable.

Parameters	coef	std err	t	$P > \|t\|$
Interceptor	74.6139	5.854	12.746	0.000
$\sqrt{O_3}$	2.3755	0.594	3.998	0.000
WSP^2	-2.1288	0.423	-5.027	0.000
$\sqrt{RH/100}$	-67.8621	4.905	-13.835	0.000

Each monitoring station records the pollutant concentration levels each hour to alert the population about a possible air quality emergency. The definition for the pollution index is according to the Mexican Standard [6] of 2014. The number of active stations at year 2018 in the 16 counties from Mexico City [5], there're existence of monitoring stations may change every year; it depends on their performance during the previous year. The Atmospheric Monitoring Directorate makes the pollution and meteorological records available to the public.

These records are collected by year, they can be downloaded in various data formats, containing the pollution concentrations that each monitoring station reports every hour. A null value is placed whenever a data validation can not be carried out [15]. We noticed that some stations have certain amount of missing data[2]. Therefore, for this work, we included only 2018.

Table 2 reports the number of null values per year and separated by time. We selected no more than one station for each county. One of the discoveries made in the analysis was that the large number of null values occur from 23:00 to 5:00 hrs, so we will consider from 6:00 to 21:00 hrs. This may be due to stations maintenance it is regularly scheduled during the night.

It was found that the number of null values separated by hour is similar, which indicates that all the monitoring stations do not have a value for at least one day. For our experiments, we use the monitoring stations that have less than 10% null values. Chosen stations for analysis are those with meteorological and pollution data available. Three techniques were used to fill in the null values:

- Bootstrap method.
- Duplicate data.
- Correlation between stations.

Each method was applied depending on the number of null values for each season and month.

[2] It comes from different reasons (e.g., equipment failures or maintenance)

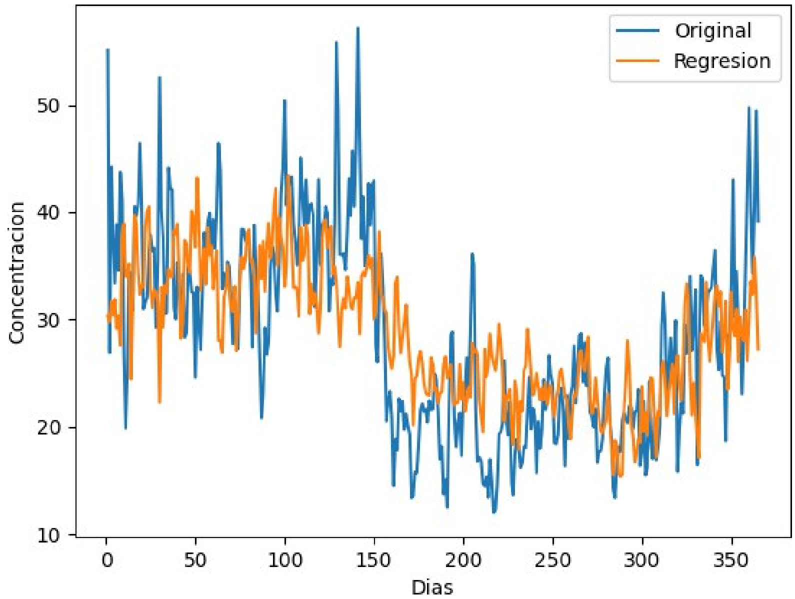


Fig. 3. Comparison of real data from PM_{10} over the year 2018 in the AJM monitoring station against the values obtained by the model 1.

3 Proposed Optimization Model

Now, we introduce our model to pursue the reduction of the pollution in Mexico City, contemplating a set of 20 native trees as show list 3, the norm [28] along with the characteristics of each tree. The proposed vegetation was provided by the CONAFOR[3] and government of Mexico City. These trees have a great capacity to absorb pollution concentration.

