# Tabu Search for the scheduling of electrics vehicles in charging station

**Lina Reyes a, Luis Tarazona b**

[a]University of the Andes, Bogota, Colombia, l.reyesa@uniandes.edu.co

[b]University of the Andes, Bogota, Colombia, le.tarazona@uniandes.edu.co

**Abstract**

This investigation was carried out with the objective of applying the Tabu Search metaheuristic to carry out the scheduling of an electric vehicle charging station, two parts were considered, the first part with an objective function of minimizing the average waiting time, considering that all the vehicles enter at the same time and the connectors with the same load capacity, and the second part is a real case where the vehicles enter at a defined time, the connectors have different types of load and there are cost considerations due to hour peaks. In addition, rescheduling at a certain time (TR) was considered. It is concluded with good results obtained in a computational time below 10 seconds for all cases, which demonstrates the speed to obtain a result.

**Keywords**

Charging station, Electric vehicles, Tabu Search, Scheduling, Rescheduling

## 1. Introduction

The International Energy Agency (IEA) mentions that in the world there are already about 16 million electric and plug-in hybrid vehicles in circulation, which have entered the vehicle market to compete with conventional vehicles due to the low environmental impact they already have. that generate up to 30% less greenhouse gas emissions and a consumption of 30 TWh per year of electricity(Gil, 2022). In Colombia the situation with these vehicles has the same scenario, for the year 2021 3008 vehicles were sold between plug-in hybrids and electric(Restrepo, 2022), while the first half of this year 1823 vehicles have been sold(Avendano, 2022), which exceeds the number of 8,200 of these types of vehicles in the country and even exceeds the goal agreed by the Single National Traffic Registry of 6,600 vehicles(Vera, 2022).

Although these vehicles have great technical and environmental advantages, the most important disadvantages are the autonomy due to the battery level that these vehicles have, since they lose an average of 2.3% autonomy per year and it will depend on the type of battery.(See, 2003), the availability of charging points in the country, taking into account that there are 210 charging points in the country, making a total of 491 connectors, so it can be assumed that there is a precarious charging infrastructure(Restrepo, 2022), and the charging time that can be fast (10-40 minutes) with an average of 50 kWh, semi-fast (1.5 - 3 hours) with an average of 7.4 kWh and slow (5-8 hours) with an average of 3.7 kWh, although there are super and ultra-fast charges that can have an average of 130 – 150 kWh(Create, 2022).

These disadvantages clearly lead to the existing limitation of charging points or stations. Since according to the operating conditions and the existing demand, an adequate distribution of the vehicles that request cargo must be carried out. These are important factors in determining the time these vehicles must wait to be recharged, in addition to making vehicle scheduling decisions for charging, which, although they can be scheduled considering a recharging reserve, must also be addressed according to the time of arrival of these vehicles at the station. It is for this reason that in this research the application of a Tabu Search algorithm is carried out to solve the problem of electric vehicle charging scheduling, seeing this as a scheduling of electric vehicles.

## 2. Definition of the problem and mathematical formulation

### 2.1 Definition of the problem

The problem is defined as follows: a charging station that serves in a working day T, has M connectors to serve N electric vehicles that require a quantity of charge Q. Some authors have studied this problem and have conditioned some factors within the evaluation, as is the case of Athulya (2020), that evaluated the scheduling in a charging station considering vehicle entry times, penalty for exceeding the maximum demand limit and kW level for peak and non-peak hours. Deng, Yongxi, Fengji, & Yunfei (2021) conducted research to plan a charging station by utilizing second-life battery energy storage systems, Hutson, Kumar, & Corzine (2008) applied a method to schedule the use of available energy storage capacity of plug-in hybrid electric vehicles and electric vehicles. Wang, Jochem, & Fichtner (2020), carried out a study where they programmed the charging of electric vehicles under uncertainty of vehicle availability and charging demand.

