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Electric Power Distribution Maintenance Crews Routing for Fault Location: Time to Bite the Road-Network Disruptions Bullet ⋆

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Abstract: The power distribution system is the most critical, among the power systems, in delivering electricity. Consequently, faults that occur in most cases due to the weather, can cause diverse socio-economic impacts. Hence, considering fault location, the lion's share of the literature addresses maintenance crews patrol routing by merely regarding the power distribution system faults, despite possibly blocked roads or devices accessibility be affected by the weather as well. To properly optimize power distribution system crews inspection routing, the blocked roads must be avoided and the optimization must be conducted to reachable devices. This process is initiated by filtering the blocked roads from the road-network, then a genetic algorithm based on permutation operators is employed on the suitably coded solutions. Furthermore, it was proposed a test case, for the optimization procedure, with a road-network, where the blocked roads were gradually included, and a power distribution system. The resulting solutions showed optimized inspection routes that deviate from blocked roads and skipped from unreachable devices, which is a possible consequence of road-network disruptions. In this manner, they may impact on power distribution maintenance crews routing. Therefore, the suggested methodology proved suitable for a maintenance crew routing under road-network blockage.

Keywords: Routing, Road-network, Power distribution system, Patrol, Fault location, Blocked roads, Genetic algorithm

1. INTRODUCTION

Despite being the most critical component when it comes to reliability indices, the power distribution system gets the least attention (Brown, 2017). As the final stage of the delivery of electric power, distribution systems account for up to 90% of all customer reliability problems (Short, 2018). Therefore, faults on the power distribution system cause severe socioeconomic impacts and most of them occur during periods of adverse weather (Short, 2018).

After a fault occurs, customers can be reconnected to intact parts of the feeder or relocated to healthy interconnected feeders, when it is possible, by automated devices and remotely controlled or manually operated switches (Fanucchi et al., 2019a). Essentially, the utilities try to find the faults and restore the system as faster as possible, for which (Bahmanyar et al., 2017) compares several fault location procedures. Among them, maintenance crews are dispatched for patrol and restore the faulted part of the system (Brown, 2017).

As pointed by Zhichun et al. (2019), there is a gap of unified standards and procedures for power distribution network patrol. Generally, the patrol strategy is manually formulated, affected by all kinds of human mistakes. The same study developed a heuristic search algorithm that performs path optimization aiming the shortest patrol event considering traffic information, where each inspection route must use the base location as the starting and ending points, similar to depots on vehicle routing problems.

Another study proposed a two-stage stochastic program, in the first stage, the crews are dispatched to already known damaged components so that the distribution network is operated in the second stage. Besides, the routing problem is defined at a complete graph (Arif et al., 2018a). In the same year, the authors also suggested a routing method that maximizes the picked-up loads and minimizes the repair time based on clustering damaged power generation

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components, considering their distances to bases and the availability of repair resources (Arif et al., 2018b).

Two mixed-integer linear routing models that assign a set of disrupted components to each restoration crew was suggested by Morshedlou et al. (2018). By assuming that some disruption affects only the infrastructure network, not the road-network, a heuristic identifies the route with the minimum total traveling time associated with each restoration crew. Still, in mixed-integer programming, Karakoc et al. (2019) developed a multi-objective formulation to schedule the restoration of disrupted components from interdependent infrastructure networks relied on socioeconomic and demographic information. Although, the same study suggested, for future works, treating other interdependent infrastructure networks as transportation.

In a previous study, a stochastic method was proposed to adjust the number of required repair crews given a weather scenario (Fanucchi et al., 2019b). Other aspects involving power distribution system repair crews routing, such as vehicle average speed and crew's initial location were discussed in a methodology, which assumes feeder bars failure rate to guide the routing process (Fanucchi et al., 2019a). By involving metaheuristics, XiaoLiu Shen et al. (2016) employed an improved ant colony algorithm to solve a patrol route planning model based on the vehicle routing problem.