It is worth noticing that our model considers the natural death of a certain number of trees over time after they are seeded. These tree species already exist in Mexico City, proving to be part of the existing ecosystems—this later is a very important consideration [28]. The considered species are:

– Ahuejote,
– Aile,
– Cazahuate,
– Colorin,
– Copal,
– Cuajiote,
– Encino blanco,
– Encino chico,

[3] National Forestry Commission of CDMX

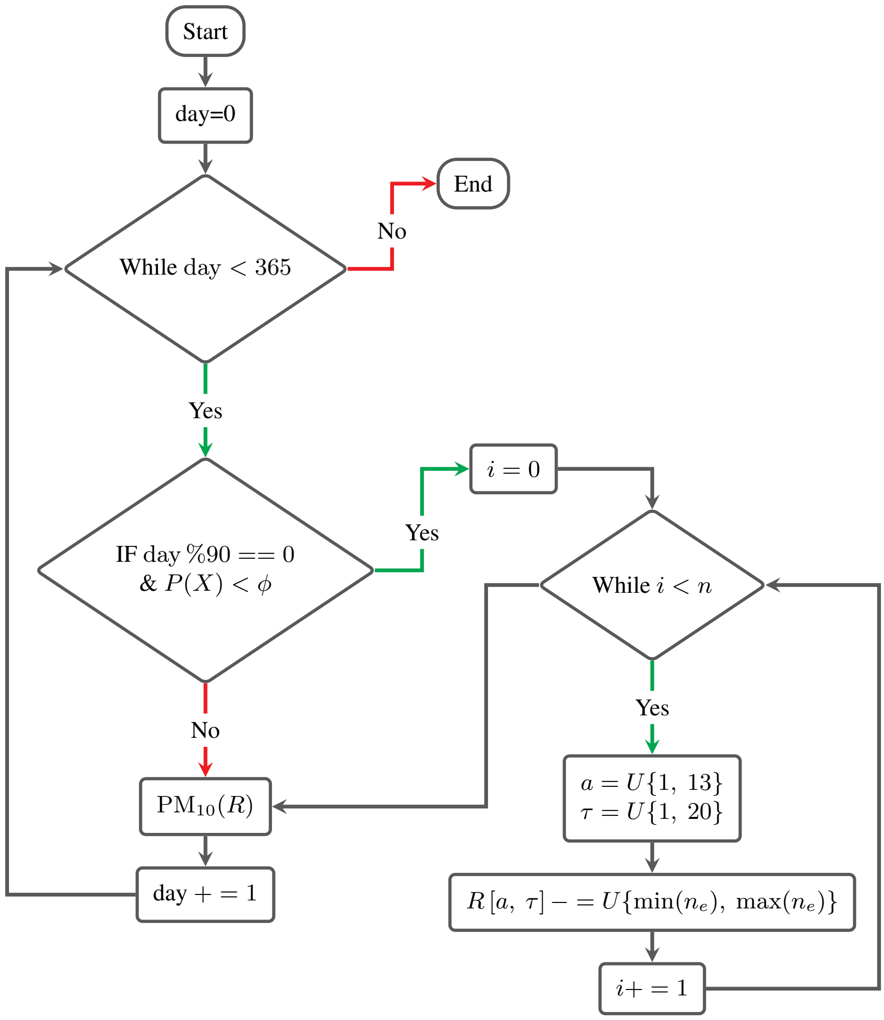
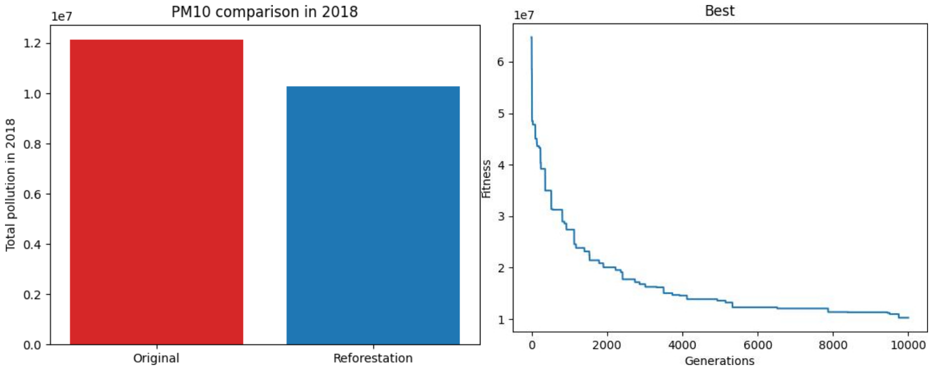


Fig. 4. Diagram to adjust the tree-mortality factor.

