COMPLEMENTARY MATERIAL

A BIO-INSPIRED ALGORITHM FOR SWITCH ALLOCATION PROBLEM WITH DISTRIBUTED GENERATION

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1 Hyperparameter Optimization

1.1 Phase 1

In this phase, the reset mechanism was not considered. The algorithm was executed a single time for each combination of Table 1, so the total execution was 180 iterations. The outcome of each execution can be seen in Table 2, which is ordered by cost.

Table 1: Hyperparameters alongside respective values evaluated.

hyperparameter	Description	Search space
m_r	Mutation rate	{0.01, 0.05, 0.1, 0.2, 0.3}
pm_r	Manual switch allocation rate after selection for mutation	{0.01, 0.05, 0.1, 0.2}
N_s	Neighborhood size	{1, 2, 3}
M_{max}	Maximum number of neighbour evaluation	{5, 15, 25}
G_r	Maximum number of generations to *reset*	{15, 20, 25, 30, 35}
G_t	Total generations number	{100}

The five best hyperparameter combinations are shown in Table 3.

1.2 Phase 2

For greater reliability of results and reduction of uncertainties, the five best combinations of Phase 1 were executed 30 times each. Figure 1 shows in a scatter plot, the final result of each run for each combination, providing an overview of the outcomes. This chart provides an overview of all results obtained, but it is still not possible to identify a trend indicating which combination yields superior solutions. Figure 2 presents a boxplot of each combination, and the cost distributions are similar among the combinations it is possible to verify the existence of only one outlier and in general, the cost distributions appear similar between the combinations.

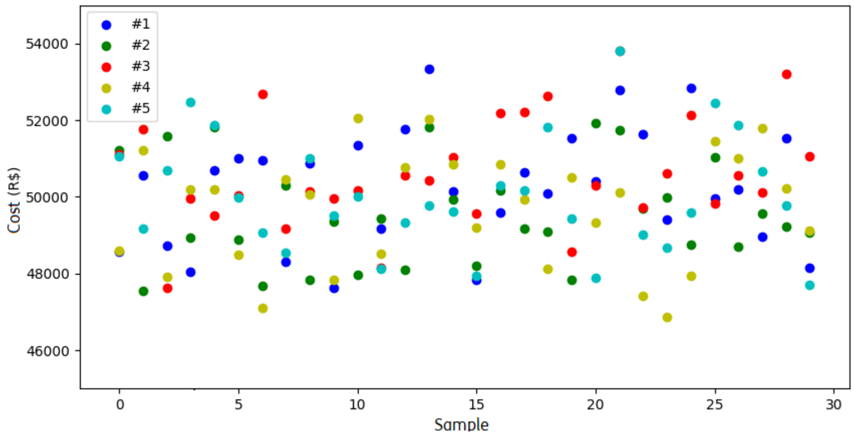

Figure 1: Scatter graph of hyperparameter optimization for Phase 2.

