Large-Scale Distribution Planning—Part II: Macro-Optimization With Voronoi's Diagram And Tabu Search

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***Abstract*—This paper is the second of two and presents a planning methodology for low-voltage distribution network planning. Combined optimization of transformers and associated networks is applied, considering the street layout which connects the different consumers. In the first section, a planning zone division into smaller mini-zones is performed; the smaller zones are optimized independently.**

This second section develops macro-optimization methodologies that use the results and techniques of the previous stage, which allow performing a global analysis of the planning zone. Three methodologies are proposed, one based on Voronoi polygons to obtain irregular mini-zones that incorporate proximity between consumers. Another is based on network recombination, with the purpose of finding potential savings produced by combining neighboring networks. Lastly, the sequential application of Voronoi polygons and network recombination is performed.

The methodology is applied to a zone having 20 215 consumers distributed in an area of 12.9 km^2, corresponding to a district in the city of Santiago, Chile, to subsequently apply this to the entire city, an area having a surface of 2118 km^2 and approximately 1 300 000 customers.

***Index Terms*—Low voltage, network planning, power distribution planning, tabu search, Voronoi.**

I. Introduction

THE problem which is solved in the first part of this paper, "Large-scale distribution planning—Part I: Simultaneous network and transformer optimization" [1] consists in the definition of a set of optimum low-voltage facilities for supplying a set of loads, for which only location and demand are presently known. That is, the size and location of the distribution transformers, the layout of the low-voltage network associated to each of the transformers and the type of conductor in each network are identified. The available types of transformers and conductors, capacity limits, voltage drop restrictions and connectivity between among the various consumers are considered.

In order to solve this problem, following the line of [2] and [3], which solve real problems, in part I it was decided that the large-scale planning zone would be divided into smaller zones called mini-zones.

Connected components were determined for each mini-zone, that is, all the independent street network sets existing within each mini-zone. An iterative algorithm, based on the relationship existing between transformation capacity and associated networks, is applied to each connected component. This procedure, known as micro-optimization, starts with the identification of a transformer at the load center; the capacity of the transformer is determined in terms of associated consumers. Subsequently, the network topology was determined by means of a minimum expansion tree aligned with the street topology. Then, the conductor to be used in each segment of the network was determined and, lastly, the cost of losses which act as penalties for voltage drops were included. Thus, the global cost of transformation, conductors and network losses was calculated. The following iteration defines two transformers using k-means, and the same procedure described was performed, finding the total cost of installing the two transformers. The process is repeated until a minimum has been identified, that is, when the total cost is higher in the following iteration. Reference [1] illustrates that this micro-optimization process allows a basic Greenfield planning. However, division into regular mini-zones is arbitrary, because it does not allow a less expensive supply, for certain mini-zone loads, from a transformer in another mini-zone.

In order to incorporate such effect and recognizing that division into smaller zones is necessary for large-scale network planning, this paper proposes three alternatives for a global overview of the problem. These alternatives are called macro-optimization and are the following: Voronoi polygons (Section II), network recombination (Section II), and, finally, the sequential application of both of them (Section IV).

In each section, procedures are applied to the same analysis zone as in [1], that is, a set of 20 215 consumers distributed throughout a geographic area of 12.9 km^2, to finally apply the same to a larger-scale zone in Section V.

II. Voronoi Diagrams

Assuming P is a set of n different points in the Euclidean space $\{p_1, \ldots, p_i, \ldots, p_\mathrm{n}\}$, called generating points, then point x in the plane belongs to the Voronoi polygon, V_i, generated by p_i, if and only if point x is closer to p_i than to any other generator [1]. That is

$$V_i = \bigcap_{j \neq i} \{x/ \|x - p_i\| < \|x - p_j\|, \forall\, j \neq i\}. \qquad (1)$$

The Voronoi diagram represents the union of all Voronoi polygons developed based on the generating points $\{p1, \ldots, pi, \ldots, pn\}$.