None of the aforementioned studies considers road-network damage on patrol routing optimization. By not taking into account the interdependency between the power distribution system and road-network may underestimate the gravity of the consequences. When it comes to severe weather events, as distribution lines are usually located alongside urban and suburban roads, the failure at the electrical system may come combined with road blocking (Karagiannis et al., 2019). Consequently, would power distribution system maintenance crews routing procedures be affected by considering road-network disruptions?

With that in mind, the present study aims to optimize a power distribution system maintenance crew routing through a road-network under previously known road disruptions, from vehicular social networks (VSN) (Ning et al., 2017). In this manner, a crew must patrol some devices by performing a minimum length route. Besides, the routing strategy identifies unreachable devices due to blocked roads and conducts the route optimization only to reachable devices.

Since the road-network and the power distribution system are represented by graphs, where their vertices are assigned by georeferenced locations, it was proposed a reduced codification for the vertex sequence of a path (Bender and Williamson, 2010). Therefore, the evaluation process employs Dijkstra's algorithm on finding the best path between two consecutive nodes (Dijkstra, 1959). Moreover, the evaluation procedure was equipped with a memoization technique to speed up the computational run time. The solutions were generated by a Genetic Algorithm (GA) (Holland et al., 1992). Moreover, it was proposed a test case based on IEEE 37-bus distribution feeder, that comprises the road-network (Kersting, 1991). Finally, the results showed fast convergence and covered several kinds of situations, which included inaccessible devices and route deviation due to blocked roads.

2. PROBLEM DESCRIPTION

After a fault occurs on a power distribution system, customers can be reconnected to intact parts of the feeder or relocated to healthy interconnected feeders, when it is possible, by automated devices and remotely controlled or manually operated switches (Fanucchi et al., 2019a). Especially to restore as many customers as possible without violating the equipment's rating and isolate the faulted area. Sequentially, maintenance crews are dispatched to locate the fault and perform the repair (Fanucchi et al., 2019a).

Aiming to inspect possibly damaged devices on a power distribution system, a crew must displace on a road-network by performing a minimum length route. Besides, assuming severe weather events, the routing plan must be adjusted to avoid previously known blocked roads from a VSN (Ning et al., 2017) and, consequently, identify inaccessible devices.

3. ROAD-NETWORK ROUTING

A road-network can be described as a directed graph $G_R = \{V_R, E_R\}$, where the vertex set V_R represents georeferenced locations and the edge set $E_R \coloneqq \{(i,j)\colon\ (i,j) \in V_R \times V_R \wedge i \neq j\}$, the roads linking those vertices. As part of the methodology, the blocked roads are filtered from E_R.

Similarly, a power distribution system is represented by a graph $G_D = \{V_D, E_D\}$, where V_D is a set comprising poles, devices, or just georeferenced points and $E_D \coloneqq \{(i,j)\colon\ (i,j) \in V_D \times V_D \wedge i \neq j\}$ represents the branches or distribution power lines.

A path, or a route, is represented as a sequence of nodes $\{x_s, \ldots, x_t\} \subseteq V_R$, where the edge set connecting these $t-s+1$ nodes from x_s to x_t is given by $\{(x_i, x_{i+1}) \in E_R\}$, for all $i \in \{s, \ldots, t-1\}$ (Bender and Williamson, 2010). This representation, the so-called vertex sequence of a path, could be reduced to (s,t) or $\pi_{s,t}$, in the shortest paths case, which will motivate the problem codification on Subsection 3.1. Before detailing, Figure 1 summarizes an overview of the whole road-network routing process.

3.1 Codification

Considering a set V of devices to inspect, where $V \subseteq V_D$, the codification for the optimization problem is $\mathbf{x} = \{x_1, \ldots, x_n\}$, $n = |V|$, where each consecutive pair $(x_i, x_{i+1})\colon \forall i \in \{1, \ldots, n-1\}$ represents the shortest path from equipment x_i to x_{i+1}. In this manner, the codified solution $\mathbf{x}$ represents a list of sequential tasks, labeled according to the homonym equipment to be inspected.

