Heliyon 9 (2023) e12724

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Georeferenced rural distribution network model considering scalable growth of users in rural areas

Juan García [a,b,*], Esteban Inga [b]

[a] *Master of Electricity Program, Universidad Politécnica Salesiana, Quito 170525, Ecuador*
[b] *Master in ICT for Education, Smart Grid Research Group, Universidad Politécnica Salesiana, Quito 170525, Ecuador*

ARTICLE INFO

Keywords:
Planning
Optimization
Heuristics
Resources
Underground electrical distribution networks

ABSTRACT

This paper presents a georeferenced optimal planning model of a rural distribution network for deploying an underground network considering a real scenario for increasing electrification in this area. A model is presented based on a heuristic process that minimizes the resources required to route the grid for a defined time horizon. Then, the model is scalable according to the population density, the established and georeferenced zone, and the specified period; that is, it adjusts to any of these variables. Additionally, the modeling is presented in CYME software, considering a series of technical criteria to provide the actual scenario with a verifiable planning model of an underground network. Therefore, the voltage drop and level of overload in transformers and feeders are considered to deliver an optimum power quality to the end-user. These results will be tabulated and presented as an alternative to different planning and design models that an electric distribution company may have to minimize the resources used in an underground deployment.

1. Introduction

In general terms, the optimal planning models for electrical distribution networks are associated with a particular model applied to traditional electrical distribution networks (EDS) in the search for an algorithm that allows them to minimize resources when planning a network, whether it is an overhead or underground network of a distribution system [1]. However, the proper planning of an underground network is more relevant in the search for minimizing these resources due to its high cost concerning an overhead distribution network. On the other hand, it is worth mentioning that adequate planning of an underground distribution system will allow minimizing the resources used within a network, such as transformers, the planning of civil works, both in the reduction of inspection wells and the route of the pipeline. It will make it possible to reduce the way of transformer station feeders and provide a prediction of the number of circuits suitable for a given transformer station. Thus expanding the network in specific periods, taking into account user demand and the fact that equipment tends to reduce its consumption and not increase, significantly avoids an oversizing of transformer changeability resources [1,6]. An optimal planning problem of an underground distribution network involves a significant number of variables to consider, so throughout this paper, A technique to solve this problem through a heuristic for obtaining an optimal planning model in a georeferenced scenario to offer a scalable-optimal and generic planning model in a rural system in the United States is proposed.

---

[*] Corresponding author at: Smart Grid Research Group, Universidad Politécnica Salesiana, Quito 170525, Ecuador.
E-mail addresses: jgarcia@est.ups.edu.ec (J. García), einga@ups.edu.ec (E. Inga).

https://doi.org/10.1016/j.heliyon.2022.e12724
Received 3 May 2022; Received in revised form 2 August 2022; Accepted 22 December 2022

One of the biggest challenges when defining an EDS or planning a possible expansion of the same is the approach of the resources associated with the planning of a network, as mentioned in previous paragraphs, i.e., several significant variables that are considered; these will depend on how the authors handle their problems. Such is the case of authors like Jooshaki, who propose stochastic models in distribution networks to solve distributed generation problems (DG) [16]. In contrast, Xueqian presents stochastic modeling considering a dynamic correlation and dimension reduction in a distribution network where instead of deterministic models, there are probabilistic models applied to power flows (PPF) [1,24]. In other words, these authors consider a specific objective historical basis in the approach of stochastic models.

Nowadays, EDS with the incorporation of DG and energy storage systems (ESS) [13], have become active distribution networks (ADS), i.e., the traditional EDS that only carries energy to the final consumer now has energy injection employing renewable systems [23]. Therefore, the modeling criteria for the optimal planning of an ADS are much broader as they involve more significant consideration of variables, such as Distributed Energy Resources (DER), in the most economical, reliable, and safe way reliable and secure, considering that DERs have a high level of uncertainty, which increases the complexity of planning and finding a solution. Therefore, multi-criteria models are chosen to find the best planning scenario in an ADS since this type of electrical distribution network considers the insertion of variables such as renewable energies. [31]. However, it is not necessarily possible to resort to stochastic models when dealing with DG; other authors, such as Xiang, who proposes resilience in a redistribution network with the insertion of DG, submit hierarchical clustering algorithms based on the tree edit distance (TED), i.e., applying graph theory [37,20]. On the other hand, problems associated with the resilience of an EDS are generally not addressed through graph theory; authors such as Saboori aim to improve the strength of an EDS by optimal planning of energy storage systems through a nonlinear mixed-integer optimization problem (MIP) and is solved through a particle swarm optimization (PSO) algorithm, [27]. As mentioned in the previous paragraph, an ADS should consider many variables in its planning. In this context, authors such as Ghanbari also propose the insertion of non-renewable energies and energy and heat storage systems into the ADS [11]. It is possible to consider the insertion of electro-power stations [30], considering the microgrids attached to the ADS; this is known as Vision of Future Energy Networks (VOFEN), which consists of the use of multiple energy systems (MES). Therefore, this author proposes an optimization model that considers all these variables inserted into the multi-carrier microgrids for optimal planning of an ADS.

Despite these new technologies, what is intended is to analyze a traditional DSG, commonly found in a rural scenario, which may contain renewable energy consumers, but not customers that inject surplus energy to the grid, i.e., discarding DG ESS and MES technologies. Consequently, the proposed scenario is reduced to a traditional EDS in a rural sector, for which some variables and design criteria are much less than an ADS [8].

Then the starting point is reduced to the authors who propose the best planning methods when there are no or poor historical-statistical data available for a given EDS [10] to be planned or expanded, where most authors suggest the use of a clustering method based on graph theory, i.e., solving a heuristic problem. The distribution network will be simulated using appropriate software such as CYME to give a more significant amount of technical criteria to the heuristic problem posed. After the algorithm's approach and results, it will allow obtaining an optimal allocation of resources in a given case study, minimizing the number of resources to get an optimal and scalable planning model in a georeferenced rural sector scenario.

For the optimal deployment of an underground network, it is necessary to reconstruct the proposed scenario; since the data are extracted through OpenStreetMap, both the rendering of the figure and the latitude and longitude data of the area or plan that are selected for the study, to later recover, debug and sort those data in the MATLAB software, as it will be exposed throughout this document.

What is intended to be solved in the optimal planning is to give a time horizon to the heuristic problem posed based on the proposed real scenario, where users will have a random expansion character, simulating the expansion of the network or the increase of users in 5 years. Furthermore, a percentage of 20% to reach the total number of end-users will allow solving one of the objects of this document, which is the increase of electrification in an authentic rural scenario.

It is worth mentioning that the Dijkstra algorithm is used for planning models, as stated by Pavón [25]. His article allows finding the shortest route between the elements that make up an area distribution network, both in the shortest connection path between users and poles and between poles and transformers, resulting in a minimum spanning tree (MST). Hence, considering its characteristics, the model also applies to an underground network.

Consequently, the algorithm does solve the optimization problem combined with the planning problem since the randomization algorithm of the users considers the actual location of the houses in the scenario and does not repeat the houses in a specific time horizon, but the sum considering the expansion of the network. However, the proposed scenario considers a unified stratification model for all the users. It corresponds to a scenario of 380 users, so a rural area can be considered [37].

It has been mentioned that the described algorithm solves the network expansion problem, gives an optimized result in a proposed time horizon, but it is necessary not only to corroborate the optimization of the problem, since some authors such as [25,32], have solved these problems, however it do not expand the technical criteria involved in the voltage drop problem that may present the feeders of each of the transformers, so the CYME tool was used, which allows modeling overhead and subway distribution systems. This allows solving and increasing the number of technical variables considered, such as the voltage drop of the feeders, and the chargeability of the transformers over the 5-year time horizon, since the chargeability and voltage drop allow knowing if the criteria solved by the algorithm are really useful in a real scenario and in a way give an indication of the quality of energy delivered to the end-users and the pressure to which a transformer station is subjected as the network expands, with the resulting resource optimization.