In this context, in this investigation the problem was raised as follows: there is a charging station, with a working day T, which has M connectors to serve N vehicles that require a quantity of charge Q, It is known that the vehicles request cargo, so they are registered and scheduled considering that the first in the registration is the first out (FIFO), in addition, that it seeks to reduce the average global waiting time, it is assumed that the vehicles enter the same time, that the connectors have the same charging power and that there is no penalty for exceeding the maximum demand limit.

This problem is similar to parallel machine scheduling, where the objective function is to minimize the average global waiting time and as the main constraint is that the first in the list is the first to leave the charging station (FIFO). The mathematical formulation was adapted from the proposal by Mena & Daniel (2015).

### 2.2 Mathematical formulation

**variables**

$e_i$: waiting time for each vehicle

$$x_i \begin{cases} 1\ if\ job\ is\ done\ and\ after\ job\ i' \\ 0\ if\ job\ is\ not\ done\ i\ after\ job\ i' \end{cases}$$

$p_i$: charging time of each vehicle

$q_i$: load required by each vehicle

$t_i$: charging start time of each vehicle

$c_i$: required load of each vehicle

$r_i$: registration number of each vehicle

**Sets**

N: set of vehicles

M: set of connectors on the charging station

L: big number

A: Record set

**Parameters**

K: Load capacity of each station connector

**Objective Function**

$$\min \frac{\sum_{i=1}^{N} e_i}{N} \tag{1}$$

**Restrictions**

$$\min \sum_{i=1}^{N} x_i \qquad \forall\, i = 1,2,3,\ldots,N \tag{two}$$

$$\sum_{i=1}^{N} x_i \ \leq 1 \quad \forall\, i = 1,2,3,\ldots,N \tag{3}$$

$$t_i \geq t_{i'} + p_{i'} - (1 - x_i) \quad \forall\, i = 1,2,3,\ldots,N;\ \forall\, i' = 1,2,3,\ldots,N \tag{4}$$

$$c_i = t_i + p_i \quad \forall\, i = 1,2,3,\ldots,N \tag{5}$$

$$r_i < r_{i'} \quad \forall\, i = 1,2,3,\ldots,R \tag{6}$$

$$c_i \ \leq t_i \tag{7}$$

**Formulations**

$$p_i = \frac{q_i}{K} \tag{8}$$

$$e_i = c_i - p_i \tag{9}$$

### 2.3 Representation

Formula (1) represents the objective function of minimizing the average vehicle waiting time, Formula (2) is the constraint that guarantees that each job is performed only once, Formula (3) is the constraint that forces to perform a job on a single machine, formula (4) is the restriction that indicates that the start time of a job must be greater than or equal to the completion time of a job that was performed before it on the same machine, formula (5) is the constraint that calculates the completion time of a job, formula (6) ensures compliance with the FIFO, formula (7) is the constraint that ensures that the start time of a job is greater than or same as the completion time of a preceding job. Formula (8) calculates the charging time for each vehicle and formula (9) calculates the waiting time for each vehicle.

## 3 metaheuristics

Tabu search is an optimization method belonging to local search techniques, this type of search increases the performance of the local search method by using memory structures, once a solution is found, it is marked as "tabu". so that the algorithm does not look for it again during a certain period of time (tenure). This metaheuristic was proposed by Fred Glover in 1986. (Glover, 1986).

The metaheuristic procedure of the present investigation was divided into 2 parts: The first part consisted of assuming that all vehicles enter at a time equal to zero (with a required load (and that the connectors have the same load capacity), then it is generated the initial solution taking into account the FIFO and finding an average waiting time, to later apply the Tabu Search that improves the previous average waiting time Figure 1 shows the pseudocode for this first part. Figure 2 shows the pseudocode for this second part. The rescheduling part is shown in Figure 3. It should be noted that the rescheduling is carried out on those vehicles that the start time is less than the TR and the departure time is greater than the TR.

```
Step 1: Initial solution
        Input→Data (, M, )qᵢrᵢ
        Sequence = R
        Apply FIFO
        Output→ e

Step 2: Tabu Search
        SWAP positions in Sequence
            Save SWAP
            Update Sequence
        Apply FIFO
            Store SWAP as Taboo
        If taboo size = tenure
            Remove Taboo SWAP
```

```
        Output→ $e$
        If Solution Step 2 < Solution Step 1
            update sequence
            Output→ $e$
        Else Repeat until Iterations = Iterations
            update sequence
            Output→ $e$
```