#	m_r	pm_r	N_s	M_{max}	Cost (R$)	#	m_r	pm_r	N_s	M_{max}	Cost (R$)	#	m_r	pm_r	N_s	M_{max}	Cost (R$)
1	0.05	0.20	2	15	46507.48	61	0.10	0.05	1	25	51016.19	121	0.20	0.01	3	15	54640.53
2	0.05	0.20	3	15	48036.35	62	0.10	0.05	1	15	51016.19	122	0.20	0.01	3	25	54640.53
3	0.10	0.01	1	25	48150.89	63	0.01	0.20	3	5	51064.26	123	0.20	0.10	3	5	54748.26
4	0.10	0.01	1	15	48150.89	64	0.20	0.01	1	15	51119.76	124	0.01	0.01	3	15	54786.27
5	0.05	0.05	2	25	48305.10	65	0.20	0.01	1	25	51119.76	125	0.01	0.01	3	25	54786.27
6	0.05	0.01	3	25	48330.84	66	0.01	0.10	3	5	51154.78	126	0.01	0.20	1	15	54789.79
7	0.05	0.05	1	5	48373.15	67	0.10	0.05	3	5	51165.23	127	0.20	0.20	2	5	54931.02
8	0.05	0.10	3	5	48377.90	68	0.05	0.10	1	5	51239.10	128	0.30	0.05	2	5	54936.41
9	0.05	0.01	3	5	48671.61	69	0.10	0.05	3	15	51423.36	129	0.01	0.10	2	5	54949.86
10	0.05	0.10	2	5	48738.14	70	0.10	0.05	3	25	51423.36	130	0.20	0.20	3	5	55000.24
11	0.05	0.05	3	5	48754.66	71	0.10	0.10	1	5	51524.80	131	0.01	0.05	3	5	55292.54
12	0.05	0.20	2	5	48832.58	72	0.10	0.20	3	15	51692.02	132	0.30	0.10	1	5	55308.82
13	0.05	0.20	3	25	48845.96	73	0.20	0.01	1	5	51726.62	133	0.01	0.05	1	5	55358.95
14	0.05	0.20	3	5	48881.87	74	0.10	0.10	2	5	51768.99	134	0.30	0.20	3	5	55389.35
15	0.10	0.01	3	5	48886.18	75	0.10	0.20	2	5	51945.70	135	0.01	0.20	1	25	55416.50
16	0.10	0.10	3	5	49053.67	76	0.01	0.01	1	5	52423.15	136	0.20	0.05	1	25	55626.42
17	0.05	0.01	2	5	49110.45	77	0.01	0.10	3	25	52425.58	137	0.20	0.05	1	15	55626.42
18	0.05	0.01	1	5	49231.24	78	0.01	0.10	3	15	52425.58	138	0.20	0.20	2	15	55652.40
19	0.10	0.20	2	15	49479.99	79	0.10	0.05	2	5	52518.74	139	0.20	0.20	2	25	55652.40
20	0.05	0.01	3	15	49495.44	80	0.10	0.10	2	25	52561.28	140	0.01	0.05	3	25	55711.20
21	0.05	0.01	2	25	49510.95	81	0.10	0.10	2	15	52561.28	141	0.01	0.05	3	15	55711.20
22	0.05	0.01	2	15	49510.95	82	0.20	0.05	1	5	52614.06	142	0.20	0.20	1	5	55747.06
23	0.05	0.01	1	25	49513.82	83	0.10	0.20	3	5	52670.36	143	0.30	0.20	2	15	55976.82
24	0.05	0.01	1	15	49513.82	84	0.20	0.05	3	15	52680.03	144	0.30	0.20	2	25	55976.82
25	0.05	0.10	1	25	49599.65	85	0.20	0.05	3	25	52680.03	145	0.30	0.01	3	15	56240.84
26	0.05	0.10	1	15	49599.65	86	0.20	0.05	3	5	52723.76	146	0.30	0.05	2	25	56293.76
27	0.10	0.01	3	25	49602.43	87	0.01	0.01	3	5	52784.62	147	0.30	0.05	2	15	56293.76
28	0.10	0.01	3	15	49602.43	88	0.01	0.20	1	5	52820.58	148	0.20	0.01	2	25	56333.00
29	0.05	0.20	1	15	49750.03	89	0.01	0.20	2	25	52855.31	149	0.20	0.01	2	15	56333.00
30	0.05	0.20	1	25	49750.03	90	0.01	0.20	2	15	52855.31	150	0.30	0.01	1	15	56361.63
31	0.10	0.20	3	25	49752.86	91	0.20	0.10	2	15	52892.37	151	0.30	0.01	1	25	56361.63
32	0.01	0.01	2	5	49806.82	92	0.20	0.10	2	25	52892.37	152	0.30	0.10	3	5	56508.07
33	0.10	0.10	3	25	49845.78	93	0.01	0.01	2	15	53050.52	153	0.30	0.01	3	25	56757.02
34	0.10	0.10	3	15	49845.78	94	0.01	0.01	2	25	53050.52	154	0.30	0.10	2	5	56837.10
35	0.05	0.05	2	5	49895.53	95	0.20	0.10	2	5	53282.42	155	0.30	0.05	3	15	56865.76
36	0.05	0.10	3	25	49955.82	96	0.10	0.20	1	25	53285.49	156	0.30	0.05	3	25	56865.76
37	0.05	0.10	3	15	49955.82	97	0.10	0.20	1	15	53285.49	157	0.30	0.05	1	5	57105.90
38	0.05	0.05	1	25	50054.65	98	0.30	0.01	1	5	53338.65	158	0.20	0.10	1	5	57188.70
39	0.05	0.05	1	15	50054.65	99	0.20	0.05	2	15	53342.99	159	0.30	0.05	3	5	57688.24
40	0.01	0.20	2	5	50119.28	100	0.20	0.05	2	25	53342.99	160	0.30	0.05	1	15	57803.28
41	0.05	0.20	2	25	50224.90	101	0.01	0.10	1	5	53365.13	161	0.30	0.05	1	25	57803.28
42	0.10	0.20	1	5	50250.24	102	0.01	0.05	2	15	53632.42	162	0.30	0.20	2	5	57971.32
43	0.05	0.10	2	25	50264.42	103	0.01	0.05	2	25	53632.42	163	0.30	0.10	3	15	58101.21
44	0.05	0.10	2	15	50264.42	104	0.20	0.01	3	5	53766.76	164	0.30	0.10	3	25	58101.21
45	0.05	0.05	2	15	50345.10	105	0.01	0.10	2	15	53978.98	165	0.20	0.20	1	15	58249.02
46	0.05	0.20	1	5	50359.15	106	0.01	0.10	2	25	53978.98	166	0.20	0.20	1	25	58249.02
47	0.05	0.05	3	25	50384.55	107	0.20	0.05	2	5	54043.00	167	0.30	0.01	2	25	58264.20
48	0.05	0.05	3	15	50384.55	108	0.30	0.01	2	5	54107.62	168	0.30	0.01	2	15	58264.20
49	0.10	0.01	2	5	50403.61	109	0.20	0.01	2	5	54393.75	169	0.30	0.20	3	15	58622.08
50	0.10	0.01	1	5	50416.55	110	0.20	0.10	1	25	54422.99	170	0.30	0.20	3	25	58622.08
51	0.10	0.10	1	25	50452.08	111	0.20	0.10	1	15	54422.99	171	0.30	0.10	2	15	58744.87
52	0.10	0.10	1	15	50452.08	112	0.20	0.10	3	25	54484.74	172	0.30	0.10	2	25	58744.87
53	0.10	0.20	2	25	50614.96	113	0.20	0.10	3	15	54484.74	173	0.30	0.01	3	5	58862.75
54	0.10	0.05	1	5	50663.49	114	0.01	0.10	1	15	54557.14	174	0.30	0.20	1	5	59134.84
55	0.01	0.20	3	15	50672.43	115	0.01	0.10	1	25	54557.14	175	0.01	0.05	1	25	59605.35
56	0.01	0.20	3	25	50672.43	116	0.20	0.20	3	25	54565.60	176	0.01	0.05	1	15	59605.35
57	0.10	0.05	2	25	50828.93	117	0.20	0.20	3	15	54565.60	177	0.30	0.10	1	15	60277.83
58	0.10	0.05	2	15	50828.93	118	0.01	0.05	2	5	54596.88	178	0.30	0.10	1	25	60277.83
59	0.10	0.01	2	25	50869.72	119	0.01	0.01	1	15	54602.40	179	0.30	0.20	1	25	61285.94
60	0.10	0.01	2	15	50869.72	120	0.01	0.01	1	25	54602.40	180	0.30	0.20	1	15	61285.94

Table 2: Results of each execution of hyperparameter optimization - Phase 1.

Figure 3 illustrates the progression of costs (y-axis) across 30 executions (x-axis), with each color denoting a distinct set of hyperparameters. Each subplot depicts the outcome of a specific generation.

Table 4 shows the mean and standard deviation for 30 executions of each com-

Table 3: Top 5 results of hyperparameter optimization from Phase 1.

Combination	m_r	pm_r	N_s	M_{max}	*Cost (R$)*
#1	0.05	0.20	2	15	46507.48
#2	0.05	0.20	3	15	48036.35
#3	0.10	0.01	1	15	48150.89
#4	0.05	0.05	2	25	48305.10
#5	0.05	0.01	3	25	48330.84

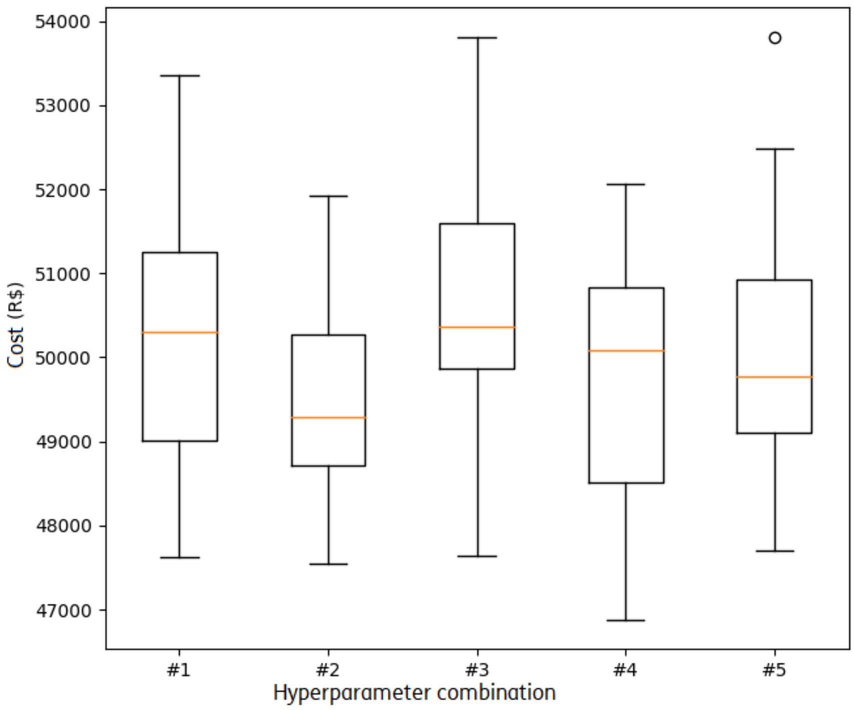

Figure 2: Box plot of hyperparameter optimization for Phase 2.