This technique has been used for the optimum placement of resources; the work of Akabane should be highlighted [1],

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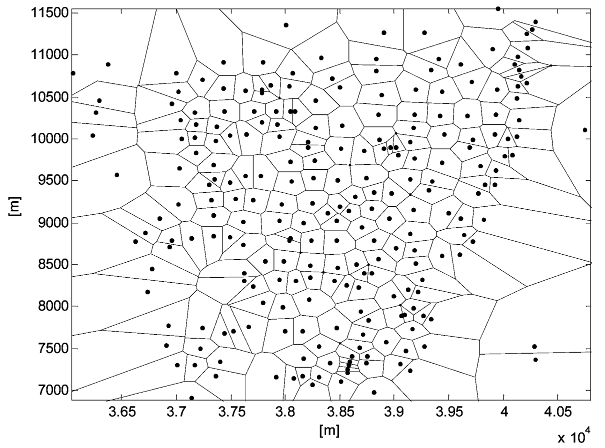

Fig. 1. Planning zone Voronoi diagram.

where control centers for power quality control are located in function of demand and voltage.

This paper proposes the use of Voronoi polygons for the development of irregular planning mini-zones. The assumption is that consumers are better clustered in each polygon. Therefore, the network cost for each one of the polygons is less than in an arbitrary division of the planning zone.

The methodology proposed is to:

1) perform the micro-optimization process in the zone to be planned. That is, dividing the region into mini-zones and optimizing each of one of them;
2) elaborate a Voronoi diagram (with MATLAB). The locations of transformers found in step 1 are used as generating points;
3) apply the micro-optimization process to each Voronoi polygon and each irregular mini-zone.

In applying the procedure to the zone analyzed, the first step results in 284 transformers, with an installed capacity of 54 MVA and a total cost of CLP 1 837 274 576. The output of this step, micro-optimization, is the base case with which the macro-optimization methodologies developed in II, III, and IV are compared.

Subsequently, in the second step, 284 irregular polygons result (Fig. 1), and, finally, when the micro-optimization process is applied to each irregular polygon, step 3, the result is 375 transformers with an installed capacity of 54 MVA and energy savings of only 0.3%.

The number of transformers after step 3 is, necessarily, greater than or equal to the number of transformers obtained in step 1, since these correspond to the generating points of the Voronoi diagram. Therefore, if the desired result is the potential for reducing the number of transformers and thus reducing costs, less Voronoi polygons should be developed. To this purpose, locations in step 1, whose associated transformer is greater than or equal to a specific capacity, are considered.

To the purpose of correctly observing the effect of the number of polygons, the proposed procedure is applied taking as limit different capacity levels (Table I), where 100% represents the total cost of the base case.

To the extent that the limit level increases, and therefore the size of polygons increase, greater savings are achieved

TABLE I
MACRO-OPTIMIZATION WITH VORONOI DIAGRAM

Level (kVA)	Number of Polygons	Total Cost (%)	Number of Transformers	Installed Capacity (MVA)	Processing time (minutes)
10	252	99.7	375	54.3	3.2
15	238	99.3	363	54.4	3.1
30	228	99.1	356	54.1	3.1
45	221	98.8	354	53.9	3.1
75	211	98.2	336	53.2	2.9
100	203	97.4	331	52.9	3.0
150	183	96.5	301	52.5	2.9
300	100	96.1	229	47.5	3.2
500	15	128.8	113	41.2	21.2

versus the initial case. If the limit amounts to 500 kVA, only 15 polygons exist and, therefore, the zone covering each of these is larger. This requires a longer execution period and worsens the solution by increasing costs related to losses. The greatest saving in the case analyzed results when taking into consideration the 300-kVA limit and amounts to 3.9%.

For the creation of the generating points, a complete micro-optimization process is used, which only requires the location of transformers. This situation increases execution time because, subsequently, the micro-optimization process must be applied again to each polygon created to find definitive results. For this reason, the following simplified micro-optimization process is performed.