It is important to notice that the crew's initial position is not included in the codified solution since this codification represents sequential tasks and not the nodes *per se*. Along these lines, the permutation-based operators described in Section 4 do not affect the crew's initial position. Nevertheless, the evaluation process on Subsection 3.2 uses initial position x_0 to calculate the route's length.

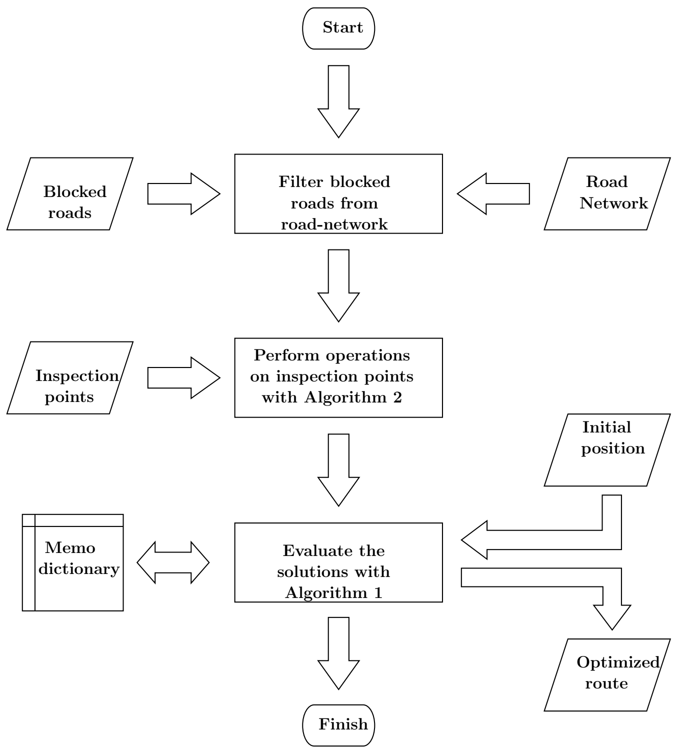

Figure 1. The routing process starts by filtering the blocked roads from the road-network. Then, the genetic algorithm evolves by exchanging the inspection points sequence through its operators. Next, the solutions and the initial position are jointly evaluated and the process returns the minimum length route. Furthermore, the memo dictionary plays an important role in the execution time.

3.2 Evaluation

After codification is established, the objective function to be minimized, on (1), is composed by the lengths $\delta_{x_i,x_{i+1}}$ of the shortest paths $\pi_{x_i,x_{i+1}}$, in which x_i and x_{i+1} are consecutive elements of the coded solution $\mathbf{x} = \{x_1, \ldots, x_n\}$. In this way, $\mathcal{P}_{x_i,x_{i+1}}$ is a set containing all simple paths between x_i and x_{i+1} and $I_A \colon X \to \{0, 1\}$ is an indicator function given by (2). It is important to emphasize that if there is no path between x_i and x_{i+1}, $\mathcal{P}_{x_i,x_{i+1}} = \{\}$, which implies $I_{\mathcal{P}_{x_i,x_{i+1}}}(\pi_{x_i,x_{i+1}}) = 0$. The objective function can be evaluated by the Algorithm 1, which receives a coded solution $\mathbf{x} = \{x_1, \ldots, x_n\}$ and return the path's total length.

$$\min f(\mathbf{x}) = \sum_{i=0}^{n-1} \delta_{x_i,x_{i+1}} I_{\mathcal{P}_{x_i,x_{i+1}}}(\pi_{x_i,x_{i+1}}) \tag{1}$$

$$I_A(x) \coloneqq \begin{cases} 1 & \text{if } x \in A, \\ 0 & \text{if } x \notin A \end{cases} \tag{2}$$

Additionally, it is required the crew's initial position x_0 and a dictionary, called *memo*, that associate a tuple, as its key, to a distance measure. By inserting this data structure, the memoization concept of dynamic programming is incorporated to reduce the average time complexity (Cormen et al., 2009). Performing a lookup operation on any element in the dictionary takes $\mathcal{O}(1)$ in the worst case (Milliken, 2020).