bination of Table 3. To compare the mean value among combinations first, we check if they have normal distributions using *Shapiro-Wilk* test shapiro1965analysis. Subsequently, we use the *Levene* test levene74 to inspect if the results for each combination have the same variance. Performing these tests, we can say that the distributions follow a normal distribution and have close variances. A hypothesis z-test is then conducted to determine if the means differ. The confidence interval for this test was defined as 95%. Table 5 shows the hypothesis test results.

We can observe in red the comparisons in which the hypothesis was rejected, thus their means cannot be told apart, one can state that combinations 2 and 4 are better than combination 3. The combination 2 was chosen because it includes a smaller number of local search movements (M_{max}), reducing computational effort.

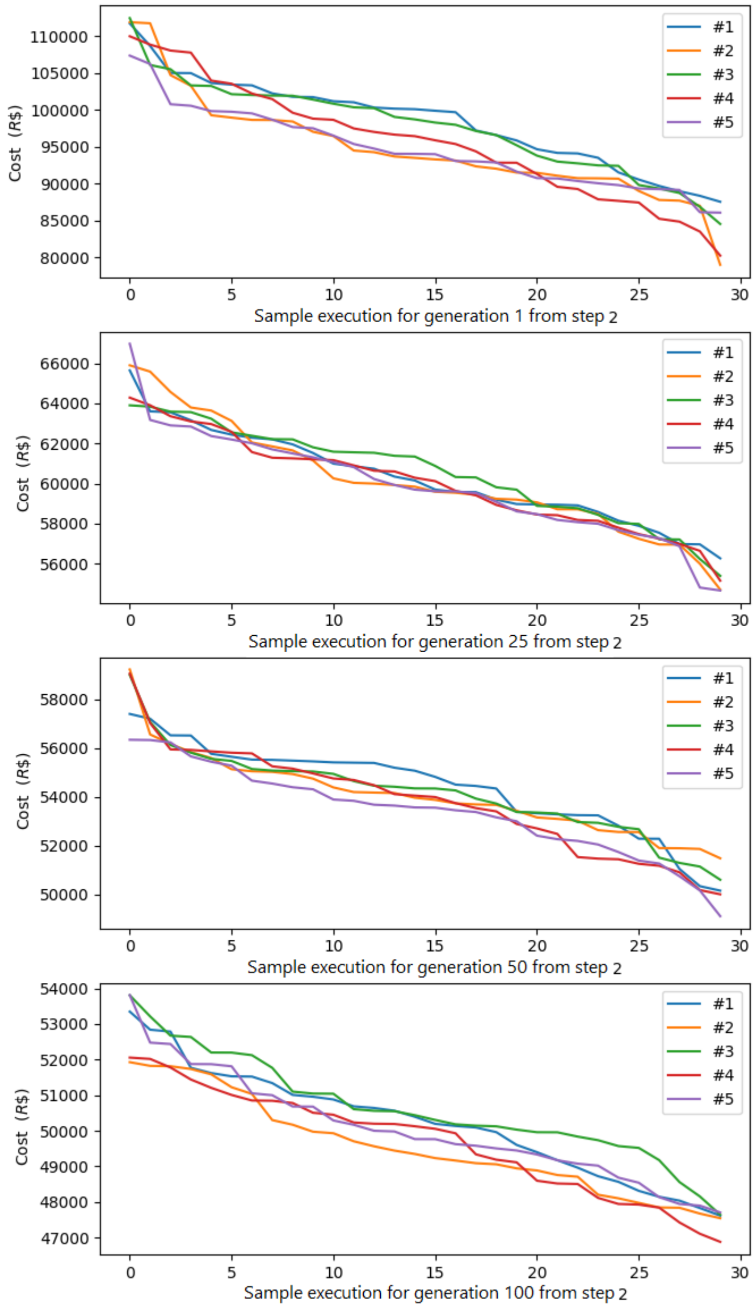

Figure 3: Evolution of costs per generation of Phase 2 executions.

1.3 Phase 3

The last phase consisted in finding an optimal choice for G_r, with five different values being considered, namely, $G_r = \{10, 15, 20, 25, 30, 35, 40\}$. Each combina-

Table 4: Mean ($\mu_{\bar{X}}$) and standard deviation ($\sigma_{\bar{X}}$) of the samples by hyperparameter combination on Table 3 - Phase 2.

Combination	#1	#2	#3	#4	#5
$\mu_{\bar{X}}$	50222.57	49554.56	50629.89	49673.41	50045.61
$\sigma_{\bar{X}}$	1536.20	1363.05	1454.43	1499.92	1499.36

Table 5: z-test results for Phase 2.

Combination	#1	#2	#3	#4	#5
#1	-	92,52%	70,84%	83,88%	34,86%
#2	-	-	99,69%	25,19%	81,56%
#3	-	-	-	98,78%	87,45%
#4	-	-	-	-	66,36%
#5	-	-	-	-	-

tion was executed 30 times, leading to a total of $7 \times 30 = 210$ runs. The same analysis from Phase 2 was performed to determine the best value for G_r. The results obtained for each value of G_r can be observed in Figure 4, which shows a decline in cost values as G_r increases.