**Figure 1. Tabu Search pseudo code for the first part**

```
Step 1: Initial solution
        Input→Data (, M,$q_i r_i, h_i, w_i , C_i, h_i$)
        Sequence = R
        Apply FIFO
            Determine for each$c_i r_i$
            Determine for each$C_i r_i$
            Output→ $e , U$

Step 2: Tabu Search
        SWAP positions in Sequence
            Save SWAP
            Update Sequence
        Apply FIFO
            Store SWAP as Taboo
        If taboo size = tenure
            Remove Taboo SWAP
            Output→ $e , U$
        If Step 2 < Step 1 and Step 2 > Step 1$eeUU$
            update sequence
            Output→ $e , U$
        Else Repeat until Iterations = Iterations
            update sequence
            Output→ $e , U$
```

**Figure 2. Tabu Search pseudo code for the second part**

```
Step 1: Initial solution
        Input→Data (, M,$q_i r_i, h_i, w_i , C_i, h_i$)
        Sequence = R
        Apply FIFO
            Determine for each$c_i r_i$
            Determine for each$C_i r_i$
            Output→ $e , U$

Step 2: Rescheduling
        Input→Data , M,($q_i r_i, h_i, w_i , C_{i,}, h_i, TR$)
            Yes, and$h_i < TR s_i > TR$
              Select$r_i$
              To update$h_i = TR$
              Update Sequence

        SWAP positions in Sequence
            Save SWAP
            Update Sequence
        Apply FIFO
            Store SWAP as Taboo
        If taboo size = tenure
            Remove Taboo SWAP
```

```
            Output→ e , U
      If Step 2 < Step 1 and Step 2 > Step 1eeUU
            update sequence
            Output→ e , U
      Else Repeat until Iterations = Iterations
            update sequence
            Output→ e , U
```

**Figure 3. Pseudo code for rescheduling**

# 4 Experimentation

## 4.1 Research assumptions and charging station parameters

For the first part, the following assumptions were considered:

- All vehicles enter at an entry time equal to zero.
- There is no limit on working hours.
- The station connectors have the same load capacity.
- There is no defined departure time
- All sockets are available at zero time.
- You cannot load another vehicle until you finish a previous vehicle.

For the second part, the following assumptions were considered:

- Each vehicle has a defined entry time.
- There is no limit on working hours. There is no defined departure time
- All sockets are available at zero time.
- Connectors have different load capacity
- The charge cost will depend on the time the charge is being made
- Another vehicle can be charged if a previous vehicle has not finished charging (only when reprogrammed).

The parameters of the charging station have been obtained from Athulya, (2020) and are next:

- Vehicle load capacity (kW/h): 12, 15, 19
- Price per hour ($/kW): 4, 5, 6
- Sale price ($/kW): 6.5
- Peak hours (considering initial hour 0)
    - Low peak hours: 0 to 4 hours

- Average peak hours: 4 to 8 hours
- High peak hours: 8 or more hours

### 4.2 instances

10 instances have been generated that contain the input times (applied to the second part) and the required load, no instances were found for the first part, so a respective discussion could not be made, while for the second part, 10 instances have been found. also used the instances proposed by(Athulya, 2020)(Instance 11) and by(Sedighizadeh, 2019)(Instance 12).