First, at Line 1, the cardinality of $\mathbf{x}$ is stored on n, which is the number of devices to inspect. Next, the for loop between the Lines 4 and 15 check for all pairs of consecutive elements of $\mathbf{x}$, including the crew's initial position x_0, if they were already calculated and stored on *memo* dictionary, as stated at Line 5, which takes $\mathcal{O}(n)$.

In case that it was not previously computed and if the path exists, as verified by Line 6, the shortest path length between two nodes x_i and x_{i+1}, where $i \in \{0, \ldots, n-1\}$, denoted by $\delta_{x_i,x_{i+1}}$, is obtained by Dijkstra's algorithm at Line 7 (Dijkstra, 1959). Which, equipped with the Fibonacci heap, performs in the worst case the running time complexity of $\mathcal{O}(|E_R| + |V_R| \log |V_R|)$ (Fredman and Tarjan, 1984).

On the other hand, if the equipment is unreachable due to the blocked roads, it is inserted in the *unreachable* list at Line 9 and ignored on calculation, as stated by the Lines 10 and 11. This strategy is based on answering the following question: can a route be drawn, despite unreachable devices? Finally, the length of the entire route is calculated at Line 14.

Algorithm 1 Objective Function Evaluation

Require: initial position x_0
coded solution $\mathbf{x} = \{x_1, \ldots, x_n\}$
dictionary *memo*

1: $n \leftarrow |\mathbf{x}|$
2: $length \leftarrow 0$
3: $unreachable \leftarrow \{\}$
4: **for all** $i \in 0 \colon (n-1)$ **do**
5:   **if** $(x_i, x_{i+1}) \notin keys(memo)$ **then**
6:     **if** $\exists\, \delta_{x_i,x_{i+1}}$ **then**
7:       $memo\left[(x_i, x_{i+1})\right] \leftarrow \delta_{x_i,x_{i+1}}$
8:     **else**
9:       insert x_{i+1} into *unreachable*
10:       $x_{i+1} \leftarrow x_i$
11:       $memo\left[(x_i, x_{i+1})\right] \leftarrow 0$
12:     **end if**
13:   **end if**
14:   $length \leftarrow length + memo\left[(x_i, x_{i+1})\right]$
15: **end for**

Ensure: *length*, *unreachable*

4. GENETIC ALGORITHM

In the optimization context, each chromosome represents a solution $\mathbf{x} = \{x_1, \ldots, x_n\}$. Each element of a solution, i.e., x_i, $i \in \{1, \ldots, n\}$, is called a gene. At each iteration, a new generation of solutions, named offspring, is created based on the last generation.

Algorithm 2 shows off the genetic algorithm dynamics. First, at Line 1 the population is initialized by randomly shuffling a coded solution $\mathbf{x}$. Then, each chromosome of the population is evaluated according to the objective function, at Line 2.

Subsequently, the loop between Lines 3 and 14 performs the genetic operations until a stopping criterion is reached,

Algorithm 2 Genetic Algorithm

```
1:  Create the initial population of chromosomes
2:  Evaluate each chromosome in population
3:  while Stopping criterion not satisfied do
4:    repeat
5:      Select parent chromosomes
6:      if Crossover condition satisfied then
7:        Perform crossover
8:      end if
9:      if Mutation condition satisfied then
10:       Perform mutation
11:     end if
12:     Evaluate each chromosome in population
13:   until sufficient offspring created
14: end while
```

which is, in the proposed methodology, the number of generations.