Therefore, the main contributions of this paper will be a planning model considering the quality of power reaching the end user in a rural scenario in the USA by determining the shortest distances in the search for resource optimization. Taking into account the

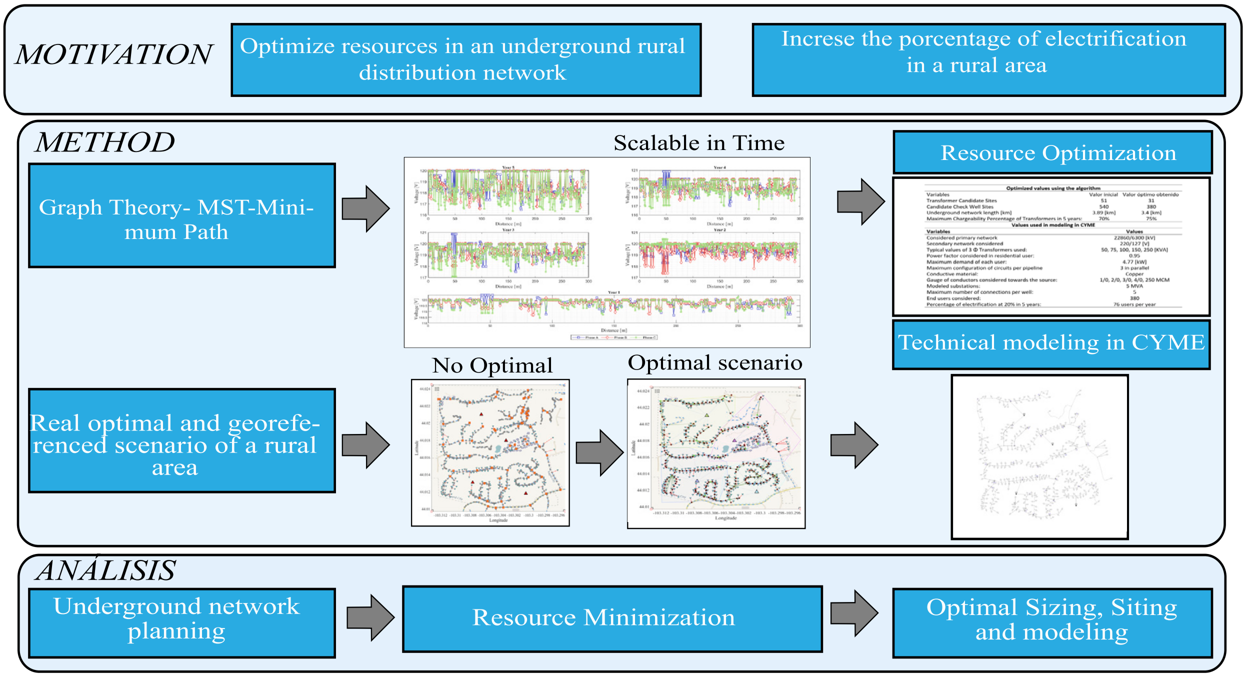

Fig. 1. Georeferenced optimal planning proposal for a rural distribution network.

voltage drop analysis in a given time horizon, where the results are obtained by running an unbalanced power flow, i.e., additional constraints are posed, from the energy point of view, both in the algorithms and in the CYME modeling.
Therefore, the contribution of the optimal modeling of the planning of a subway network for a rural area proposed in this paper considers technical criteria associated with power quality in an ESD, unlike other authors who only propose to solve heuristics without previously modeling the network, nor presenting a georeferenced model, nor focusing on the most relevant standards such as power quality from the point of view of the end-user to the transformer. Another way of understanding this implies that the planning model can be considered to give a more realistic approach to electrical design in the realm of subway distribution systems, delving into optimization and planning without neglecting the technical criteria mentioned above. [26].

In Fig. 1 shows a conceptual graph of the proposed georeferenced optimal planning model when the objective is to optimize resources in a rural underground distribution order to increase the percentage of electrification of the area. The method described in the figure is the one that is being used throughout this document. The method described in the figure is the one that is being used throughout this document where through the use of MST (Minimum Spanning Tree) in a non-optimal georeferenced scenario. It is intended to reach an optimal georeferenced scenario, thus optimizing the resources over time. Then, in the optimal scenario, propose realistic modeling in CYME to obtain the voltage profiles and analyze the power quality of the end user. The present proposal does not work on a classic model of a defined number of busbars, which implies a significant innovation. The proposal includes a planning model that considers scalability in the growth of the users referred to in terms of electricity demand. The system model is then simulated in specialized software to evaluate the heuristics. Henceforth, the present article is organized as follows: Section 2 presents a brief review of related work. Section 3 presents the traditional problem formulation and the methodology to solve it. Section 4 contains the results' analysis and the proposed model's validation. Finally, in section 5 conclusions are presented in this article.

2. Related works

Specifically, the use of graph theory in the planning of an EDS starts from a problem of optimal resource allocation, in which the aim is to find the most appropriate routing between users and the different elements that make up an EDS [36], this optimal location and sizing of resources require prior planning, which is achieved through various clustering models.

Not necessarily the problem can be treated in a real scenario and much less be only about the optimal location of the elements that make up an EDS, authors such as Zhang propose the optimal site of Distributed Renewable Generation (DRG) in EDS, using a proposed clustering model and making a brief comparison between other models [40]. Most authors propose DSGs with radial topologies due to the low installation and maintenance costs; despite this, there is a discrepancy since these radial models fall short of in-service restoration to the end-user. Therefore, authors such as Sekhavatmanesh propose real scenarios, applying clustering methods [28] to plan an ADS, where the service restoration requirements are a variable to be considered within a finite system. An Immunological Algorithm (IA) is applied to solve the nonlinear optimization problem.

Despite the existence of different types of electrical distribution systems, at present, any planning model must be projected to the needs of the users, providing them with a high quality of energy regardless of the geographical characteristics, such as a rural area, a city with a high population density or an ecological reserve, practices and environmental factors that must be considered when presenting a georeferenced planning model.

However, certain technical and economic limitations can simplify the restrictions considered in elaborating a georeferenced optimal planning algorithm, such as the spans considered for the poles in case of the overhead network and the revision wells in case of the underground network. The topology of the proposed scenario must be considered, among which the intersections and streets will allow delimiting the necessary vectors for the reconstruction of the system, and the proposal of a non-optimal scenario [34].

These aforementioned variables are only part of the consideration of the scenario itself, since the randomness of the population of a particular sector has a high degree of uncertainty, that is to say, the final users or houses considered have a high degree of randomness at the moment of being established, but one can be confident that at the moment of proposing the design of an urbanization or community the lots or houses can be defined as such and as these are acquired by the users this population growth makes sense. This can be controlled as is the proposed planning model where the randomness of this is 20% population growth per year, until reaching a ceiling of 100% in a period of 5 years, understanding this as a problem where it is necessary to increase the percentage of electrification and expand the network, other authors consider random population increases, however the algorithm proposed in this paper is scalable for any actual and reasonable scenario, to which a network can be expanded, modeled, planned and designed [19].

2.1. Considerations in the optimal planning of underground distribution networks

Of course, there is a moderate increase worldwide of underground networks, for aesthetic reasons and implementation of new technologies in public lighting systems and underground networks, compared to traditional aerial EDS, whose cost is lower than a subway EDS, as mentioned above by the authors in their documents. Despite their cost aesthetically more viable, the underground networks currently have a higher level of security than the aerial networks, as mentioned in the literature. Therefore, the treatment of minimizing resources in an underground network is fundamental, both for any design and planning model [38,21,18].

Therefore, it is stated that the underground electrical distribution networks are mainly used for urban reasons for all types of residential users, cities, and metropolises. However, it can and is used in the city's outskirts in private urbanizations or in communities where autonomous decentralized governments seek aesthetic and technical urban alternatives that solve the problem of electrification expansion. Eventually, there will also be the seismic consideration of the area or region, but in urbanizations outside the cities, it becomes very viable due to a large amount of green space and the type of buildings considered as such in urbanizations [18].

The advantages and feasibility of underground networks in rural-residential sectors were mentioned in previous paragraphs. In most literature, there is a deficit in estimating the costs vs. benefits of planning methods in underground electrification networks by the companies in charge of distribution systems; for this reason, it is relevant to propose a planning model that allows the development of the urban environment and solve the technical needs of electrification. As such, an underground topology is usually in a ring, traditionally for cost reasons, which is why the channeling proposed along an underground network must respond to a series of technical criteria, such in the civil work, reinforced smooth PVC pipes of 4 to 6 inches are usually used, with a tri-duct for the passage of the telecommunications system. However, this channeling often responds to the needs of the topography of the region being analyzed. The cost is reduced to a great extent by the number of review wells [2]. Generally, the revision wells are standardized according to the region. Usually, it has different measures depending on the section of circuits; it has and is usually necessary for maintenance or reconnection operations, being these revision wells and respective channeling are reduced according to the needs of the users and the nearby transformation and sectioning centers by proposing an algorithm that allowed to obtain the minimum distances between the different elements mentioned in this document. It is possible to optimize the resources satisfactorily. Then the starting point in searching for an algorithm for the optimal planning of an ESD will be the use of graph theory, as mentioned throughout this document. It is applied in a real scenario, a rural sector, defined later, attending to this need for georeferencing; authors such as Pavón propose heuristic methods in the optimal routing of a subway EDS [25], providing as a basis a georeferenced scenario. It defines as restrictions on a particular physical space and a certain number of users, from which the idea of the algorithm to be proposed will start, to subsequently develop a simulation of the optimal network proposed.

Continuing this trend of heuristic methods, authors such as Valenzuela propose a georeferenced optimal planning model, with a user coverage capacity of 100% [33,15], through the implementation of Minimum Spanning Trees (MST) techniques, which is an additional constraint that is not much addressed in Pavón's article; however, both pieces propose subway EDSs with radial topologies.