### 4.3 Process

The following experimental procedure was carried out considering the following variables:

**Table 1. Experimental design**

| No. of connectors | iterations |
|---|---|
| 3 | 1000 |
| 4 (second part only) | 5000 |
| 6 | |

## 5 Results

Table 2 shows the results for 3 connectors and 1000/5000 iterations for the first part, positive and significant variation can be seen for 9 of the 10 instances, where the lowest value of variation was for instance 2 with 0% where there was no improvement in the waiting time and a greater value of variation was for instance 3 where there was an improvement in the waiting time of 25%, all this for 1000 iterations. For 5000 iterations no significant improvements have been shown. The computational times were below 2 seconds for 1000 iterations and below 10 seconds for 5000 iterations, which shows that the algorithm is fast to return a result.

**Table 2. Results for 3 connectors and 1000/5000 iterations first part**

| | | | | No. iterations | | 1000 | No. iterations | | 5000 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Tenure | | 5 | Tenure | | 10 |
| No. connectors | 3 | Initial | | TabuSearch | | %variation | TabuSearch | | %variation |
| inst | No. Vehicles | initial FO | Tcomp | fo | Tcomp | | fo | Tcomp | |
| 1 | 7 | 2.6 | 0.01 | 2.07 | 1.27 | 20.38% | 2.07 | 6.46 | 20.38% |
| 2 | 15 | 4.46 | 0.08 | 4.46 | 1.31 | 0.00% | 4.46 | 6.99 | 0.00% |
| 3 | 20 | 9.2 | 0 | 6.9 | 1.48 | 25.00% | 6.9 | 6.93 | 25.00% |
| 4 | 25 | 11.65 | 0.01 | 9.38 | 1.59 | 19.48% | 9.38 | 7.23 | 19.48% |
| 5 | 31 | 14.6 | 0 | 12.22 | 1.68 | 16.30% | 12.22 | 7.94 | 16.30% |
| 6 | 36 | 20.16 | 0.01 | 16.93 | 1.66 | 16.02% | 16.93 | 8.09 | 16.02% |
| 7 | 41 | 21.55 | 0 | 17.46 | 1.7 | 18.98% | 17.46 | 8.57 | 18.98% |
| 8 | 20 | 10.04 | 0.01 | 9.44 | 1.51 | 5.98% | 9.44 | 7.06 | 5.98% |
| 9 | 46 | 23.85 | 0 | 20.21 | 1.8 | 15.26% | 20.21 | 8.42 | 15.26% |
| 10 | 51 | 26.32 | 0 | 22.61 | 1.83 | 14.10% | 22.61 | 8.73 | 14.10% |

Table 3 shows the results for 6 connectors and 1000/5000 iterations for the first part, positive and significant variation can be seen for 8 of the 10 instances, where the lowest value of variation was for instance 1 and instance 2 with 0% where there was no improvement in the waiting time and a greater value of variation was for instance 7 where there was an improvement in the waiting time of 21.02%, all this for 1000 iterations. For 5000 iterations no significant improvements have been shown. The computational times were below 2 seconds for 1000 iterations and below 10 seconds for 5000 iterations, which shows that the algorithm is fast to return a result.

**Table 2. Results for 6 connectors and 1000/5000 iterations first part**

| | | | | No. iterations | | 1000 | No. iterations | | 5000 |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Tenure | | 5 | Tenure | | 10 |
| No. connectors | 6 | Initial | | TabuSearch | | %variation | TabuSearch | | %variation |
| inst | No. Vehicles | initial FO | Tcomp | fo | Tcomp | | fo | Tcomp | |
| 1 | 7 | 0.34 | 0.01 | 0.34 | 1.26 | 0.00% | 0.34 | 6.44 | 0.00% |
| 2 | 15 | 1.55 | 0.02 | 1.55 | 1.32 | 0.00% | 1.55 | 6.47 | 0.00% |
| 3 | 20 | 3.29 | 0.01 | 2.62 | 1.46 | 20.36% | 2.62 | 7.24 | 20.36% |
| 4 | 25 | 4.6 | 0.01 | 3.84 | 1.55 | 16.52% | 3.84 | 7.4 | 16.52% |
| 5 | 31 | 6.08 | 0 | 5.22 | 1.72 | 14.14% | 5.22 | 7.76 | 14.14% |
| 6 | 36 | 9.09 | 0.03 | 7.46 | 1.92 | 17.93% | 7.46 | 8.13 | 17.93% |
| 7 | 41 | 9.85 | 0.01 | 7.78 | 1.88 | 21.02% | 7.78 | 8.42 | 21.02% |
| 8 | 20 | 3.96 | 0.01 | 3.73 | 1.45 | 5.81% | 3.73 | 7.33 | 5.81% |
| 9 | 46 | 11.03 | 0.01 | 9.11 | 1.78 | 17.41% | 9.11 | 8.66 | 17.41% |
| 10 | 51 | 12.2 | 0.01 | 10.34 | 1.89 | 15.25% | 10.34 | 8.82 | 15.25% |