To keep all the solutions in the feasible region of the search space, the genetic algorithm must support permutation-based operations, described in Subsection 4.1 (Wirsansky, 2020).

4.1 Genetic Operators

The selection method, at Line 5 on Algorithm 2, consists of randomly sampling some chromosomes from the population. From this sampled group, named the tournament size, the one with the most advantageous score is picked.

After selecting two chromosomes, called parents, employing the aforementioned method, a number is sampled from $U(0, 1)$ and if it is less or equals the crossover rate, the ordered crossover (OX1) is performed. This condition is stated in Line 6 from Algorithm 2. Consequently, at Line 7, two section points are randomly generated, whose interjacent genes are kept in place in both parents. Then, the remnant genes are ordered according to the other parent's sequence. This binary operation may be better understood in Figure 2 with two chromosomes of length six.

Parent A

0	1	2	3	4	5
x_1	x_4	x_2	x_3	x_5	x_6

Child A

0	1	2	3	4	5
x_4	x_2	x_3	x_1	x_6	x_5

Parent B

0	1	2	3	4	5
x_2	x_4	x_3	x_1	x_6	x_5

Child B

0	1	2	3	4	5
x_4	x_1	x_2	x_3	x_5	x_6

Figure 2. Ordered crossover operation (OX1) performed on two chromosomes of length six: Parent A and Parent B. The operation start by randomly setting two section points: indices 2 and 4. The interjacent genes from Parent A are x_2, x_3, and x_5. Next, the remnant genes from Parent A ordered according to Parent B are x_4, x_1, and x_6. They are employed to fill in the missing elements, which engenders Child B. Child A derives from the same process performed on Parent B.

As conditioned by Line 9, a number is sampled from $U(0, 1)$ and if it is less or equal the mutation rate, the swap mutation is performed, Line 10. This unary operator randomly exchanges two genes position in a chromosome. This process is illustrated in Figure 3 for a chromosome of length six.

Before

0	1	2	3	4	5
x_4	x_2	x_3	x_1	x_6	x_5

After

0	1	2	3	4	5
x_4	x_2	x_6	x_1	x_3	x_5

Figure 3. The swap mutation operator performed on a chromosome of length six. Two genes are randomly chosen: x_3 and x_6. The next step is to exchange their position.

5. TESTS

The tests were performed on a computer with a 64-bits Intel® Core™ i3-4005U processor, 4 Gb RAM, and the algorithm was developed on Python 3.6. The library employed to model the graph structures was Networkx 2.4 (Hagberg et al., 2008).

Following Wirsansky (2020) suggestions, the GA parameters were set as follows:

- population size: 200
- crossover rate: 0.9
- mutation rate: 0.1
- tournament size: 3
- number of generations: 50

Apart from optimizing patrol routes, the present study also introduces a test case in Appendix A, for routing purposes, based on IEEE 37-bus distribution feeder (Kersting, 1991). Table A.1 includes all the nodes from $V_R \cup V_D$ and their positions. Seeing that another information necessary to describe a network is its links set, Tables A.2 and A.3 define the roads and the power lines, respectively.

Crew's initial position was randomly sampled from the road-network nodes set. Similarly, the blocked roads were randomly sampled from the road-network edges set. For each case of this simulation, which the Algorithm 2 ran 30 times, blocked roads were inserted sequentially as enumerated below:

(1) $\{\}$
(2) $\{(730, 703)\}$
(3) $\{(730, 703), (5, 799)\}$
(4) $\{(730, 703), (5, 799), (16, 17)\}$
(5) $\{(730, 703), (5, 799), (16, 17), (2, 701)\}$

6. RESULTS AND DISCUSSION

The whole simulation ran in a few minutes as shown in Table 1. Although the best solution found codification was coincidentally the same, for the first four cases, the route length divergence is due to the blocked roads, featuring different routes. For instance, Figure 4 represents the fourth test case route, where there were three blocked roads simultaneously. In the last case, there was unreachable equipment, 701. This fact explains why the best route length and the mean running time were lower since there was one less equipment to patrol.