EA subway EDS is more expensive than an overhead EDS; however, for a rural network, an overhead EDS with a radial topology will be strictly considered, so it is necessary to consider considerations associated with the design of an EDS for rural users. These regulations will define the technical needs at the time of planning the equipment, which will allow an adequate arrangement of these, respecting the essential design criteria such as admissible voltage drops, circuit layout, and configuration, design demand as well as the selection of conductors and rated capacity of the equipment in a Medium Voltage (MV) network [35,4].

As observed in some articles, distribution companies at the local level tend to stratify users according to a consumption prediction. Then, to propose the algorithm, we will consider residential and industrial rural users of medium and low impact, i.e., the lowest stratification for the residential part. In contrast, for industrial users, we will consider the considerations described in the regulations of the distribution company that has the scope in the rural area being analyzed [29].

Eventually, we can define that the algorithm could be sought for a rural overhead EDS with radial topology when analyzing these articles. It will be through graph theory, applying a heuristic method based on MST [29], where the optimal routing of MV feeders will be sought [18], where the optimal routing of the MV feeders will be pursued [4], as well as the optimal transformer assignment. [26] as well as the optimal allocation of transformers [7,22] It does not mean that the algorithm to be proposed is intelligent planning

Table 1
Summary of related works.

Author, year	Objectives	Parameters considered				Thematic		
		Voltage	Capacity	Cost	Geo-referenced	Planning	Resilience	Graph theory
Bosisio, 2021 [5]	Minimization of cost	✓	✓	✓	-	✓	-	-
Youssef, 2021 [39]	Load loss reduction	✓	✓	-	-	-	✓	-
Bonetti, 2021 [3]	Minimization of capacity	✓	✓	✓	✓	✓	-	✓
Maleki, 2021 [21]	Design representative networks	✓	✓	-	✓	✓	-	-
Leite, 2021 [17]	Power system restoration	✓	✓	✓	-	-	✓	✓
Hamza, 2022 [14]	Power loss reduction	✓	✓	-	-	-	-	✓
Present work	Optimal Planning EDS	✓	-	✓	✓	✓	-	✓

Table 2
Equations Variables of the Model.

Nomenclature	Description
n	Number of users
kW	Demand of each user
FP	Power factor defined for a residential user
l_t	length between circuit sections
KVA_m	Apparent power in each section of the network
k	Constant corresponding to the maximum voltage drop of 1%
r	Feeder resistance is given in micro ohms
x	Feeder reactance is given in micro ohms
V	Nominal voltage of the feeder
T_f	Voltage drop percentage
KVA_{con}	Apparent power of the feeder
D_t	Spherical distance between a point i;j
r_t	Terrestrial radio
Lat	Latitude
$Long$	Longitude
Δ_{Lat}	Difference between initial (i) and final (j) latitude
β_{ij}	Optimal connection between wells
P_j^{well}	Optimal review well
r_{max}	Maximum distance established between the optimal transformer and the optimal well
d_{min}	Minimum distance between nodes
d_{ij}	distance between a node i to j
G	Connectivity Matrix
V	Set of all user-nodes
E	Set of all possible connections (between edges)
$x_{i,j}$	Node traversal from $i \rightarrow j; \forall i, j$
$C_{i,j}$	Node traversal cost from $i \rightarrow j; \forall i, j$
$e_{i,j}$	It represents the relationship between the cost of the underground network and the minimum cost from $i \rightarrow j; \forall i, j$

[9,17,12] because it involves other Distributed Energy Resources (DER) considerations, all this more associated with an ADS than an EDS.
The Table 1 summarizes the related works selected for this research.

3. Problem formulation

Consequently, to formulate the optimal georeferenced planning problem for rural distribution networks, a heuristic method was proposed as a mathematical model to minimize the cost of the resources used in routing the network, thus optimizing the technical conditions associated with the routes of the feeders. This way, the technical conditions associated with the feeder routes are optimized according to their distance and the topological-geographical conditions of an underground network in a georeferenced scenario, considering increasing the percentage of electrification of the scenario by establishing case studies for five years where the initial percentage of users will gradually and randomly increase over the final scenario. The Table 2 shows the variables used in to denote the respective equations.

It is necessary to find the optimal location of the transformers considering their capacity, the number of users, and the voltage drop from the transformer to the end-user and the transformer to the substation. The voltage drops of 3% at a voltage level of 22860/6300V for the medium voltage network are considered. It is raised in this document that these reference values are taken from local regulations for the design of distribution systems. The voltage drop of the secondary circuits will be calculated as a function of the apparent power in each section of the network model according to equation number (1), where the length between the sections of the circuit gradually increases the percentage of final voltage drop since this apparent power will be a function of the number of users and their demand, in a directly proportional way. The energy per meter of the feeder is given by equation number (2). The equation is the function of the resistance and reactance of the feeder itself. As well as of voltage to which this feeder is

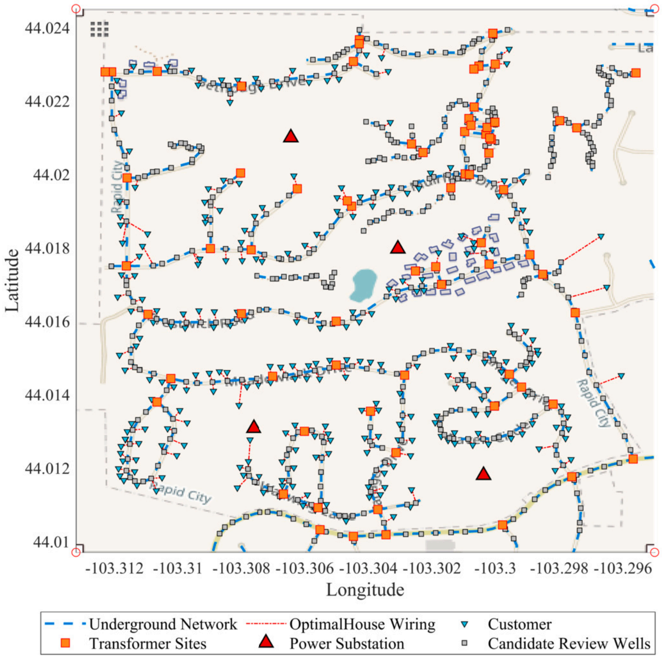

Fig. 2. Non-optimal final scenario proposed.

subjected. Then, considering that a three-phase network is modeled in this way, the voltage drop will be given by the sum of the division between the voltage drop per span and the voltage drop of the feeder, as shown in equation number (3), so it is evident that the voltage drop will be a function of the demand, of the distance to which the feeder is subjected and of the feeder's characteristics.

$$KVA_m = n * \left(\frac{kW}{FP}\right) * l_t \tag{1}$$

$$KVA_{con} = \frac{k*(V)^2}{r*\cos(FP)+x*\sin(FP)} \tag{2}$$

$$T_f = \sum_{i=1}^{n}\left(\frac{KVA_m}{KVA_{con}}\right) \tag{3}$$

On the other hand, to solve the optimal planning problem mentioned in this document, as indicated in previous paragraphs, a heuristic model is proposed, based on the minimization of routing costs on a real georeferenced scenario, to generate the optimal routing of a rural distribution network, taking into account the capacities of the transformers according to the users.

It aims to establish the most feasible minimum distance relation between the user and the transformer, taking into account voltage drops of less than 3%, guaranteeing the satisfaction of the end-users and a cost reduction concerning the proposed optimal undergrounding. In other words, each proposed transformer chamber will accommodate the maximum number of users in a range of coverage that allows it to have the minimum voltage drop, depending on that transformer chamber, respecting the condition of maximum voltage drop of 3% and respecting the proposed optimal routing, both in the electrical part and in part associated with the civil work.

The connection nodes of the users' service connections to these nodes will be a representation of the optimal revision wells, respecting a maximum distance between these revision wells of 40 m, as established by local regulations, but only selecting those wells that have at least one connection service connection, discarding those nodes-wells that do not affect the structure of the proposed channeling-underground.

Many variables to consider have been mentioned, so the optimization problem is solved by employing a heuristic, where initially, a non-optimal georeferenced scenario of the United States is used with UTM reference coordinate 635766.500; 4875238.029, as shown in Fig. 2.

It will have 380 users in a georeferenced scenario, indicating the 51 candidate sites of the transformers and the 540 candidate sites of the revision wells. Without optimizing it, the channeling and route of the underground feeder will be 3.89 km, as well as the optimal location of the substations and the optimal connections between the user and the nearest revision well, which will be the starting point of the optimal planning of the proposed scenario.

Consequently, to determine the minimum distances in the proposed scenario, the Haversine formula is used to find the minimum distance between two points of a georeferenced system through the geographical coordinates of latitude and longitude denoted by the expression (4). The expression defines a variation between latitudes and longitudes considering that this expression will allow calculating the distance between the geographic coordinates to be analyzed and the equation (5), it is part of the Haversine formula considering the spherical radius between an initial and final node.

Table 3
Variables used in the algorithm.