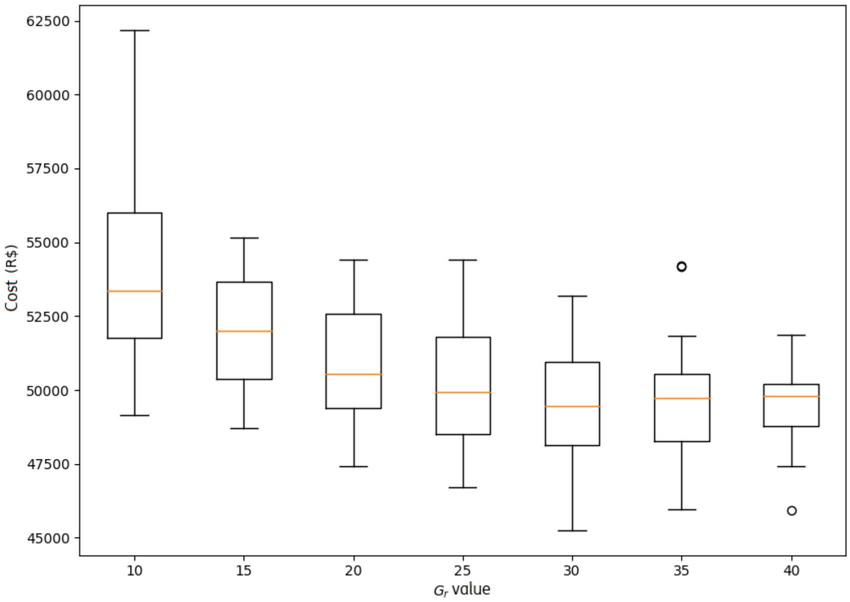

Figure 4: Box plot Phase 3.

In Figure 5, we can observe the reduction of each combination across generations, with the initial images showing closer values, followed by subsequent images displaying a gradual increase in the differences.

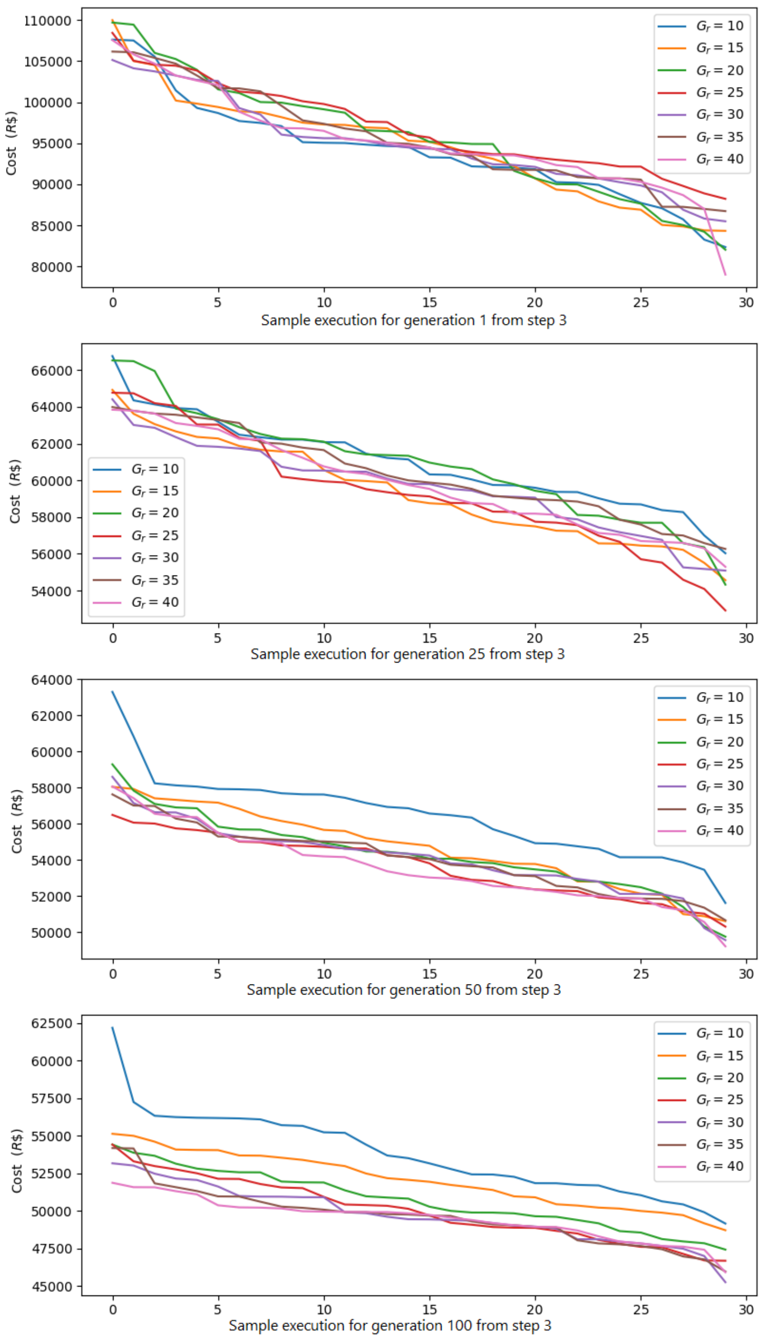

Figure 5: Evolution of costs per generation of Phase 3 executions.

All solution sets for each scenario have a normal distribution. However, the $G_r = \{10, 40\}$ values have the same variance as other values considered in this test. Therefore, these two values were discarded from the analysis. Table 6 shows the mean and standard deviation for each combination that remains in the analysis.

A hypothesis test was then performed comparing the lowest sample mean (Table 7).

Table 6: Mean ($\mu_{\bar{X}}$) and standard deviation($\sigma_{\bar{X}}$) of the samples for hyperparameter combination of Phase 3.

G_r	15	20	25	30	35
$\mu_{\bar{X}}$	52051.13	50736.51	50034.87	49729.81	49632.65
$\sigma_{\bar{X}}$	1837.61	1944.55	2123.97	1892.38	1916.53

Table 7: z-test results for Phase 3.

G_r	15	20	25	30	35
15	-	99.69%	99.99%	100.00%	100.00%
20	-	-	81.80%	95.79%	97.32%
25	-	-	-	44.31%	55.81%
30	-	-	-	-	15.66%
35	-	-	-	-	-

Table 8: Final hyperparameter set.

Parameter	**Value**
G_t	100
M_{max}	15
m_r	0.05
N_s	3
pm_r	0.20
G_r	35

Regarding the results, it is possible to observe that $G_r = \{30, 35\}$ are the best values, and they are statistically equivalent. Nonetheless, we selected a final value of $G_r = 35$, since fewer restarts lead to reduced computational costs. The set of hyperparameters' final values are displayed in Table 8.

2 Case Studies

2.1 Methods Comparison - Networks without DG

Figures 6, 7, and 8 depict the progression of the total cost across the 30 runs of the algorithm, for R_1, R_2, and R_3 respectively. In this scenario, there is no distributed generation in the networks. The sub-graphs illustrate a particular generation.