Another way to assess this simulation is through Figures 5 and 6 for route length and run time, respectively. The first ensures convergence for all cases. Significantly, all cases converged to the best solution found until the fifth generation as demonstrated by the variance graph. Despite fast convergence, it was not premature, since the variance was composed of the best solution of each sample and not by the population *per se*. The second shows that mean run time decreases with the number of generations, which was the intent of the memo dictionary from Figure 1.

Table 1. Summary of the results of the tests performed according to Section 5. The best solution for the first four cases is $\{706, 737, 734, 708, 713, 701\}$ and for the last case is $\{706, 737, 734, 708, 713\}$, where the equipment 701 is unreachable.

Test cases	Best solution length	Mean run time [s]	Inaccessible equipments
1	31964.18	3.51	{}
2	35008.39	3.77	{}
3	35008.39	3.76	{}
4	35008.39	3.78	{}
5	30442.08	3.13	{701}

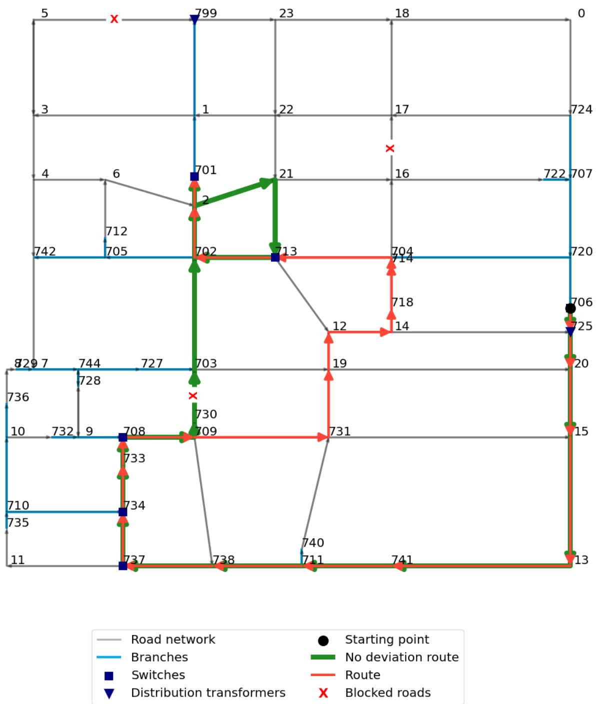

Figure 4. Graphical representation of the fourth test case route and the route from the first test case, without deviation, based on Tables A.1, A.2, and A.3, where nodes 701, 708, 713, 734, 737, and 706 are switches to be inspected; nodes 799 and 725 are distribution transformers; crew's initial position is given by node 706; the blocked roads are {(730, 703), (5, 799), (16, 17)}.

Despite being a small system, the simulation allowed noticing the interdependence between the road-network and power distribution system on maintenance crew routing. However, the literature, presented in Section 1, has been negligent on this issue. Even when more infrastructure systems are considered as in (Karakoc et al., 2019), the road-network was ignored.