Nomenclature	Description
x_h, y_h	Coordinates vector for users-households
Y	Set of combined users and households
x_{tr}, y_{tr}	Transformer candidate site coordinate vector
x_{poz}, y_{poz}	Check-hole candidate site review wells ≤ 40
x_{sub}, y_{sub}	Substation coordinate vector
$p_i(kt)$	Vector that predicts the randomness of the scenario, for each year of study
d_i	Random vector with the positions for each year of study, avoiding repetition of the positions in the same scenario
c_i	Coordinates position vector that occupies that position
$comp_{(i)}$	Vector of the comparison between randomized, available, and unavailable households
v_{ix}	Vector of randomized households, by year in the latitude coordinate
v_{iy}	Vector of randomized households, by year in longitude coordinate
Gr_i	Vector of randomized households, by year in latitude and longitude
G	Connectivity Matrix
$ways$	Vector containing the reconstruction of the streets, using the graph
$Long$	Longitude
$Dist_{haver}(i,j)$	Haversine distance, calculated for the different cases
Poz_{minxy}	Minimum distance between the user and review well, (optimal review well)
$clus_{op1}$	Cluster containing the optimal burial and the optimal review wells used
tr_{minxy}	Minimum distance between review well and transformer, (optimal transformers)
sub_{minxy}	Minimum distance between transformer and Substation, (Substation Coverage)

$$\begin{aligned} D_h = \left(\frac{d_t}{r_t}\right) = \sin^2\left(\frac{\Delta_{Lat}}{2}\right) + \ldots + \cos\left(\Delta_{Lat_i}\right) \\ + \cos\left(\Delta_{Lat_j}\right)\sin^2\left(\frac{\Delta_{Lon}}{2}\right) \end{aligned} \tag{4}$$

$$d\,(i;j) = 2\arcsin\left(\sqrt{D_t}\right) \tag{5}$$

Once the Haversine distance is defined, we could define the variables that will allow us to formulate the necessary algorithm for the optimal georeferenced planning model. Then the expression referred to will correspond to an ordered pair, known as the connectivity matrix, which will contain the set of all user nodes and the set of all possible connections between all edges of the scenario, as presented in equation (6).

$$G = (V, E) \tag{6}$$

Next, understanding that the underground network is modeled, MST will be considered in order to define the objective function, it allows minimizing when it is assumed that there is an origin node of the underground network to a destination node. Consequently, it is possible to define an objective function for the georeferenced optimal planning of a distribution network for the rural area proposed as an equation (7): Objective Function:

$$\text{Min: } \sum_{i=1}^{n}\sum_{j=1}^{n} C_{ij}x_{ij} = \sum_{(i,j)\epsilon U} C_{ij}e_{ij} \tag{7}$$

Subject to:

$$\sum_{(i,j)\epsilon U} \beta_{ij}^{n} = P_j^{well}, \quad \forall_j \epsilon U \tag{8}$$

$$\left(\sum_{j\epsilon U} P_j^{well} \leq T_j^S\right) \leq rmax, \forall_j \epsilon S \tag{9}$$

$$\Delta_{cluster(n-well)} \leq 3\%\ (T_f) \tag{10}$$

$$d_{ij} \leq d_{min} \tag{11}$$

Equation (8) refers to each user's service connection being connected to the nearest optimal service well, and in turn, this process is carried out in all optimal service wells, thus guaranteeing the elimination of unnecessary service wells, i.e., optimizing the service wells and the service connections of the houses, according to the non-optimal modeling.

In turn, the equation (9) establishes that each service connection when the optimal well is located makes the connection to the nearest transformer and that this, in turn, does not exceed an established maximum distance or range between the optimal transformer and the well. Therefore, limiting the maximum capacity of users in a transformer and eliminating the candidate sites that were possibly not discarded, thus optimizing the transformers.

Equation (10) establishes a maximum voltage drop percentage of 3% from the end user to the nearest optimal transformer; equation (11) fulfills the condition of building the minimum cost tree subject to the minimum distance, looking for minimum connection routes between substations, transformers, wells, and users as far as the proposed network is concerned.

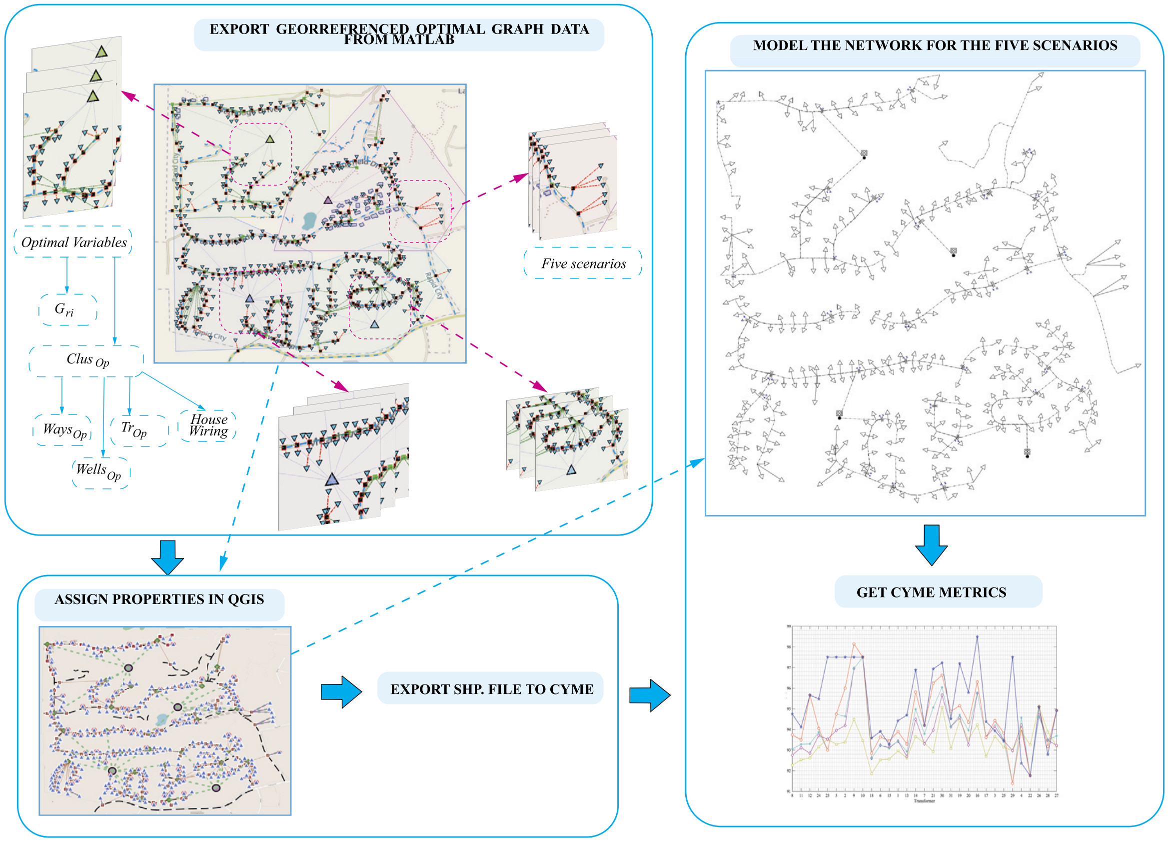

Fig. 3. Methodology used in CYME.

However, as mentioned in this section, the objective is to establish an optimal, georeferenced and scalable planning model, where the model's scalability is achieved by selecting 5 case studies. The algorithm considers that the end user is randomized in groups of 76 users per case study; that is, there will be an increase of 76 users per year randomly and in their real position concerning the final scenario, which will allow modeling a CYME network with a 5-year projection for the transformers, not exceeding their chargeability by 85%, until reaching the last system.

The variables used in the different pseudocodes for the georeferenced optimal planning mathematical model for a rural subway distribution network are shown in Table 3, while Algorithm 1 shows the pseudocode used in MATLAB, and Fig. 3 shows the conceptualization of the methodology used in CYME, where the coverage of the substations will depend on the number of transformers close to the substations, i.e., the minimum distance from the substation to the modeled optimal transformers.

Algorithm 1 describes the pseudo-collection process. In the first step, all the information will be collected from OpenStreetMap, to be extracted and duly purified, such as streets, houses and also to define the variables such as inspection wells, candidate transformer sites, etc. Subsequently, in the second step, the scenario will be randomized for a period of 5 years in order to be able to adequately plan each population expansion scenario per year. In the third step, each scenario will be reconstructed for each planning year, taking into account the optimal scenario for each of the 5 planning years, all this in relation to the optimal scenario obtained. In the fourth step, the optimal distance from the house to the well will be obtained, while in the fifth and sixth steps the optimal criteria for the underground network will be obtained, that is, eliminating those streets that do not contain an expansion of housing as such, and the criteria for selecting the optimal transformer, with respect to the previously defined candidate sites, respectively, to finally define the substation coverage and propose the respective scenarios that were planned for the 5-year period.

4. Analysis of results

To start with the optimization problem of a subway distribution network, as started from a model considered non-optimal, which considers specific initial parameters, as shown in Table 4, to corroborate that there is an optimization in the resources used to model the network. These, in turn, are compared with the final optimal results, as shown in Table 4, which also details the electrical parameters considered to increase the percentage of electrification of the network modeled in CYME.