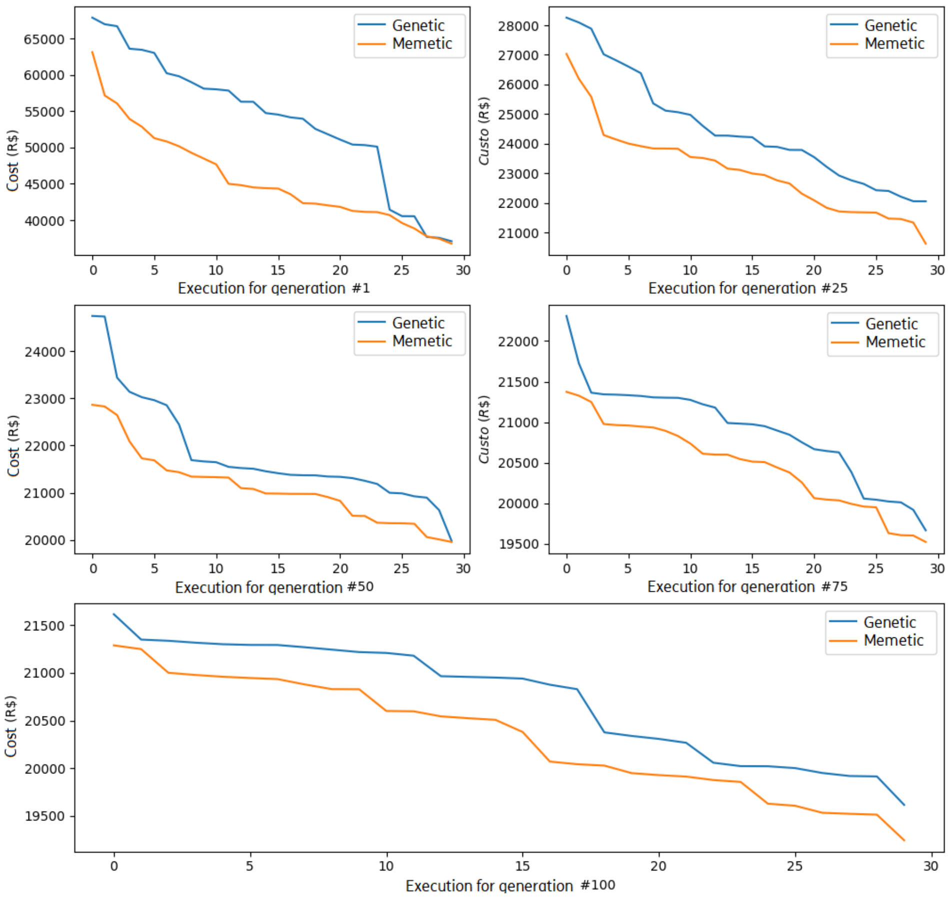

Figure 6: Costs evolution per generation of R_1 network - **without** DG.

2.2 Methods Comparison - Networks with DG

Figures 9, 10, and 11 display the progression of the total cost across the 30 executions of the algorithm, for R_1, R_2, and R_3 respectively. In this scenario, there is distributed generation placed in the networks. The sub-graphs illustrate a particular generation.

2.3 Assess of Distributed Generation Impact

The results with the average execution of the comparison of scenarios with GD versus without GD are shown in the graphs in Figure 12.

2.4 Switches Placement of Best Solutions with DG

Figures 13, 14, and 15, show the best solutions found by the memetic algorithm proposed for networks R_1, R_2 and R_3, respectively.

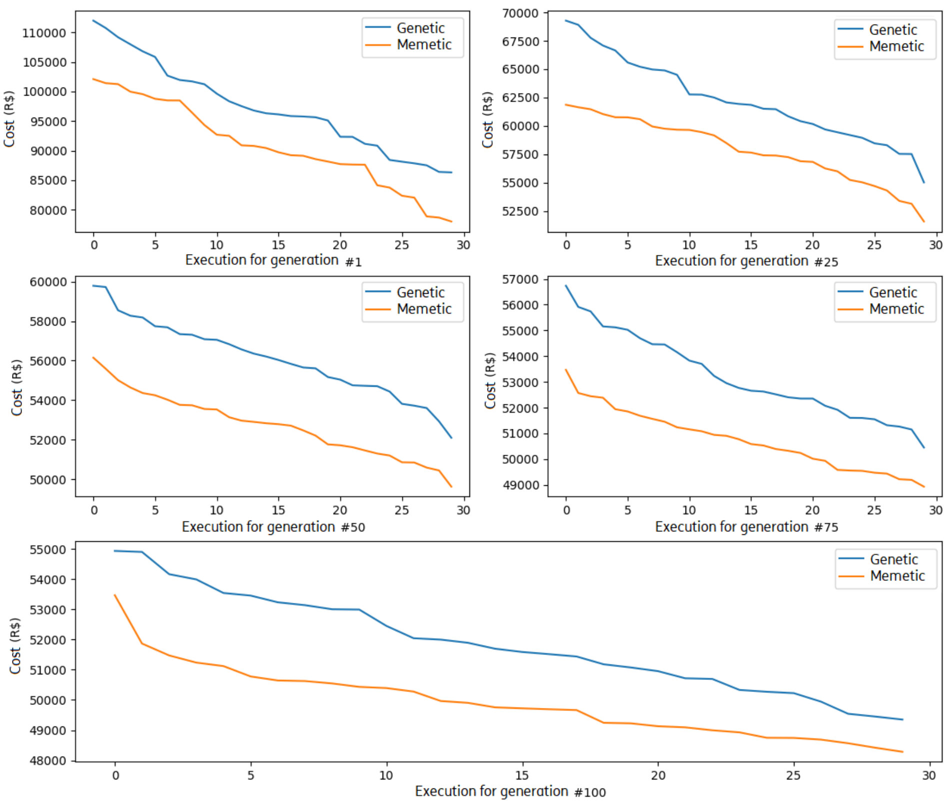

Figure 7: Costs evolution per generation of R_2 network - **without** DG.