Due to the results obtained for the first part, it was decided not to carry out more tests for 5000 iterations, since it does not improve the solution at 1000 iterations. Table 4 shows the results for 4 connectors and 1000 iterations for the second part, positive and significant variation can be seen for 7 of the 10 instances created, where the lowest value obtained was 0% and the highest value was 41% for the average waiting time (Instance 3) and 8.45% for the utility (Instance 9). Regarding the instance proposed by(Athulya, 2020)(Instance 11), no major improvements are shown because the instance contemplates only 6 vehicles and 6 connectors in addition to applying FIFO. Regarding the instance proposed by(Sedighizadeh, 2019)(Instance 12), no major improvements are shown, in this instance it includes 43 vehicles and 5 connectors, in addition to applying FIFO. Also, keep in mind that the assumptions have been specific to each investigation, including this one. Regarding the computational time, the computational times were below 10 seconds and, in some instances, it has been shown that for the Tabu Search results were obtained in less time compared to the time used for the initial solution, this shows that the algorithm is fast to display a result.

**Table 3. Results for 4 connectors and 1000 iterations part two**

| | | | | | No. iterations | | | 1000 | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Tenure | | | 5 | |
| No. connectors | 4 | | Initial | | | TabuSearch | | %varwaits | %varutility |
| Instance | No. Vehicles | initialwait | initial profit | Tcomp | Wait | Utility | Tcomp | | |
| 1 | 7 | 1.36 | 477.5 | 0 | 1.36 | 477.5 | 1.87 | 0.00% | 0.00% |
| 2 | 15 | 1.4 | 651 | 0 | 1.29 | 701 | 2.39 | -7.86% | 7.68% |
| 3 | 20 | 1.56 | 1050 | 0 | 0.92 | 1063 | 3.24 | -41.03% | 1.24% |
| 4 | 25 | 2.1 | 1131 | 0 | 2.07 | 1155 | 3.45 | -1.43% | 2.12% |
| 5 | 31 | 1.81 | 1212.5 | 0 | 1.8 | 1236.5 | 4.18 | -0.55% | 1.98% |
| 6 | 36 | 4.9 | 1525 | 0 | 4.9 | 1525 | 4.38 | 0.00% | 0.00% |
| 7 | 41 | 5.68 | 1496.5 | 0 | 5.2 | 1580.5 | 4.62 | -8.45% | 5.61% |
| 8 | 20 | 1.99 | 1221.5 | 0 | 1.91 | 1305 | 3.02 | -4.02% | 6.84% |
| 9 | 46 | 8.06 | 1431.5 | 0 | 7.05 | 1552.5 | 5.42 | -12.53% | 8.45% |
| 10 | 51 | 8.82 | 1511.5 | 0 | 8.82 | 1511.5 | 5.62 | 0.00% | 0.00% |
| 11 | 6 | 1.21 | 218 | 0 | 1.21 | 218 | 1.84 | 0.00% | 0.00% |
| 12 | 43 | 10.13 | 201.6 | 0 | 10.13 | 201.6 | 5.2 | 0.00% | 0.00% |