As shown in Table 4, the algorithm allowed us to minimize the initial starting point for this optimization from a total of 51 candidate transformer sites to 29 optimal locations in the proposed scenario and a total of 540 test wells considering the distance constraint. In addition, considering the distance restriction, it was possible to model only those with at least one user service

Algorithm 1 Pseudocode for the elaboration of an optimal underground distribution network.

```
Procedure:
Step:1 Georeferenced graph data from OpenStreetMap
Export georeferenced graph data from OpenStreetMap
$(x_h, y_h) \leftarrow$ Extract coordinates of households
$(ways) \leftarrow$ Extract street coordinates
$x_{tr} = \left\{x_{tr1}, ..., x_{trn}\right\}; y_{tr} = \left\{y_{tr1}, ..., y_{trn}\right\}$
$x_{poz} = \left\{x_{poz1}, ..., x_{pozn}\right\}; y_{poz} = \left\{y_{poz1}, ..., y_{pozn}\right\}$
$x_{sub} = \left\{x_{sub1}, ..., x_{subn}\right\}; y_{sub} = \left\{y_{sub1}, ..., y_{subn}\right\}$
Step:2 Randomize the scenario, for 5 years
$Y = \left\{x_h, y_h\right\}$
for $a == size(Y)$ do
end for
while $i == 5$ do
    for $k_i = 1 : 1 : G = 76$ do
        $p_i(k_i) = randi\,(size\,(Y))$
    end for
    $d_i = unique\left(sort\left(p_i\right)\right)$
    $c_i = ismember\left(sort\left(Y', d_i\right)\right)$
    $\left(comp_{(i)}\right)\left(comp_{(i)} == 1\right) = inf$
    for $i = 1 : 1 : size(d_i)$ do
        $v_{ix}(i, :) = x_h(d_i, 1))$
        $v_{iy}(i, :) = y_h(d_i, 1)$
        $Gr_i = \left\{v_{ix} v_{iy}\right\}$
    end for
end while
Step:3 Rebuild streets underground network according to connectivity matrix:
$Cluster_{max} = num$
for $i = 1 : 1$ do
    for $i = 1 : 1 : size(Cluster_{max})$ do
        $set(axes)$
        $G = (V, E)\}$
        $ways = \{w(:, 1)w(:, 2)\}$
    end for
end for
Step:4 Find the optimal distance from house to well per year of study:
$s = size\left\{v_{iy} v_{ix}\right\}$
$s_a = size\left\{y_{poz} x_{poz}\right\}$
for $i = 1 : s$ do
    for $j = 1 : s_a$ do
        $Dist_{haver}(i, j) = haversine(s(i, :), s_a(j, :))$
        $POZ_{minxy} = find(dist_{haverc-w} == min(dist_{haver}(i, :))$
    end for
end for
Step:5 Selection criteria for optimal underground network and optimal review wells
if $Poz_{min} == 1$ then
    $(ways) \leftarrow$ Find Ways
    $clus_{op1} = (ways, Poz_{minxy})$
end if
Step:6 Find the optimal transformers
$a = size\left\{y_{tr} x_{tr}\right\}$
$o_a = size\left\{y_{poz} x_{poz}\right\}$
for $i = 1 : o$ do
    for $j = 1 : o_a$ do
        $dist_{haver}(i, j) = haversine(o(i, :), o_a(j, :))$
        $tr_{minxy}(i, j) = find(dist_{haverw-t}) == min(dist_{haver}(i, :))$
    end for
end for
Step:7 Substation Coverage
$h = size\left\{y_{tr} x_{tr}\right\}$
$h_a = size\left\{y_{sub} x_{sub}\right\}$
for $i = 1 : h$ do
    for $j = j = 1 : h_a$ do
        $ist_{haver}(i, j) = haversine(h(i, :), h_a(j, :))$
    end for
end for
```

connection as a minimum distance, a total of 380 optimal revision wells obtained through the algorithm. On the other hand, the length of the underground network considered when reconstructing the scenario through the proposed algorithm managed to get a network of 3.89 km, which, through a debugging process, was able to get a network of 3.4 km, and 49 km, which through a debugging in the algorithm established the restriction that at least the underground network section must contain a well to expand the network.

However, these are the final values obtained for the fifth year of planning, as shown in Fig. 4, so that later in this document, the behavior of the network in the planning years considered is detailed.

It is interesting to note from Table 4 that the values used in the primary network can be modified and scaled to different standards according to the region, as well as the nominal power of the transformers, which are considered in the CYME modeling as three-phase transformers, and the maximum demand of each user is modified. However, since this is a specific sector without a detailed stratification, an average stratum value of 4.77 [kW] is chosen from the United States for this rural area. Similarly, the maximum number of feeders in parallel considered was three due to the characteristics of a pipeline that carries these feeders and the difficulty of expanding a more significant number of circuits in parallel in a channel; finally, typical values of conductor size for underground distribution networks from 1/0 to 250 MCM, in copper conductor material, EPR (ethylene propylene rubber insulation) were presented.

As shown in Fig. 4, the final optimal scenario, obtained through the algorithm proposed in Matlab, allowed shaping the accurate and scalable system presented as the objective of this research, where a total of 380 users of a total of five scenarios modeled, 1 per year, can be observed. The result in this optimal scenario, where users are represented with cyan triangles, the optimal maintenance holes with black squares, the optimal transformers with green squares, the connections from the houses to the optimal maintenance holes with red lines, and the coverage of the substations is represented by a grid that matches the color of the substation and gives the representation of the range of that substation.

However, the objective of this document is to give shape to a planning model, for which five study scenarios were established, the final one presented in Fig. 4 and explained in the previous paragraph, but as can be seen in Fig. 6. The first year will consist of 76 users and the same parameters established in the final scenario to shape the optimal planning model, where the 20% increase in users for each year can be satisfied with the optimal scheme proposed for the fifth year.

Thus, it is evident that Fig. 5 contains a smaller number of users but has the same number of optimal wells and optimal transformers, projected for the 20% annual increase of users, which translates into an increase in electrification of the scenario proposed, i.e., the optimal scheme satisfies an increase in users for the period analyzed, which is five years.

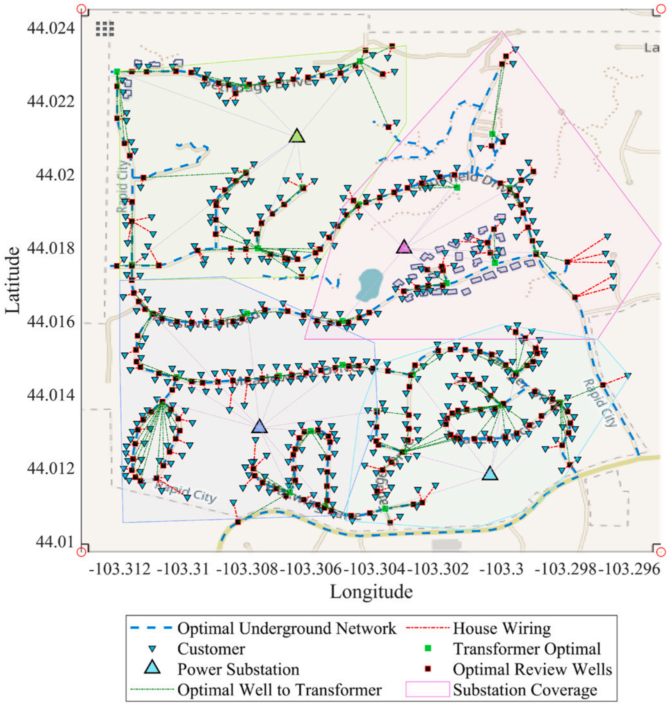

Fig. 4. Optimal Final Scenario, for the fifth year.

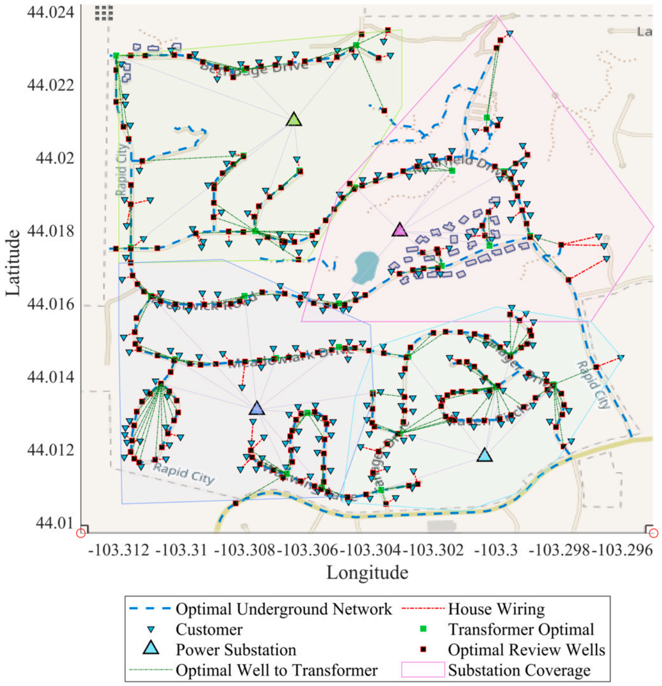

Fig. 5. Optimal scenario, for the third year.