- Encino cucharita,
- Encino laurelillo,
- Encino tezahuatl,
- Jaboncillo,
- Laurel,
- Madronio,
- Mora,
- Ocote blanco,
- Palo dulce,



(a) (b)

Fig. 5. Comparison of the total amount of pollution in 2018 without reforestation vs with reforestation (a). Decrease in concentration of PM_{10} of the individual with the best fitness across generations (b).

– Pino blanco,
– Pino patula,
– Tepozan.

In addition, we do not consider that the trees will be planted on a specific date since the government of Mexico City mentions that when carrying out a reforestation they must contemplate maintenance and continuous irrigation [5]—this depends on each species. And as [10] mentions, trees have the ability to modify the micro-climate of the area where they are found, but in our case this variation does not affect the proposed model, and therefore we can consider that the meteorological conditions are kept constant.

It is known [33, 10, 21, 22] that the variation of meteorological units like Relative humidity (RH), Wind Speed (WSP), and O_3, have a correlation with PM_{10} concentration. Considering the Pearson correlation, we ran some tests over RH and WSP in our data set. They resulted in a negative relation, which implies that if we increase the amount of these parameters, the concentration of PM_{10} will decrease. Not all the stations resulted in having the same correlation; this depends essentially on the station location.

Similarly, the relation between O_3 and PM_{10} was verified, and we obtained that they are directly related. The O_3 is composed of nitrogen oxides and volatile organic compounds, the latter make up a certain proportion of PM_{10} [25]. After some analysis, we propose a regression model to produce the concentrations of PM_{10}, under the following considerations:

1. The trees will be planted at the age of one and a half year old. They come from a nursery. This is a suitable strategy for reforestation [2].
2. The absorption percentages and contribution to levels of O_3, RH and WSP for each tree are known; also the absorption percentages and contribution to levels of O_3, RH and WSP for each tree [18].