1) The planning zone is divided into regular zones measuring 500×500 meters.
2) For each mini-zone design power is calculated for the mini-zone under the assumption that such power is supplied by a single transformer.
3) Design power is assigned to the most inexpensive transformer able to supply such power (considering the growth of demand). If there is no transformer within the feasible domain able to do so, a higher-capacity transformer is assigned. Unsatisfied demand is defined as the difference between design power and the capacity of the transformer installed.
4) If the unsatisfied demand is zero, it goes to 5, otherwise it goes to 3. Design power is defined as unsatisfied demand.
5) Once the number of transformers is known, the transformers are placed using a k-means algorithm.
6) Design power is calculated for each cluster and the optimum corresponding transformer is assigned.

This process does not consider street connectivity or the layout of the low-voltage network, but rather seeks a fast and good approximation to the location and capacity of transformers. This reduces execution time for the creation of generating points and the construction of Voronoi polygons and irregular mini-zones from 3 min to 10 s. It should be noted that each of these irregular mini-zones will be later optimized using the nonsimplified micro-optimization process.

By performing the simplified micro-optimization process and considering as generating points for the creation of polygons those transformer locations, whose capacity is equal to or greater than 500 kVA, 68 irregular mini-zones result. By optimizing each mini-zone according to the nonsimplified process, savings of 3.8%, 240 transformers and an installed capacity of 47.68 MVA are obtained.

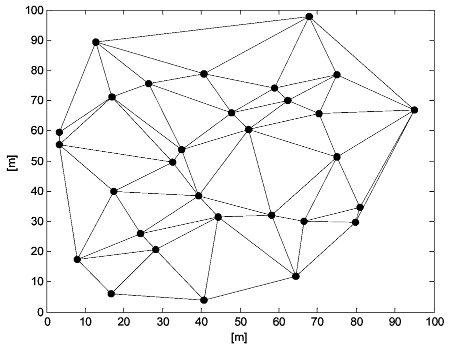

Fig. 2. Delaunay triangulation example.

This procedure does not alter the quality of the solution found and improves the execution time by eliminating the need to perform the complete micro-optimization process twice.

III. Network Recombination

This methodology seeks to improve the solution found after the micro-optimization process by analyzing the existing relationships between different mini-zones. The methodology consists in looking for potential savings produced by the combination of adjacent networks into one single network and, therefore into one single transformer.

Since the networks are spatially distributed throughout the planning zone, it makes no sense to attempt all combinations, and only those which involve adjacent networks should be used. The use of Delaunay triangulation is proposed to determine vicinity relations among the various networks. That is, given a set of points in plane P, a family of disjoint inner triangles, which vertices are P points and in which interior no P points exist, is defined.

In particular, a P triangulation is a Delaunay triangulation if, and only if, the circumference circumscribed to any of its triangles does not contain P points. Thus, the edges will connect close nodes, only if the nodes do not intersect each other. Fig. 2 illustrates Delaunay triangulation for 30 generating points uniformly distributed over a surface of $10\,000\ \mathrm{m}^2$.

In this manner, the only feasible combinations will be those networks which associated transformers, representing the generating points, are connected by the edges of the triangulation.

Once the feasible combinations have been identified, the problem must be solved and, to this purpose, two methodologies are proposed and analyzed below.

A. Solution by Means of Neighborhoods

This methodology consists of using the advantages of dividing the problem into smaller problems, reducing the number of feasible combinations and applying an intelligent clustering of the different networks by means of Voronoi polygons.

Those transformers which have an installed capacity higher than a certain limit, for example 300 kVA, are chosen as generating points and, therefore, each Voronoi polygon incorporates the rest of the closest transformers and their respective associated networks. The following process is applied to each of the neighborhoods and network clusters, given that m is established as the number of neighborhood networks.