References

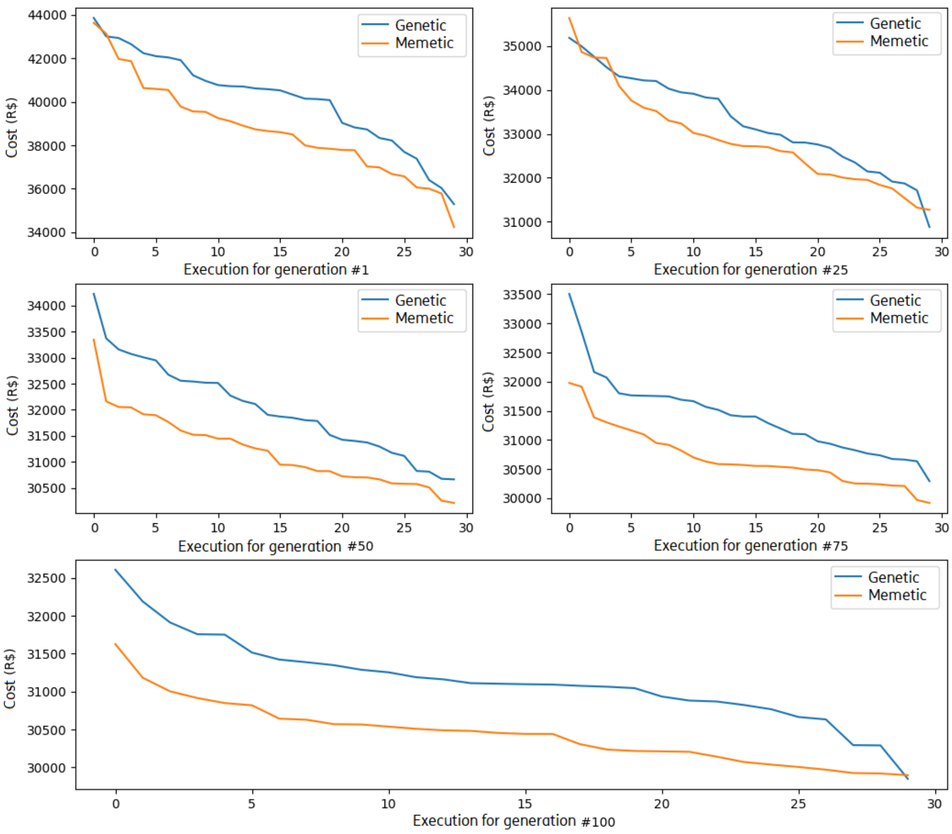

Figure 8: Costs evolution per generation of R_3 network - **without** DG.

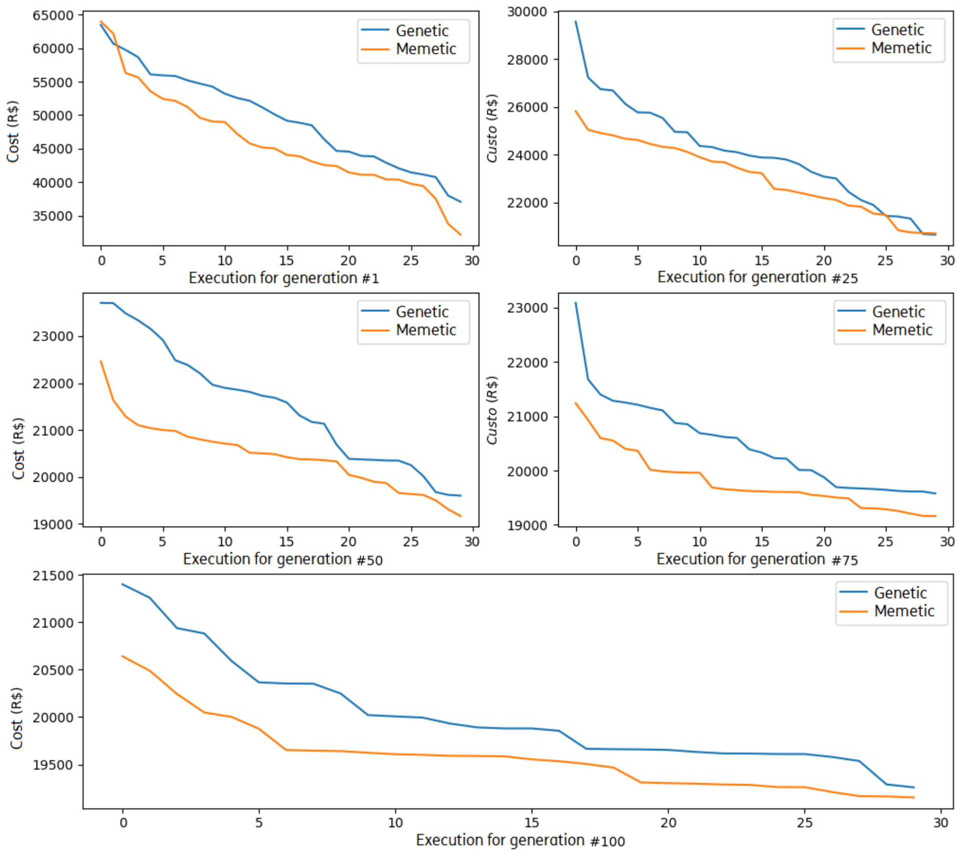

Figure 9: Costs evolution per generation of R_1 network - **with** DG.

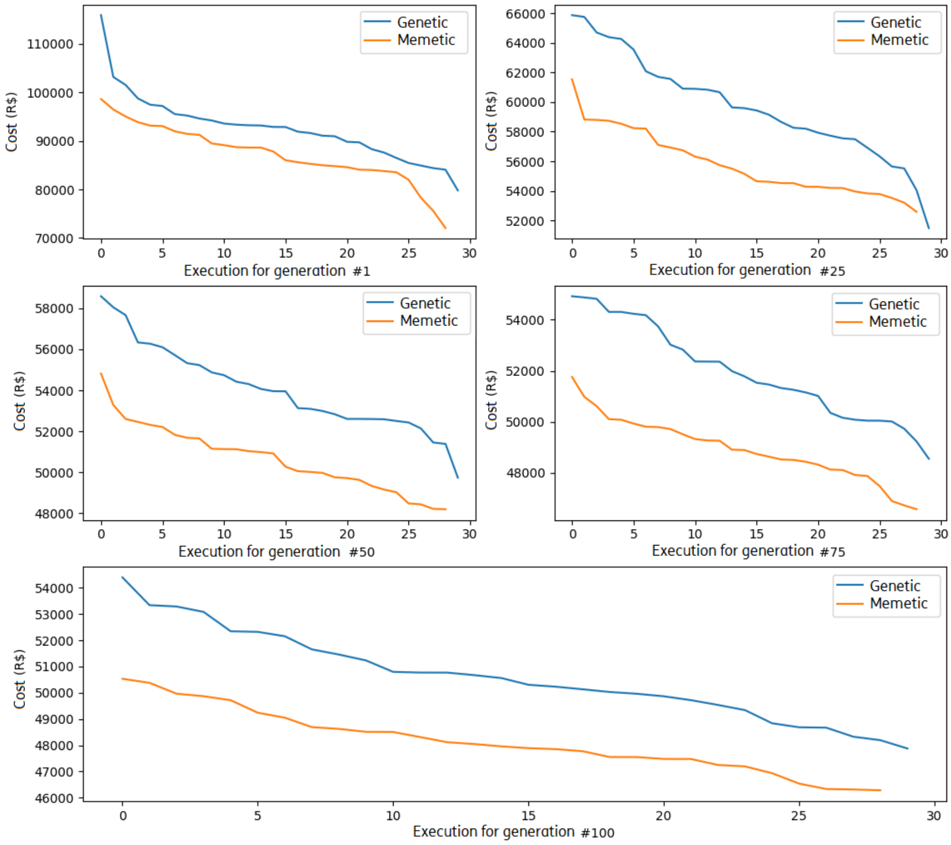

Figure 10: Costs evolution per generation of R_2 network - **with** DG.