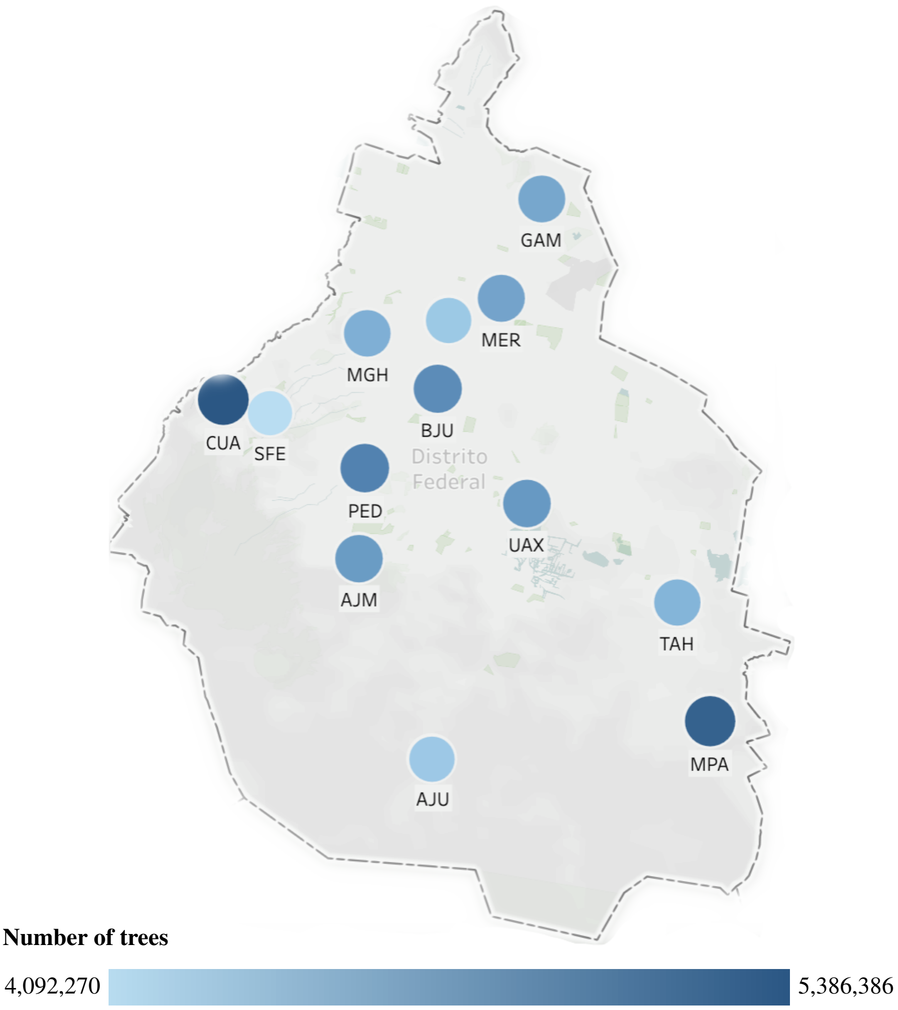


Fig. 6. This graph shows a color intensity related to the number of recommended trees to seed.

The proposed model to obtain the PM_{10} concentrations, considering the RH, WSP and O_3 levels, is given in 1. Table 3 presents the statistical results and the obtained values for each coefficient:

$$\mathrm{PM}_{10} = \beta_0 + \beta_1 \sqrt{O_3} + \beta_2 \mathrm{WSP}^2 + \beta_3 \sqrt{\frac{\mathrm{RH}}{100}}. \tag{1}$$

It was shown that the PM_{10} function is a good approximation to the real values and the Weierstrass test was performed to determine that both distributions were similar.At the end it was obtained that both distributions are similar with a p-value greater than 0.05. The figure 3 shows the PM_{10} function in orange and the real values in blue.

Table 4. Values of the parameters used with GA.

Parameter	Value
Population	100
Cross	0.9
Mutation	0.1
Mortality	0.1
Generations	10000

We computed the R^2 coefficient to verify the proposed model's relation against past-year measured values records. The proposal is related in a ratio of 42.5% to the real values. Finally, due to the validation process, we confirmed that the proposal does not have any dependent variable, so our model fulfills the independence assumption.

Each variable was analyzed, in periods of one hour, separately to see its effect on PM_{10}. Table 3 shows that each variable is significant for our proposal. Figure 3 presents the comparison for the regression against real observed values. Carrying out a T-Student test with a null hypothesis sample that both means are statistically equal.

The hypothesis will be accepted with a significance level greater than or equal to 5% [27]. The goal is to minimize the amount of PM_{10} concentration in the air over one entire 1 year (365 days) by reforesting using a particular distribution of trees over the sixteen several counties of the city. The objective function that we considered in this work is presented in (2):

$$\min_{\mathrm{PM}_{10}} \quad f_1(\delta) = \sum_{i=1}^{16} \left(\sum_{j=1}^{365} \mathrm{PM}_{10}(\delta) \right), \tag{2}$$

where:

$$\mathrm{PM}_{10} = \beta_0 + [T] \left(\%\mathrm{O}_3 \sqrt{\mathrm{O}_3} + \%\mathrm{WSP}\ \beta_2\ \mathrm{WSP}^2 + \%\mathrm{RH}\ \beta_3 \sqrt{\frac{\mathrm{RH}}{100}} \right).$$

And $\delta = [[T]_i,\ \mathrm{O}_{3i},\ \mathrm{WSP}_i,\ \mathrm{RH}_i]$. Each tree has an absorption percentage of O_3 and a percentage increase of RH y WSP. We should mention that our model considers the amount of pollen released by each one of the seeded trees, that also contribute to a raise in PM_{10} levels; otherwise, the problem could have a trivial solution. It is worth to notice that (2) implies a discrete problem.