1) Determine the Delaunay triangulation. Neighborhood transformer locations are taken as generating points.
2) Determine all the combinations of n networks, with n from 1 to m, from among m neighborhood networks.
3) Review the feasibility of each combination. A combination is feasible if:
   a) all combination elements are connected through triangulation edges;
   b) the combination does not produce connected components, that is, all consumers associated to the combination are connected by means of the street network;
   c) it generates savings. That is, the global cost is lower than the sum of the global costs of each one of the networks that make up the combination. The total cost is calculated by applying the micro-optimization process on the zone determined by consumers that belong to the combination, but only analyzing the installation of a single transformer.
4) Given the set of feasible combinations, all following potential combinations are applied, complete enumeration, taking special care to ensure that the combinations which make up a cluster cannot share a common network.
5) The global saving is determined as the sum of the savings of each combination belonging to such cluster. Finally, the cluster which produces the greatest global saving is chosen as the neighborhood solution.

When applying this methodology to the base case, considering as generating points for the creation of neighborhoods those transformer locations with a capacity greater than or equal to 300 kVA and modifying the number of networks to be combined, from 2 to the greatest number of networks present in one of the neighborhoods created, the following results are obtained.

As illustrated in Table II, although the number of combinations increases savings compared to the base case, it also reduces the speed of problem solving. Therefore, a way to produce relevant savings without the need for extensive execution time is required. To this purpose, the proposed procedure is used cyclically, but only considering combinations of two networks in order to compare only those cases which take less time, since they encompass a smaller planning zone and, additionally, also have a greater likelihood of generating savings than combinations among a greater number of networks. The algorithm proposed is the following.

1) Divide the planning zone into neighborhoods by means of the Voronoi diagram.
2) Perform all possible combinations of two elements in each neighborhood.
3) Determine all feasible combinations that produce savings.
4) Combine feasible networks to produce the final solution.
5) Update the network, including the combinations performed.
6) Return to step 2 until there are no savings in network recombination.

Development is cyclical because even though combinations of two networks are more likely to be feasible, this does not guarantee that combinations of more than two networks will not be feasible. Therefore, allowing the new networks created to

TABLE II
SAVINGS V/S NETWORKS TO RECOMBINE

Number of networks to recombine	Savings (%)	Processing time (minutes)
2	2.51	2.07
3	2.65	3.14
4	2.65	3.73
5	2.68	4.18
6	2.71	4.47
7	2.73	4.55
8	2.73	4.54
9	2.73	4.55

TABLE III
SAVINGS FOR NETWORK RECOMBINATION

Level (kVA)	Savings (%)	Processing time (minutes)
10	0.00	0.1
15	0.22	0.4
30	0.52	0.6
45	0.84	0.8
75	1.06	1.0
100	1.41	1.2
150	2.35	2.3
300	2.93	6.6
500	4.16	16.3

continue to be combined with new networks or with noncombined networks of the former stage, permits the possibility of combinations among a greater number of networks, but makes unnecessary the assessment of all possible combinations, implying execution time reduction.

With this cyclical modification and considering various limit levels for creating neighborhoods, results indicated in Table III are obtained.

Savings increase to the extent that the neighborhood creation limit increases. A limit increase implies less generating points and, therefore, larger neighborhoods with a greater number of networks within them. Thus, if the zones entail greater savings, the possibility of considering the planning zone as one single neighborhood may be analyzed.

B. Solution by Means of a Tabu Search

Consideration of the entire planning zone makes the aforementioned process nonfeasible, since the number of combinations increases exponentially in step with the size of the networks to be combined, which also happens with the number of feasible combination clusters. For this reason and, in keeping with the combinatory nature of the problem, a Tabu search is used to find a solution to the global recombination problem.