In previous paragraphs, the algorithm to randomize the users was presented, as shown in Figs. 4, 5 y 6. It respects the original position of the houses, randomizes the users in their original place concerning the final scenario in clusters of 76 users, and maintains their route to the nearest optimal revision well. In Fig. 5, the system proposed for the third year is observed, with 228 users distributed throughout the system.

Table 4
Optimum Parameters Obtained - Simulation Parameters.

Variables	Initial value	Optimum value obtained
Transformer Candidate Sites	51	31
Review Well Candidate Sites	540	380
Underground Network Length [km]	3.89 [km]	3.4 [km]
Maximum percentage of chargeability in transformers in 5 years	70%	75%

Values used in modeling in CYME

Variables	**Value**
Considered primary network	22860/6300 [V]
Secondary network considered	220/127 [V]
Typical values of Transformers 3 Φ used:	50,75,100,150,250 [kVA]
Power factor considered in residential user	0.95
Maximum demand of each user	4.77 [kW]
Maximum configuration of circuits per pipeline	3 in parallel
Material Conductor	Copper
Size of conductors considered	1/0,2/0,3/0,4/0,250MCM
Modeled substations	5 MVA
Maximum number of connections per well	5
Considered Users	380
Percentage of electrification to 20% in 5 years	76 users per year

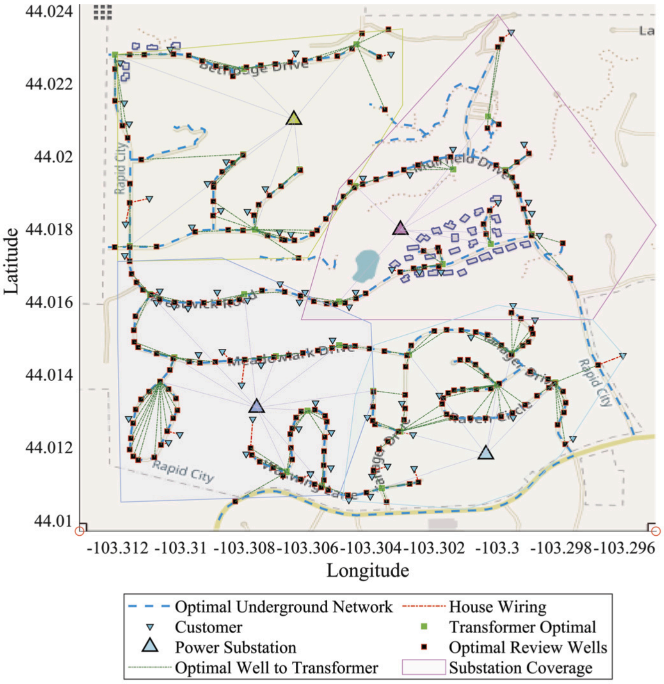

Fig. 6. Optimal scenario, for the first year.

Once the optimal scenario was defined using the MATLAB algorithm, the corresponding simulations were performed in CYME for the planning years presented in this document, corresponding to a 5-year time frame where the population expanded by 20% per year. It is noteworthy to mention that due to the randomness of user expansion, the transformer chargeability presents a random behavior, but it increases as the users are added to the optimal network, as shown in Fig. 5.

It is worth mentioning that the planning model for a 5-year time horizon was proposed, with transformers reaching a maximum of 70% chargeability in this period. When simulating in CYME, a maximum chargeability percentage of 75.3% was obtained in transformer 2, as shown in Fig. 7, a 75 kVA transformer, while the minimum chargeability percentage was reached in transformer 26, with a load percentage of 31.9%, which is a 75 kVA transformer. These chargeability values are adjusted during the simulation process by increasing or decreasing the power of the transformers. However, the CYME modeling objective is achieved concerning the chargeability percentage of this equipment, which was not higher than 75% for all users over a 5-year time horizon when running the unbalanced power flow.

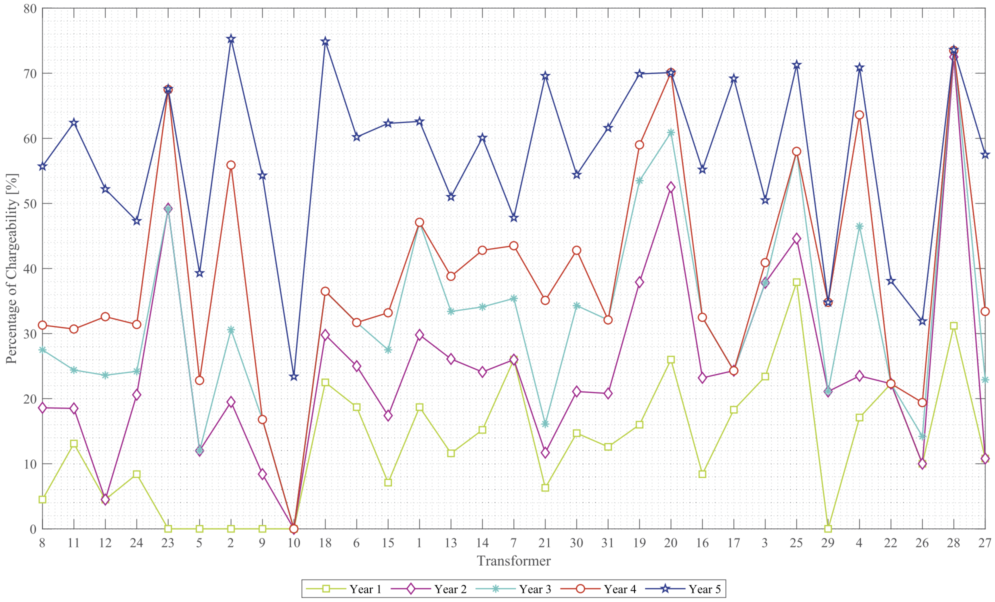

Fig. 7. Percentage of chargeability of transformers per year.

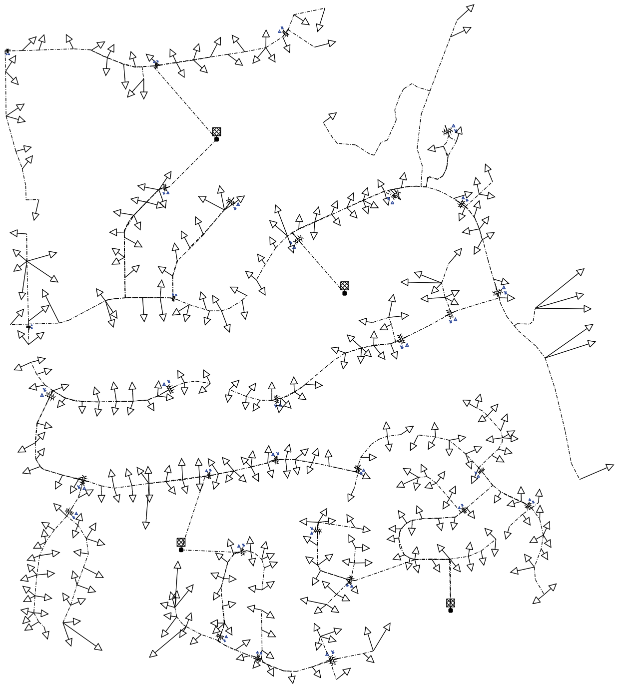

Fig. 8. Optimal model in Cyme, for the fifth year of planning.

On the other hand, the feeder gauges selected for the secondary distribution network will have a chargeability percentage lower than 50%, as shown in the Fig. 9, concerning the distance of the circuit, which is in a range of 0 to 250 meters from the source. The cables selected for the secondary network range from 1/0 gauges to a maximum gauge of 250 MCM, with a parallel configuration of a maximum of three conductors per phase, and do not exceed this range, where the highest percentage of chargeability is experienced in the section corresponding to transformer 2. Like Fig. 9, 7 will experience an increasing behavior concerning the percentage of chargeability in the secondary network during the five years of expansion simulated in MATLAB and modeled in CYME.