3.1 Genetic Algorithm

Representation. The representation of an individual is a random $R_{13\times 20}$ matrix for each $T_{a,\tau}$ is a mayor and a type of tree 3:

$$R_i = \begin{bmatrix} T_{1,1} & T_{1,2} & \dots & T_{1,20} \\ T_{2,1} & T_{2,2} & \dots & T_{2,20} \\ \vdots & \vdots & \ddots & \vdots \\ T_{13,1} & T_{13,2} & \dots & T_{13,20} \end{bmatrix}. \tag{3}$$

GA operators:

- **Mutation**: A tree is taken at random with probability η and is varied between 0 and 5000000.
- **Selection**: We take 50 individuals with the highest fitness using a tournament with 3 individuals and no replacement.
- **Crossover**: A pair of parents is taken at random with a probability of μ with a one-point crossover by columns to generate two offspring that will replace them.
- **Fitness Evaluation**: In our problem, we define the fitness of an individual as the amount of PM_{10} in 365 days.

Tree-mortality factor. As we know when doing a reforestation there is a probability that some of the trees that are planted will die either by a pest, among others [7]. The operator is used when evaluating the individual in PM_{10} function. It randomly chooses a certain number of trees to remove from R every 90 days with a probability of ϕ.

To select a $T_{a,\tau}$, n elements are taken from R with the same probability, and to determine the number of trees to be removed from R with the same probability, $T_{a,\tau}$ number of trees to be removed we take a random number between minimum and maximum of $T_{a,\tau}$ from the n elements selected, the n selected elements. Figure 4 shows the steps followed to perform this process.

Evaluation. To do the evaluation of PM_{10} we use R as well as the database of the atmospheric monitoring address that is preprocessed.

4 Problem-Solving and Results

The coding for solving the problem was developed in Python to obtain the best individual of all the generations. The following conditions were considered for our experiments:

- data is taken from 6 to 22 hrs
- stations are located within the CDMX, and
- the data is taken as the average value per day.

To obtain the values of each parameter shown in the table 4, we executed several runs varying the probabilities μ, η and ϕ and then, observed the following:

- If $\phi > 0.1$ then in less than 100 generations the amount of available trees was zero.
- Using the one-point crossover yielded better results than the two-point crossover because the problem is sensitive to large changes.
- If $\eta > 0.1$ it was observed that the algorithm convergence was severely affected.

The result presented was the best of 32 independent experiments with the same, best found, parameters. Although a county may have more than one monitoring station, only one station was considered per county.

Table 5. Optimal tree distribution by county.

	τ_1	τ_2	τ_3	τ_4	τ_5	τ_6	τ_7	τ_8	τ_9	τ_{10}
A_1	418309	375719	303090	94599	334681	217567	195576	228510	7667	398063
A_2	144408	3845	470600	302911	190923	60659	399995	189185	276041	54518
A_3	50033	124994	207623	43972	58405	224505	296112	461770	209919	98022
A_4	108242	332672	414557	141839	35557	296881	44946	397703	228142	57399
A_5	80327	329660	349215	451593	27456	341509	469595	307736	313247	238416
A_6	116992	277891	436061	220096	264982	333060	304585	393349	69190	175873
A_7	265002	176476	163733	208879	309005	154325	168721	336517	404519	350366
A_8	170870	165178	56430	497019	190832	236261	134427	484378	86706	427950
A_9	350186	406475	316707	309593	412799	432951	21011	262130	274982	38417
A_{10}	138705	188230	492681	326405	71313	50313	179803	291370	64	286392
A_{11}	16093	308462	140133	260273	481663	39364	294260	306817	394137	122410
A_{12}	62941	498795	250330	250821	8510	40430	318980	446872	74679	289328
A_{13}	404245	128481	37746	390207	158925	7715	119427	499842	83427	46076