The Tabu search was proposed by Glover in the 1980s. It consists of an iterative algorithm that explores the solution space without necessarily being confined to a local optimum. To this purpose, movements which worsen the solution are allowed and the last movements are stored in a list called a Tabu list and cannot be applied in the following iterations, in order to avoid cycles during the optimization process. Thus, the Tabu search is a combination of a local search and a short-term memory. Another element to be considered is the aspiration criteria, that is, if any of the prohibited movements stored in the Tabu list meets a certain condition and improves the solution, it may be released and used in the optimization process, a phenomenon known as strategic forgetting [6], [7].

This technique has been widely used for the solving of complex combinatory problems, and is also used for distribution system planning [8]–[10]. Specifically, in this work, it is used to determine the best set of combinations among networks. The methodology proposed is as follows.

1) Perform the Delaunay triangulation. The locations of all transformers in the planning zone are taken as vertices.
2) All possible two transformers and associated network combinations are executed, only if the same are connected by a triangular edge and a street connection between networks exists.
3) Savings produced by executing the process are calculated for each combination. If no savings result, the combination is no longer feasible.
4) The feasible combinations are organized from greatest to least, in terms of the savings produced by them.
5) The solution is initialized by choosing as the initial value the combination in the above list producing the greatest savings.
6) The best combination is selected from the following.
   a) If the new combination does not combine networks which have already been included in the solution, it is added to it.
   b) If the new combination uses at least one network belonging to the present solution, the new combination is added (worsening of the solution and/or increase of the search space) and all former combinations which involve networks included in the new combination are eliminated from the solution. The eliminated combinations go to the Tabu list and therefore cannot be used until they are removed from the list.
7) The Tabu list counter is reduced by one for each combination included in the same. If the counter reaches zero in a specific combination, this means that it can be released from the Tabu list and can be added once again to the list of feasible combinations.
8) The present list of feasible combinations is organized from largest to smallest.
9) The process continues on to step 10 if
   a) the maximum number of iterations is reached;
   b) the list of feasible solutions is empty.

   Otherwise, the procedure is to return to step 5.
10) If there are no savings, the process comes to an end, otherwise the procedure is to return to step 2.

The application of the methodology proposed for the base case leads to savings of CLP 78 054 181 or 4.2% in 19 min.

Two figures are presented as an example; the first represents the output of the micro-optimization process, made up of 252 networks (Fig. 3), whereas the second indicates the output of the macro-optimization process after recombining the networks, which produces 190 networks (Fig. 4). In both cases the transformers are indicated by a point and the load associated to each network is enclosed using a convex hull.

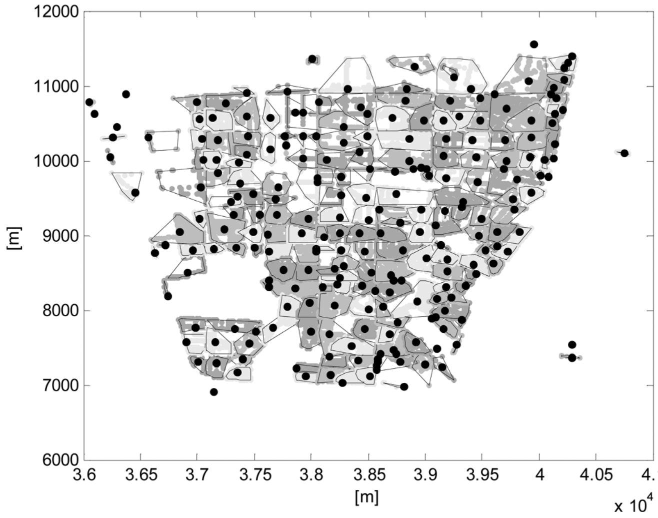

Fig. 3. Network configuration after micro-optimization.