As shown in Fig. 10, the voltage drop graphs for the secondary 220/120V network for the three respective phases show that the objective of obtaining a voltage drop of less than 3% was achieved for the five years where the optimum network was projected, modeled in CYME, with the highest voltage drop in the fifth year, in phase C, at 280 meters from the source, with a value of 116. 336

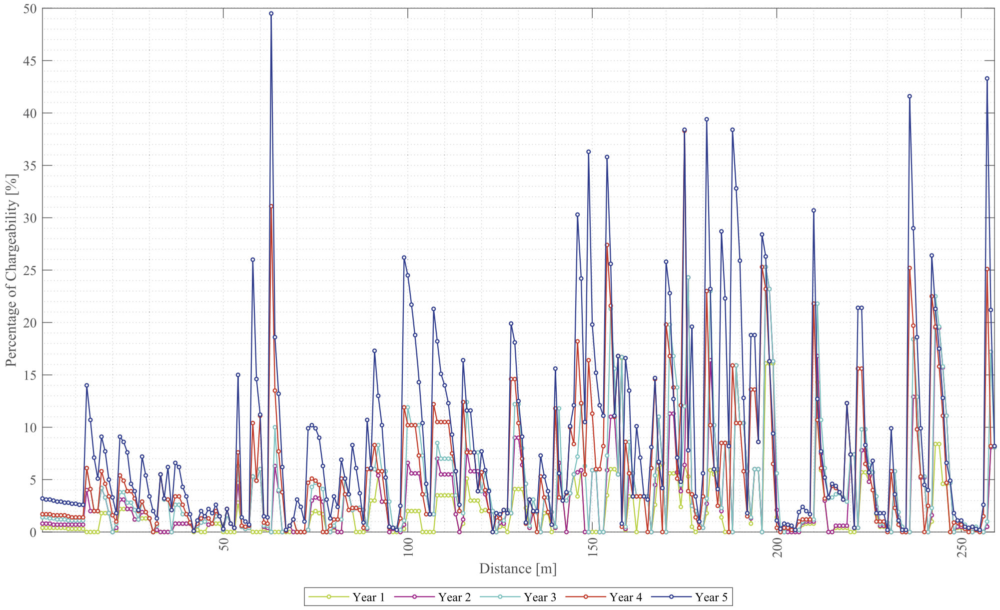

Fig. 9. Chargeability percentage of the secondary network per year.

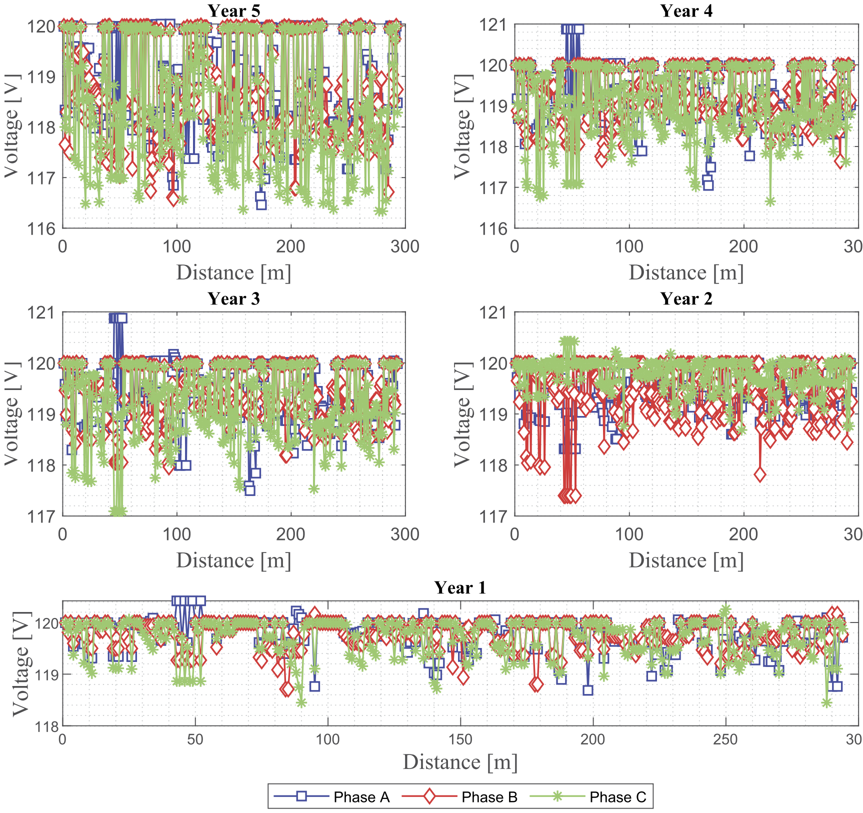

Fig. 10. Secondary network voltage drop profiles per year.

V, which is equivalent to a maximum voltage drop of 3.05% reached with the modeled optimal network, being one of the restrictions of the algorithm performed in MATLAB to guarantee that the minimum distance of the voltage drop percentage is less than 3%, concerning the feeder size proposed in the CYME modeling.

On the other hand, the graphs corresponding to the first four years will have voltage drops of less than 3%, due to the fewer users for these years. However, it is worth noting that for the second year, the phase that experiences the highest voltage drop is phase B, with phases A and C, because the CYME modeling considered an unbalanced power flow, while for the remaining years, phase C is the one that will experience the highest voltage drop about the other two phases.

When analyzing the overvoltage observed when modeling the network in CYME, it is not considerable, being the maximum values reached in the third and fourth year, which correspond to overvoltage values of 120.876 V and 120.873V, respectively, representing a maximum overvoltage of 0.73%, being this overvoltage the one reached in the range of 45 to 52 meters from the transformer and experienced in phase A, as shown in Fig. 10.

Finally, the CYME modeling of the network is presented, which was implemented for the fifth year, as shown in Fig. 8, and which is very similar to the graph illustrated in Fig. 4, which corresponds to the optimal scenario proposed for the fifth year, simulated in MATLAB. As mentioned in this document, only the expansion of the network will be based on the randomness of the users; therefore, Fig. 5, and Fig. 6, are the basis of the optimal scenario with their respective users for modeling each year of network expansion in CYME.

5. Conclusions

By elaborating a georeferenced optimal planning model for an underground and rural distribution network, the electrification could be satisfactorily increased. The algorithm elaborated in MATLAB contains all the considerations of a heuristic model to minimize the resources when establishing a planning model looking for the shortest routes between the different elements. This model is scalable in time, concerning the number of users and to a functional georeferenced area, regardless of the local regulations used, and fulfills the optimal function with the number of resources used.

The proposed optimal planning model meets the objective of minimizing resources according to the variables considered on the overhead distribution network. It will reduce the chargeability resources of transformers and feeder cables, which were later corroborated by the CYME simulations, focusing on the optimal routing of the network and the optimal sites for the transformer stations, and the optimal wells for the connection of the end-users, limiting and optimizing the number of users per transformer station concerning the distance between them.

Similarly, the CYME simulation of the proposed optimal planning model allowed modeling of an underground distribution system, considering the end-user voltage profiles, which, in the five years of network expansion, did not have significant voltage drops, which remained below 3%, i.e., the network has an adequate planning model regardless of user expansion.

In the proposed scenario, the simulation process allowed for the evaluation of specific technical parameters that are obviated during the approach of the heuristic model, giving a scope to the proposed planning model, all of which are subject to specific technical parameters of the traditional underground electrical networks. It allows giving a higher level of scalability to the model, being this applicable to other scenarios and being scalable in time and about the randomness to which a population can be subjected concerning its demographic expansion, which makes this article innovative since many readers despise are random demographic expansion, which every area experiences at the time of making an appropriate planning model.

Finally, the results obtained throughout this work can be the starting point for the design of subway distribution systems, considering optimal planning so that the design times can be minimized when looking for the optimized routing of a network, the location of transformers, and the location of wells. The optimal location of the wells and the respective coverage of each of the transformation centers avoid overloads in transformers and cables and overvoltages and under voltages that may reach the end-user, ensuring the quality of power to the latter at the time of final delivery. The scenario is populated at 100% in demographic terms.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The Universidad Politécnica Salesiana has fully covered the research.

CRediT authorship contribution statement

Juan García: Conceptualization, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing. **Esteban Inga:** Conceptualization, Methodology, Supervision, Validation, Visualization, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

Additional information

No additional information is available for this paper.

Acknowledgements

This work was supported by the Smart Grid Research Group (GIREI) of Universidad Politécnica Salesiana (Project: Chargeability of the electrical distribution network considering the massive inclusion of electric vehicles), the Power Grids and Smart Cities (RECI), Salesian Institutions of Higher Education (IUS).

References

[1] L. Ai, V.K. Ramachandaramurthy, P. Taylor, J.B. Ekanayake, S.L. Walker, S. Padmanaban, Review on the optimal placement, sizing and control of an energy storage system in the distribution network, J. Energy Storage 21 (2019) 489–504, https://doi.org/10.1016/j.est.2018.12.015.

[2] J. Barroso, S. Abata, P. Asanza, M. Chimarro, Normas Para Sistemas De Distribución Parte A - Guía Para Diseño De Redes Para Distribución, 2021.

[3] C. Bonetti, J. Bianchotti, J. Vega, G. Puccini, Optimal segmentation of electrical distribution networks, IEEE Latin America Trans. 19 (2021) 1375–1382, https://doi.org/10.1109/TLA.2021.9475868.

[4] A. Bosisio, A. Berizzi, E. Amaldi, C. Bovo, X.A. Sun, Optimal feeder routing in urban distribution networks planning with layout constraints and losses, J. Mod. Power Syst. Clean Energy 8 (2020) 1005–1014, https://doi.org/10.35833/MPCE.2019.000601.