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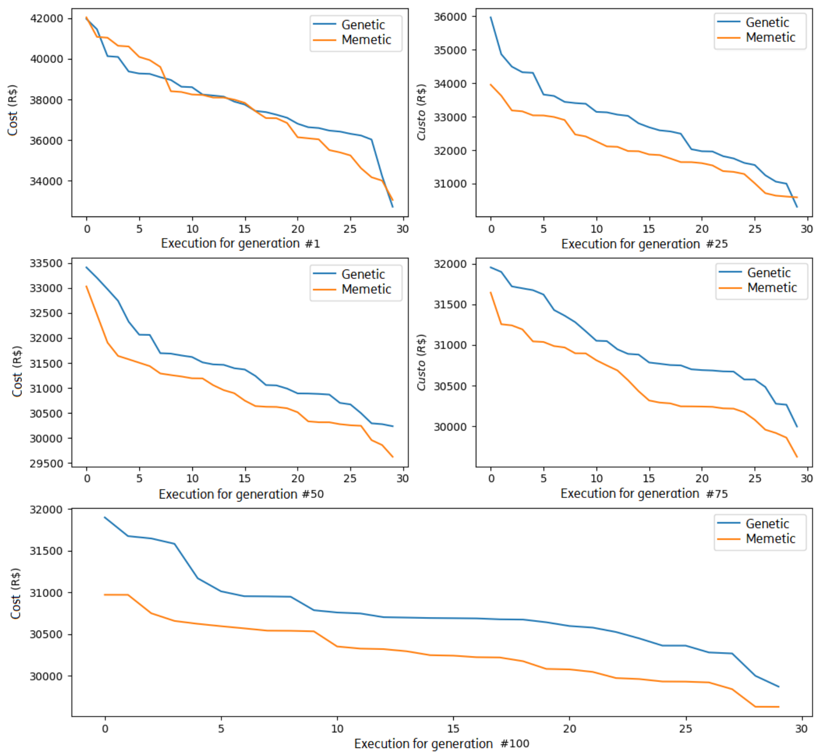
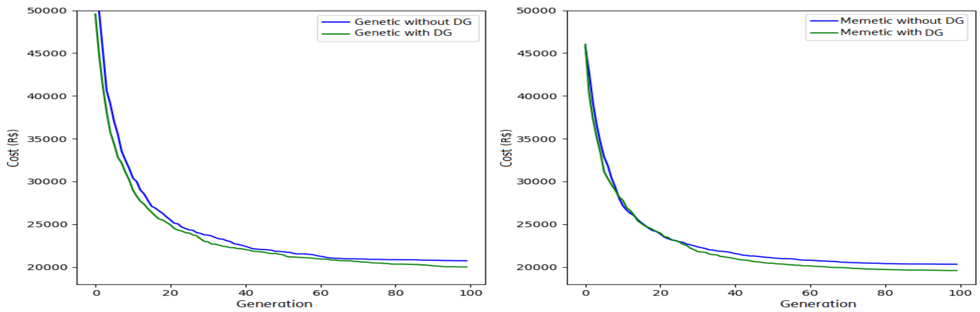
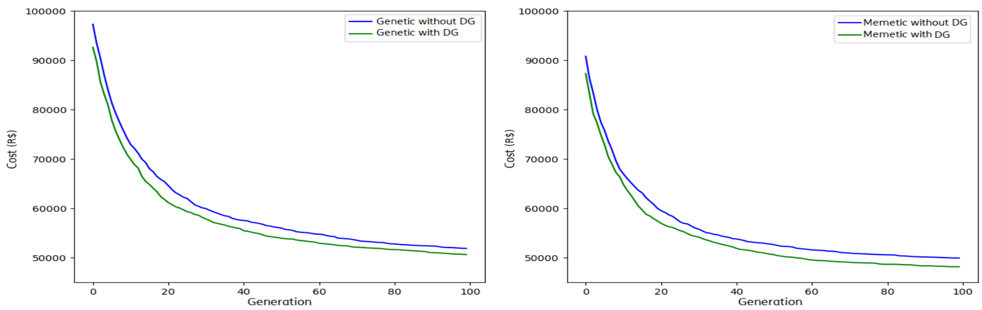


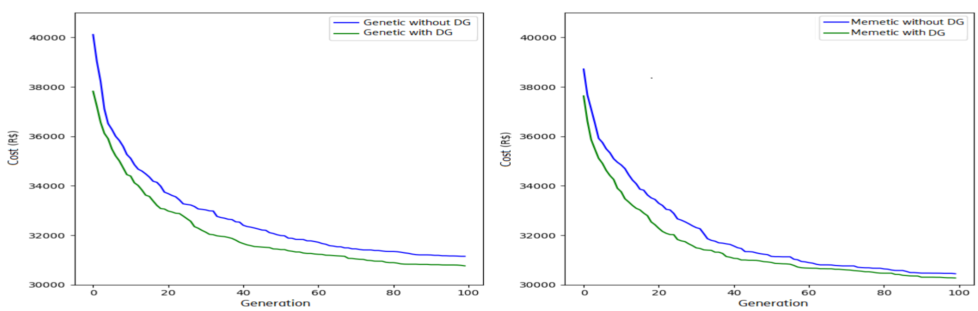
Figure 11: Costs evolution per generation of R_3 network - **with** DG.



(a) Network R_1.



(b) Network R_2



(c) Network R_3

Figure 12: Evolution of average costs per generation (30 executions) per network. Comparison of scenarios with and without DG.