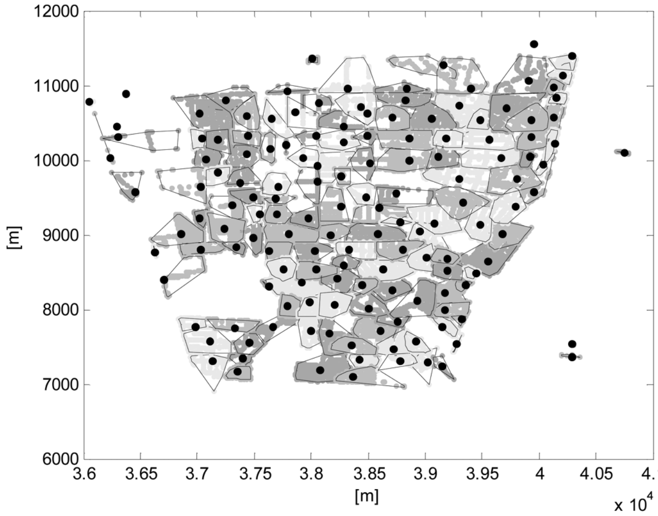

Fig. 4. Network configuration after the macro-optimization.

IV. Sequential Application of the Voronoi Diagram and the Tabu Search

Considering the benefits of the two methodologies proposed, the sequential execution of the previously mentioned methodologies is proposed. Thus, smart clustering resulting from the Voronoi diagram is included and additional information is incorporated, aiming at improving the target function through the recombination of networks thanks to the Tabu search. Therefore the recommended application sequence is the following:

1) simplified micro-optimization, without street restrictions or consideration of the electrical network;
2) layout of Voronoi diagram, considering as generating points the location of transformers obtained in the previous step;
3) complete and detailed micro-optimization of each of the Voronoi polygons;
4) macro-optimization of the recombination of all networks obtained after the micro-optimization process.

Greater savings are produced using this solution, versus the base case: in fact, total savings amount to CLP 135 972 397, distributed between 197 networks, representing a reduction of 7.34%.

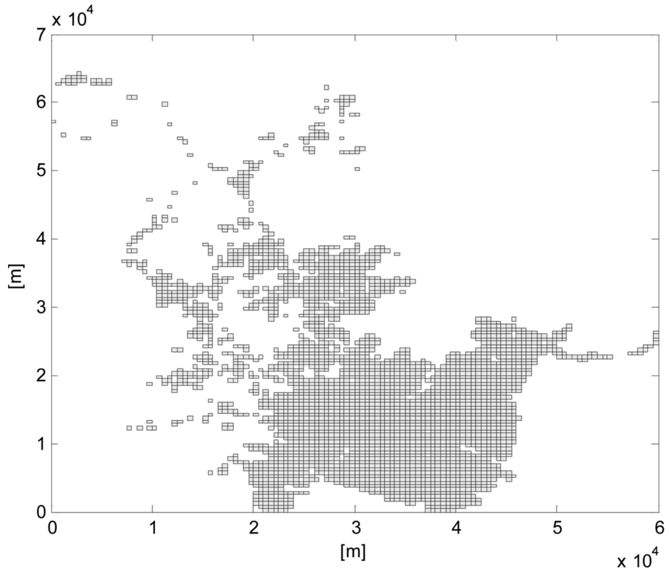

Fig. 5. Large-scale planning zone.

V. Application to Large-Scale System

To the purpose of guaranteeing the applicability of the procedures described above, a large-scale application is performed, both for the micro-optimization process explained in [1] as for the macro-optimization methodologies studied in the present paper. Greenfield planning is therefore resolved for Santiago,[1] a surface of 2118 km^2 which supplies approximately 1 300 000 low-voltage customers.

A. Application of the Micro-Optimization Process

The methodology developed in [1] is the fundamental structure of all the tools proposed, since the same enables the optimization of zones into which the main problem is divided, be these regular mini-zones, irregular mini-zones, or zones with network recombinations.

In order to ratify its convergence, it is applied to the large-scale zone, considering a division into regular mini-zones measuring 500 m x 500 m.

Thus, a total of 3103 regular mini-zones may be optimized (Fig. 5). After ten algorithm executions, a total average cost of CLP 80 093 113 476 is obtained for an average execution time of 168.3 min. Results are indicated in Table IV, considering the average cost of these executions to be 100%.