	τ_{11}	τ_{12}	τ_{13}	τ_{14}	τ_{15}	τ_{16}	τ_{17}	τ_{18}	τ_{19}	τ_{20}
A_1	148654	236331	464689	105415	421296	134009	194197	26216	146588	285046
A_2	207203	119750	19095	328261	323703	12957	468505	135282	325336	59093
A_3	289234	125286	102826	259699	280368	494208	342552	219431	462057	126735
A_4	213177	398086	472656	64368	403191	279417	154335	308697	81133	277557
A_5	211402	264516	80493	252369	332070	448782	143707	284814	11522	348147
A_6	359841	448520	394401	425817	765	12978	312141	42890	241506	15142
A_7	312749	379449	273885	9708	176994	157576	152870	268122	148644	182370
A_8	264080	45272	226295	261476	324569	170519	83320	258113	251907	190088
A_9	128023	172077	466581	215939	81869	430903	41311	195731	356574	472127
A_{10}	480242	188932	441634	166075	48421	283771	210312	165914	247269	33441
A_{11}	324561	196006	286242	397527	89466	179092	309688	303896	29336	151566
A_{12}	291557	85977	247820	282415	40763	298595	469195	363578	312774	305990
A_{13}	8642	69473	219038	265509	39713	340457	151027	416879	408536	499906

The results obtained from our experiments are promising because it suggests that by making an optimal distribution of the locations where each tree is to be planted, better air quality can be obtained. An important thing to consider is that the algorithm does not mention the exact coordinates where each type of tree should be planted inside the county.

The individual with the best suitability represents 60,819,340 trees, and decreases pollution by 15% with respect to data obtained from the 2018 CDMX Atmospheric Monitoring Directorate. Figure 5 shows the sum of PM_{10} concentration in 2018 without using our model and blue color shows the sum of PM_{10} concentration of 2018 using our model. These results are in good agreement with the results obtained in [23, 30].

Figure 5 shows the fitness of the best individual in all generations and what is observed is that in the first 5000 generations it decreases rapidly and after 5000 generations the speed with which the amount of PM_{10} concentration decreases. And although it stops in the 10000th generation, our tree distribution improved the air quality. Figure 6 illustrates the number of trees obtained according to each considered municipality.

The dots do not indicate the precise coordinate where they will be planted. The total number of trees varies from 4 million to 5 million approximately. Table 5 shows the obtained optimal distribution of native trees in the thirteen municipalities of Mexico City. The maximum number of trees of any specie to be planted is 499906, and it corresponds to the municipality A_{13} with the τ_{20} type of tree, while the minimum number of trees is 64 and corresponds to municipality A_{10} and the τ_9 specie.

5 Conclusions

In this work, we introduced a model to improve air quality in Mexico City by urban reforestation. We considered a constrained discrete optimization problem and used a genetic algorithm to obtain an optimal distribution of trees over the different counties. We used a prediction model for the solution after publicly available data about air quality and meteorological values measured along the city.

Assuming the percentages of RH, WSP and O_3 absorption for twenty considered types of trees, we were able to reduce the amount of total PM_{10} concentration. An important aspect to notice was the necessary data cleaning process since efficiently filling the database was essential for the model's success.

In 2018 Mexico City experienced an increase in the amount of pollution with an amount of 12.1×10^6 $\mu g/m^3$ of PM_{10}, and the solution obtained by simulation, after apply this proposal was 10.2×10^6; this implies at least a 15% possible improvement. In addition, our model uses native trees from Mexico City, meaning a better resistance to the local climate and fewer tree deaths.

As a future work, the problem will be approached as a multi-objective problem, with the cost of planting and maintenance of the trees as a second function. Also, the characteristics of the trees will be added as another objective function to determine the mortality of the trees using clustering techniques. And to predict the reforestation behavior along 10 years.

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