Table 5 shows the results for 6 connectors and 1000 iterations for the second part, a positive and significant variation can be seen for 5 of the 10 instances created, where the lowest value obtained was 0% and the highest value was 20% for the average waiting time (Instance 7) and 11.61% for the utility (Instance 5). Regarding the instance proposed by Athulya (2020) (Instance 11), no major improvements are shown because the instance contemplates only 6 vehicles and 6 connectors in addition to applying FIFO. The same for the instance proposed by Sedighizadeh (2019) (Instance 12) Regarding the computational time, the computational times were below 10 seconds and, in some instances, it has been shown that for the Tabu Search results were obtained in less time compared to the time used for the initial solution, this shows that the algorithm is fast to display a result.

**Table 4. Results for 6 connectors and 1000 iterations part two**

| | | | | | No. iterations | | | 1000 | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Tenure | | | 5 | |
| No. connectors | 6 | Initial | | | TabuSearch | | | %varwaits | %varutility |
| Instance | No. Vehicles | initialwait | initial profit | Tcomp | Wait | Utility | Tcomp | | |
| 1 | 7 | 0.36 | 554.5 | 0 | 0.36 | 554.5 | 2.06 | 0.00% | 0.00% |
| two | fifteen | 1.34 | 806 | 0 | 1.34 | 806 | 2.8 | 0.00% | 0.00% |
| 3 | twenty | 2.01 | 1052 | 0 | two | 1083 | 3.47 | -0.50% | 2.95% |
| 4 | 25 | 2.03 | 1133 | 0.01 | 2.03 | 1133 | 4.2 | 0.00% | 0.00% |
| 5 | 31 | 2.01 | 1214.5 | 0 | 1.77 | 1355.5 | 4.91 | -11.94% | 11.61% |
| 6 | 40 | 1.05 | 1953 | 0 | 0.89 | 1976 | 5.35 | -15.24% | 1.18% |
| 7 | 41 | 1.1 | 1983.5 | 0.01 | 0.88 | 2063 | 6.02 | -20.00% | 4.01% |
| 8 | twenty | 1.5 | 1316.5 | 0 | 1.5 | 1316.5 | 3.77 | 0.00% | 0.00% |
| 9 | 46 | 2.91 | 1895.5 | 0.01 | 2.43 | 1970 | 6.84 | -16.49% | 3.93% |
| 10 | 51 | 3.13 | 1975.5 | 0 | 3.13 | 1975.5 | 7.26 | 0.00% | 0.00% |
| eleven | 6 | 0 | 218 | 0 | 0 | 218 | 1.89 | 0.00% | 0.00% |
| 12 | 43 | 8.8 | 206.4 | 0.02 | 8.8 | 206.4 | 6.25 | 0.00% | 0.00% |

Regarding rescheduling, the rescheduling time was 7, Figure 4 shows a comparison of the average waiting time for the test of 4 connectors and 1000 iterations of the second part, it can be seen that for rescheduling for instances 5, 6, 7, 9 and 10 is greater considering that the number of vehicles is less, so you can assume that rescheduling can significantly affect the average waiting time.