B. Application of the Macro-Optimization Process

To the purpose of avoiding a potential transformer surplus and eventual additional costs associated to the arbitrary division of the area covered by the analysis, additional methodologies have been developed to provide an intelligent fragmentation of the problem; these methodologies are applied to the larger-scale planning zone.

[1]Chile's capital city, specifically the zone to be planned corresponds to the zone supplied by the distributor Chilectra.

TABLE IV
PLANNING ZONE MICRO-OPTIMIZATION

Executions	Total Cost (%)	Time (minute)
1	99.86	173.5
2	100.08	167.8
3	100.09	167.6
4	99.88	167.6
5	100.22	167.3
6	99.86	168.9
7	99.85	167.4
8	100.13	167.0
9	99.92	167.4
10	100.11	168.7

TABLE V
MACRO-OPTIMIZATION OF SANTIAGO

	Micro-Optimization	Macro-Optimization				
	Base Case	Voronoi Diagram	Simplified Voronoi Diagram	Network union with neighborhoods	Network union with tabu search	Voronoi diagram and tabu search
Total Cost (%)	100	97.69	98.43	96.47	95.07	93.87
Number of Transformers (#)	12.052	11,966	11,815	9,357	8,404	7,686
Network length (Km)	7.822	8,210	8,261	8,167	8,746	8,935
Installed Capacity (MVA)	2.859	2,895	2,892	2,741	2,664	2,625
Processing time (minute)	167	346	184	345	421	391

Since the comparison is done versus the micro-optimization process and such methodology is nondeterministic, a specific methodology launch will be considered as the basis, to ensure that the reference is the same in macro-optimization processes.

Results of the large-base case and the application of the macro-optimization procedures are presented in Table V, where 100% represents the large-scale base case appraised at CLP 79 981 044 404.

Some relevant aspects when determining Table V are as follows.

1) The methodology based on the Voronoi diagram: the locations of transformers greater than or equal to 300 kVA in the base case are considered as the polygon generating points.
2) The simplified methodology based on the Voronoi diagram: it avoids the 167 min associated to the base case. Transformer location is established in only 14 min and transformers with a capacity equal to or greater than 500 kVA are used as generating points.
3) The neighborhood-based methodology: to create neighborhoods, the locations of transformers with a capacity greater than or equal to 500 kVA are used as generating points. There are 4103 neighborhoods determined for the city of Santiago by applying this process.
4) The Tabu search-based methodology: economies stemming from the combination of neighboring networks are sought to provide the best combination among all networks obtained after the base case.
5) The Voronoi–Tabu sequential methodology: This process uses the afore mentioned methodologies in the following order:
    a) simplified micro-optimization (14 min);
    b) complete micro-optimization (170 min);
    c) macro-optimization of Tabu search with single neighborhood (207 min).

The tools developed were successfully applied in the 2008 tariff process of the Santiago distribution company, Chilectra, process that requires the optimal Greenfield design of both the low voltage and mid voltage networks, in a model company tariff approach. The tariff study is done every four years, and the proposed methods were used to design the optimal low voltage network. The authors plan to share the results of this application in a future publication.

VI. CONCLUSIONS

This paper proposes a methodology that allows Greenfield planning for a real size distribution company. The existing relationship between transformation capacity and network cost are considered, as are current street restrictions.

Given that division into mini-zones proposed in [1] is arbitrary, a series of methodologies which rescue the relationships between load and nearby mini-zones were created. Thus, the procedure which provided the best results is the one that applied Voronoi diagrams and Tabu searches in a sequential manner. Thus, optimum planning requires a simplified micro-optimization process in order to obtain preliminary transformer locations and, thus, the creation of Voronoi polygons. Subsequently, each is completely optimized by means of the micro-optimization process indicated in part I, and the networks obtained are recombined in pursuit of savings by means of the Tabu search. This enables the establishment of a planning zone with over one million consumers in 391 min.

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