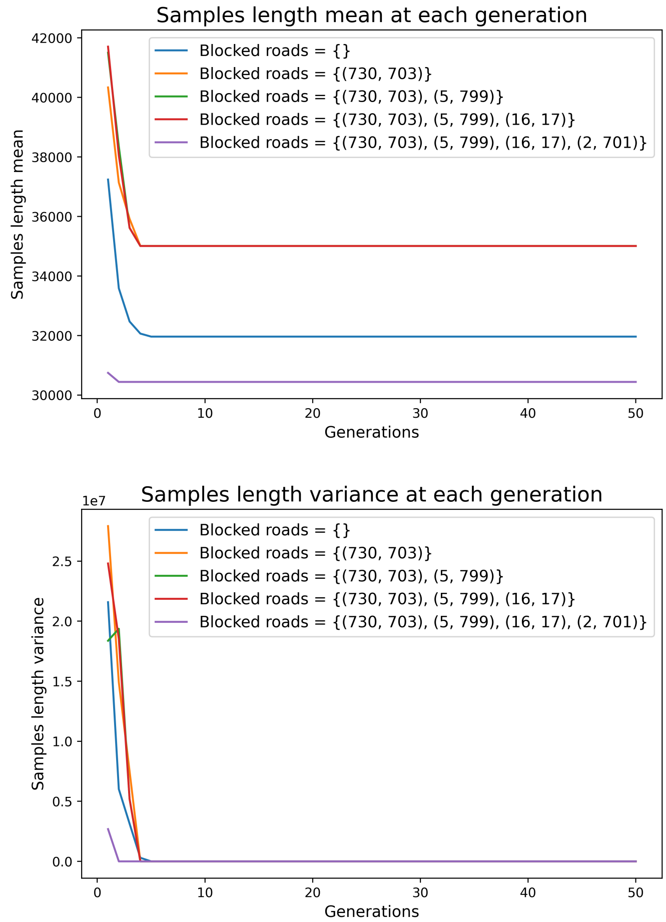

Figure 5. For each generation, the best solution length was employed to compose the mean and variance. Both graphs showed fast convergence, until the fifth generation.

7. CONCLUSIONS

By answering the question made in Section 1, the results showed that even for a small system, it is possible to notice the interdependence between the road-network and power distribution system, when it comes to maintenance crew routing problems aiming fault locations after weather events. Moreover, the presented method proved suitable for this purpose, both in terms of finding good solutions as of execution time. Another important feature successfully put in proof was the capacity of keeping the routing on despite inaccessible devices.

Thinking of power distribution system peculiarities, it might be relevant to consider more crews on the routing problem. Another consideration that could improve this method would be by estimating the most probable locations of blocked roads and avoiding them or placing crews in such a way that minimizes road disruption impacts on patrolling procedures.

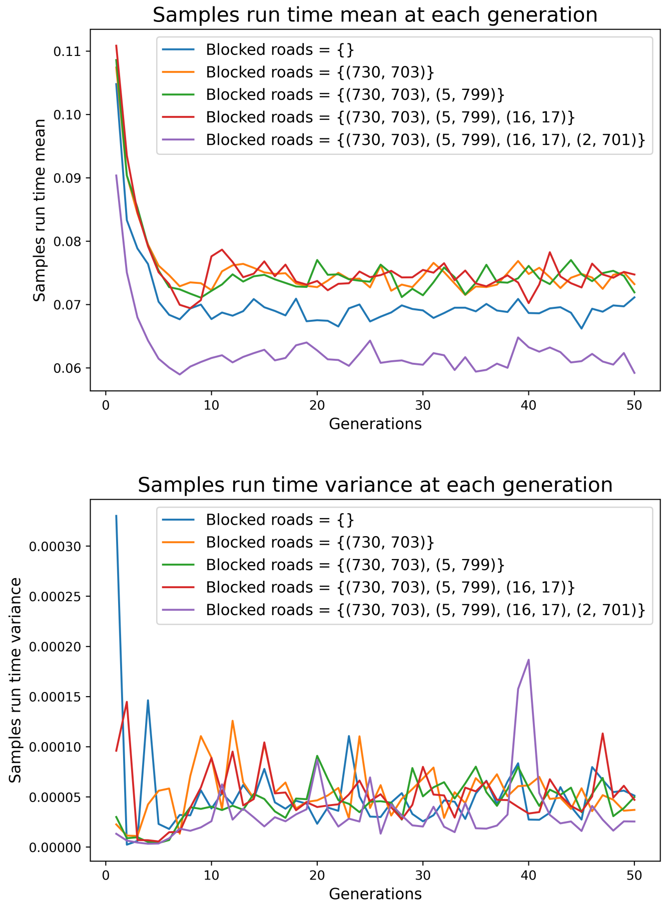

Figure 6. Mean and variance samples run time of each generation. The mean run time decrease was due to the employment of the memo dictionary described in Section 3.2.