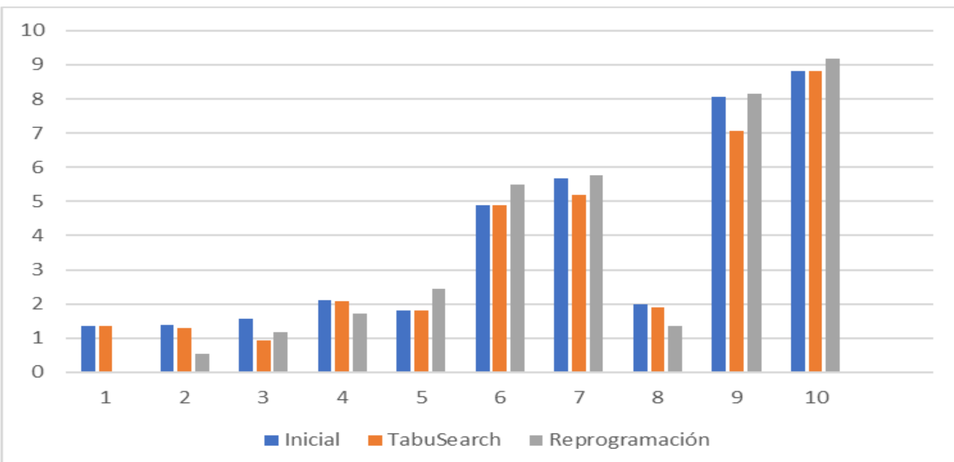


**Figure 4. Average Wait Time Comparison 4 Connectors**

Figure 5 shows a comparison of the average wait time for the test of 6 connectors and 1000 iterations of the second part, it can be seen that for the rescheduling, instance 4 returns a result well above the results of the solution and the Tabu Search, in the rest of the instances it is evident that the average waiting time is equal to or greater than the results of the initial solution and the Tabu Search, so it can be assumed that rescheduling can significantly affect the time average wait.

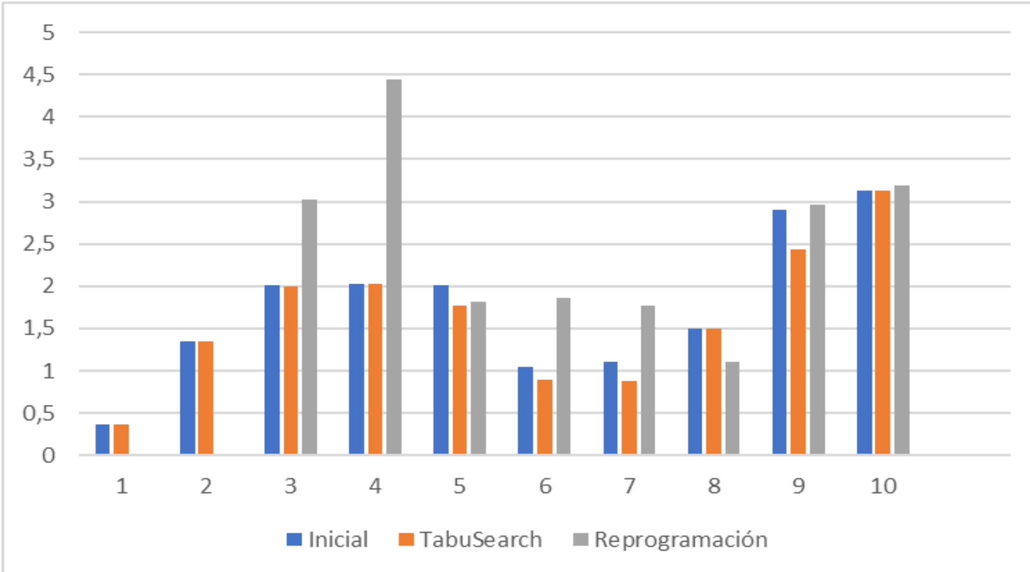


**Figure 5. Average Wait Time Comparison 6 Connectors**

Figure 6 shows a comparison of the utilities expected for the test of 4 connectors and 1000 iterations of the second part, an interesting behavior can be seen for instances 6, 7, 9 and 10 where the utility in rescheduling is the half of the initial solution and Tabu Search, this can be assumed as a utility improvement for the charging station. In the rest of the instances, a low utility can be evidenced, which does not mean that it does not adjust to the rescheduling, but rather, this will depend on the consideration of peak hours, since the cost of energy varies depending on those hours and therefore if the rescheduling is done in peak hours the profits will be less.