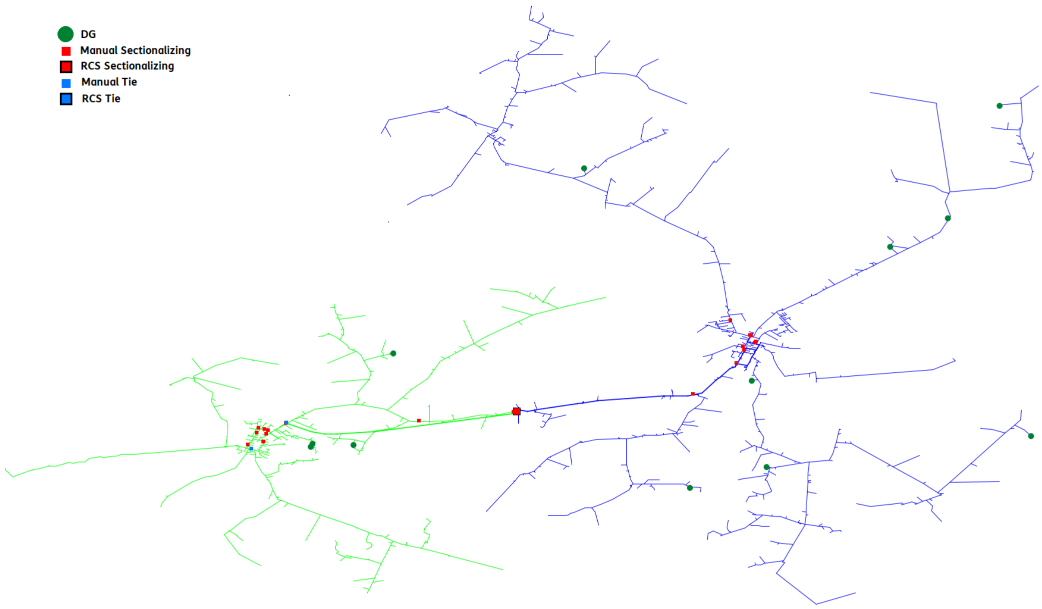


Figure 13: The best solution found by MA **with** DG - Network R_1.

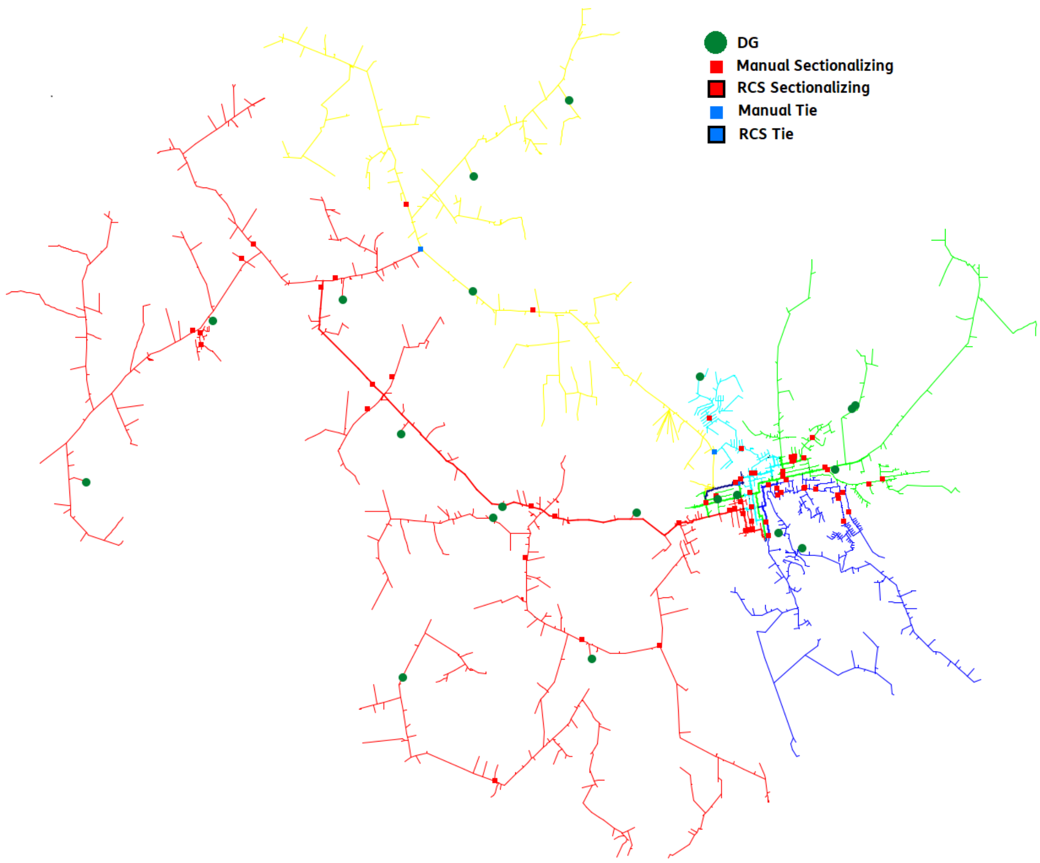


Figure 14: The best solution found by MA **with** DG - Network R_2.

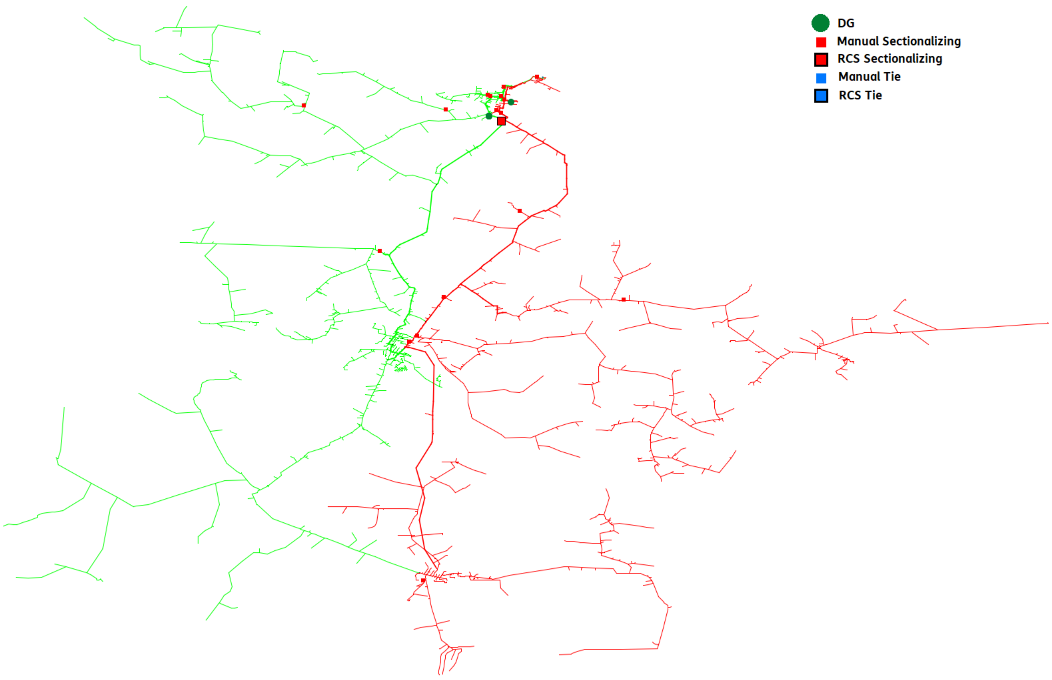


Figure 15: The best solution found by MA **with** DG - Network R_3.