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Appendix A. IEEE 37-BUS DISTRIBUTION FEEDER AND ROAD-NETWORK

Table A.1. Test case based on the IEEE 37-bus distribution feeder. The nodes set comprises the IEEE distribution feeder nodes and fictional road nodes. Their position is given by Cartesian coordinates (X, Y).

Node	X	Y	Node	X	Y
701	0	-1850	734	-320	-5810
702	0	-2810	737	-320	-6450
705	-400	-2810	738	80	-6450
713	360	-2810	728	-520	-4330
703	0	-4130	729	-800	-4130
727	-240	-4130	799	0	0
730	0	-4730	0	1680	0
704	880	-2810	1	0	-1130
714	880	-2890	2	0	-2200
720	1680	-2810	3	-720	-1130
742	-720	-2810	4	-720	-1890
712	-400	-2570	5	-720	0
706	1680	-3410	6	-400	-1890
725	1680	-3690	7	-720	-4130
707	1680	-1890	8	-840	-4130
724	1680	-1130	9	-520	-4930
722	1560	-1890	10	-840	-4930
708	-320	-4930	11	-840	-6450
733	-320	-5250	12	600	-3690
732	-640	-4930	13	1680	-6450
709	0	-4930	14	880	-3690
731	600	-4930	15	1680	-4930
710	-840	-5810	16	880	-1890
735	-840	-6010	17	880	-1130
736	-840	-4530	18	880	0
711	480	-6450	19	600	-4130
741	880	-6450	20	1680	-4130
740	480	-6250	21	360	-1890
718	880	-3410	22	360	-1130
744	-520	-4130	23	360	0

Table A.2. Test case based on the IEEE 37-bus distribution feeder. The edge set comprises fictional roads. Considering the position of the nodes, in Table A.1, the edge weight is calculated by euclidean metrics. Since the road-network is a directed graph, the edge from nodes 702 to 2, in the first row, for instance, is a one-way road. Whereas, two-way roads are declared two times, by swapping the position of the nodes likewise the nodes 3 and 5.

From	To	From	To	From	To
702	2	17	22	7	744
2	701	22	1	737	734
709	738	0	724	738	737
701	1	2	21	737	11
1	799	21	16	728	9
702	705	16	722	9	728
713	702	733	708	8	729
703	702	732	9	5	799
705	742	9	708	799	23
705	712	708	709	23	18
704	713	734	733	18	0
727	703	10	732	1	3
730	703	709	731	6	2
744	727	731	19	5	3
709	730	19	12	3	4
714	704	735	710	4	6
720	704	710	10	12	14
718	714	10	736	15	13
707	720	710	734	3	5
720	706	11	735	704	16
4	742	736	8	16	17
742	7	741	711	17	18
712	6	711	740	703	19
706	725	711	738	19	20
14	725	13	741	731	15
725	20	740	731	713	12
20	15	14	718	23	22
724	707	744	728	22	21
722	707	728	744	21	713
724	17	729	7		

Table A.3. Test case based on the IEEE 37-bus distribution feeder. The edge set comprises the power lines. Considering the position of the nodes, in Table A.1, the edge weight is calculated by euclidean metrics.

From	To	From	To
701	702	707	724
701	799	707	722
702	705	708	733
702	713	708	732
702	703	708	709
705	742	733	734
705	712	709	731
713	704	710	735
703	727	710	736
703	730	710	734
727	744	711	741
730	709	711	740
704	714	711	738
704	720	744	728
714	718	744	729
720	707	734	737
720	706	737	738
706	725		