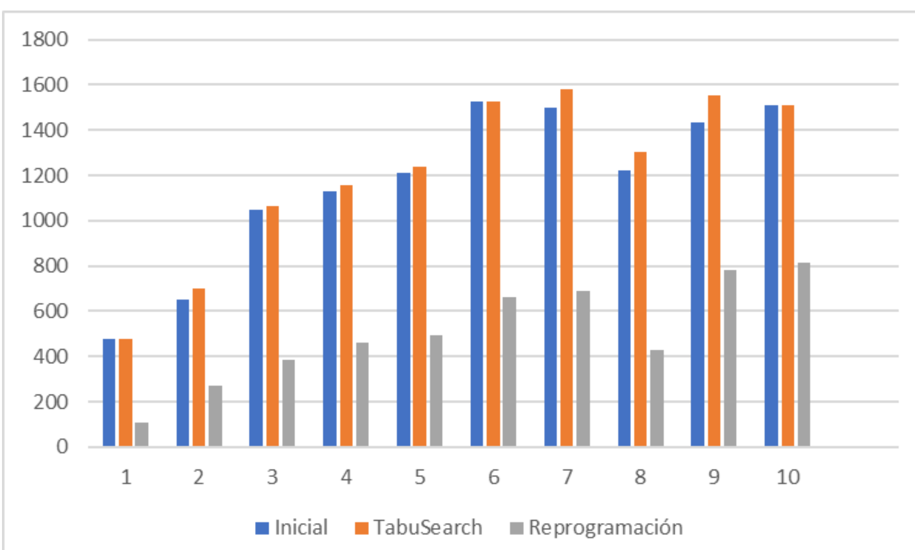


**Figure 6. Utility Comparison 4 Connectors**

Figure 7 shows a comparison of the expected utilities for the test of 6 connectors and 1000 iterations of the second part, you can see a general behavior of the utility, where it is lower since it is due to the consideration of peak hours , since the cost of energy varies depending on those hours and therefore if the rescheduling is done in peak hours the utilities will be lower, it is clear that the nervousness of the system occurs, and therefore the initial scheduling is significantly altered.

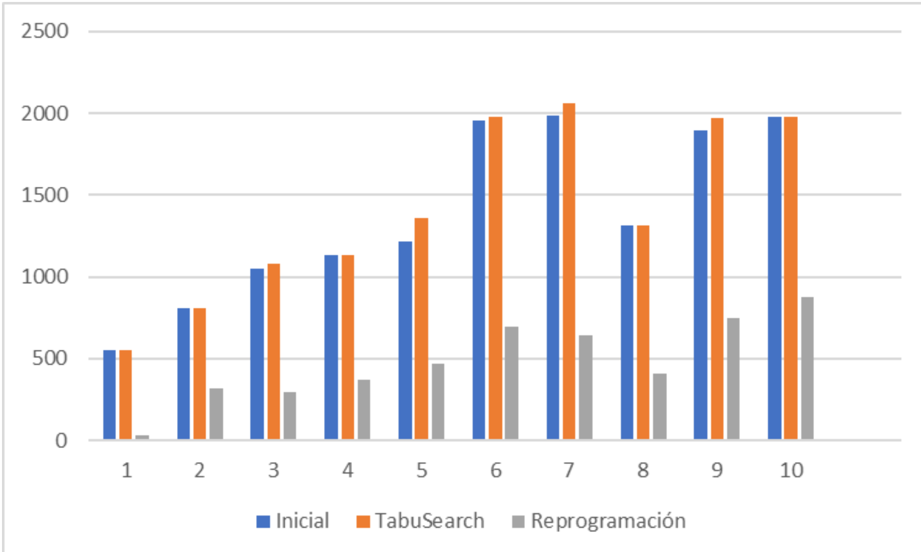


**Figure 7. Utility Comparison 6 Connectors**

## 6 Conclusions and recommendations.

The Tabu Search metaheuristic was applied to solve the electric vehicle charging station scheduling problem, considering minimizing average waiting time and maximizing charging station profits as a multi-objective function. The rescheduling of vehicles at a scheduling time (TR) of 7 was taken into account, obtaining results that suggest the importance of considering peak hours for energy costs, and that the nervousness of the system can significantly affect the utility and average waiting time.

It's recommended to adjust the rescheduling and do an analysis of effectiveness to reduce the nervousness of the system.

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