[5] A. Bosisio, M. Moncecchi, A. Morotti, M. Merlo, Machine learning and GIS approach for electrical load assessment to increase distribution networks resilience, Energies 14 (2021) 1–23, https://doi.org/10.3390/en14144133.

[6] G. Celli, N. Chowdhury, F. Pilo, G.G. Soma, M. Troncia, I.M. Gianinoni, Multi-criteria analysis for decision making applied to active distribution network planning, Electr. Power Syst. Res. 164 (2018) 103–111, https://doi.org/10.1016/j.epsr.2018.07.017.

[7] A. Ehsan, Q. Yang, Optimal integration and planning of renewable distributed generation in the power distribution networks: a review of analytical techniques, Appl. Energy 210 (2018) 44–59, https://doi.org/10.1016/j.apenergy.2017.10.106.

[8] A. Ehsan, Q. Yang, State-of-the-art techniques for modelling of uncertainties in active distribution network planning: a review, Appl. Energy 239 (2019) 1509–1523, https://doi.org/10.1016/j.apenergy.2019.01.211.

[9] S. Freitas, T. Santos, M.C. Brito, Impact of large scale PV deployment in the sizing of urban distribution transformers, Renew. Energy 119 (2018) 767–776, https://doi.org/10.1016/j.renene.2017.10.096.

[10] P.S. Georgilakis, N.D. Hatziargyriou, A review of power distribution planning in the modern power systems era: models, methods and future research, Electr. Power Syst. Res. 121 (2015) 89–100, https://doi.org/10.1016/j.epsr.2014.12.010.

[11] A. Ghanbari, H. Karimi, S. Jadid, Optimal planning and operation of multi-carrier networked microgrids considering multi-energy hubs in distribution networks, Energy 204 (2020) 1–13, https://doi.org/10.1016/j.energy.2020.117936.

[12] V. Gouin, M.C. Alvarez-Hérault, B. Raison, Innovative planning method for the construction of electrical distribution network master plans, Sustain. Energy, Grids Netw. 10 (2017) 84–91, https://doi.org/10.1016/j.segan.2017.03.004.

[13] J. Gouveia, C. Gouveia, J. Rodrigues, L. Carvalho, C.L. Moreira, J.A. Lopes, Planning of distribution networks islanded operation: from simulation to live demonstration, Electr. Power Syst. Res. 189 (2020) 1–8, https://doi.org/10.1016/j.epsr.2020.106561.

[14] M.H. Hamza, GIS-based planning and Web/3D Web GIS applications for the analysis and management of MV/LV electrical networks, Appl. Sci. 12 (5) (2022) 2554.

[15] C. Hauk, A. Ulbig, A. Moser, Integrated planning of grids and energy conversion units in municipal multi-energy carrier systems, Energy Inform. 4 (2021), https://doi.org/10.1186/s42162-021-00178-0.

[16] M. Jooshaki, H. Farzin, A. Abbaspour, M. Fotuhi-firuzabad, A model for stochastic planning of distribution network and autonomous DG units, IEEE Trans. Ind. Inform. 16 (2019) 1–11, https://doi.org/10.1109/TII.2019.2936280.

[17] J.B. Leite, R.A.V. Peralta, J.R.S. Mantovani, Restoration switching analysis in the integrated architecture for distribution network operation, Electr. Power Syst. Res. 194 (2021), https://doi.org/10.1016/j.epsr.2021.107069.

[18] H. Li, W. Mao, A. Zhang, C. Li, An improved distribution network reconfiguration method based on minimum spanning tree algorithm and heuristic rules, Int. J. Electr. Power Energy Syst. 82 (2016) 466–473, https://doi.org/10.1016/j.ijepes.2016.04.017.

[19] Z. Lin, Z. Hu, Y. Song, Distribution network expansion planning considering notation N-1 criterion, IEEE Trans. Power Syst. 34 (2019) 2476–2478, https://doi.org/10.1109/TPWRS.2019.2896841.

[20] Z.F. Ma, M. Jiang, M. Khoshmanesh, X. Cheng, Time series phase unwrapping based on graph theory and compressed sensing, IEEE Trans. Geosci. Remote Sens. 60 (2022) 1–12, https://doi.org/10.1109/TGRS.2021.3066784.

[21] J. Maleki, A. Arefi, G. Ledwich, A. Borghetti, J. Garcia, A distribution network planning model considering neighborhood energy trading, Electr. Power Syst. Res. 191 (2021) 106894, https://doi.org/10.1016/j.epsr.2020.106894.

[22] M. Nick, R. Cherkaoui, M. Paolone, Optimal planning of distributed energy storage systems in active distribution networks embedding grid reconfiguration, IEEE Trans. Power Syst. 33 (2018) 1577–1590, https://doi.org/10.1109/TPWRS.2017.2734942.

[23] A. Ouammi, H. Dagdougui, R. Sacile, Optimal planning with technology selection for wind power plants in power distribution networks, IEEE Syst. J. 13 (2019) 3059–3069, https://doi.org/10.1109/JSYST.2019.2903555.

[24] F. Pabón, E. Inga, M. Campaña, Planning underground power distribution networks to minimize negative visual impact in resilient smart cities, Electricity 3 (2022) 463–479, https://doi.org/10.3390/electricity3030024.

[25] W. Pavón, E. Inga, S. Simani, Optimal routing an ungrounded electrical distribution system based on heuristic method with micro grids integration, Sustainability 11 (2019) 1–18, https://doi.org/10.3390/su11061607.

[26] P.C. Ramaswamy, C.D. Marmol, D. Schyns, F.X. Bouchez, S. Rapoport, D. Vangulick, Smart planning: an innovative tool for the investment planning of smart distribution networks, CIRED - Open Access Proc. J. 2017 (2017) 2539–2542, https://doi.org/10.1049/oap-cired.2017.1042.

[27] H. Saboori, R. Hemmati, M.A. Jirdehi, Reliability improvement in radial electrical distribution network by optimal planning of energy storage systems, Energy 93 (2015) 2299–2312, https://doi.org/10.1016/j.energy.2015.10.125.

[28] H. Sekhavatmanesh, R. Cherkaoui, Optimal infrastructure planning of active distribution networks complying with service restoration requirements, IEEE Trans. Smart Grid 9 (2018) 6566–6577, https://doi.org/10.1109/TSG.2017.2716192.

[29] I. Shahrour, H. Bian, X. Xie, Z. Zhang, Smart technology applications for the optimal management of underground facilities, Undergr. Space 6 (2021) 551–559, https://doi.org/10.1016/j.undsp.2020.12.002.

[30] S. Shojaabadi, S. Abapour, M. Abapour, A. Nahavandi, Optimal planning of plug-in hybrid electric vehicle charging station in distribution network considering demand response programs and uncertainties, IET Gener. Transm. Distrib. 10 (2016) 3330–3340, https://doi.org/10.1049/iet-gtd.2016.0312.

[31] B.V. Venkateswaran, D.K. Saini, M. Sharma, Approaches for optimal planning of the energy storage units in distribution network and their impacts on system resiliency — a review, CSEE J. Power Energy Syst. 6 (4) (2020) 816–833, https://doi.org/10.17775/cseejpes.2019.01280.

[32] A. Valenzuela, E. Inga, S. Simani, Planning of a resilient underground distribution network using georeferenced data, Energies 12 (2019) 644, https://doi.org/10.3390/en12040644, http://www.mdpi.com/1996-1073/12/4/644.

[33] A. Valenzuela, E. Inga, S. Simani, Planning of a resilient underground distribution network using georeferenced data, Energies 12 (2019) 1–20, https://doi.org/10.3390/en12040644.

[34] A. Valenzuela, I. Montalvo, E. Inga, A decision-making tool for electric distribution network planning based on heuristics and georeferenced data, Energies 12 (2019), https://doi.org/10.3390/en12214065.

[35] A. Valenzuela, S. Simani, E. Inga, Automatic overcurrent protection coordination after distribution network reconfiguration based on peer-to-peer communication, Energies 14 (2021), https://doi.org/10.3390/en14113253.

[36] C. Wang, G. Song, P. Li, H. Ji, J. Zhao, J. Wu, Optimal siting and sizing of soft open points in active electrical distribution networks, Appl. Energy 189 (2017) 301–309, https://doi.org/10.1016/j.apenergy.2016.12.075.

[37] Y. Xiang, Y. Wang, Y. Su, W. Sun, Y. Huang, J. Liu, Reliability correlated optimal planning of distribution network with distributed generation, Electr. Power Syst. Res. 186 (2020) 106391, https://doi.org/10.1016/j.epsr.2020.106391.

[38] M. Yosef, M.M. Sayed, H.K. Youssef, Allocation and sizing of distribution transformers and feeders for optimal planning of MV/LV distribution networks using optimal integrated biogeography based optimization method, Electr. Power Syst. Res. 128 (2015) 100–112, https://doi.org/10.1016/j.epsr.2015.06.022.

[39] K.H. Youssef, Optimal routing of ring power distribution systems, Electr. Power Syst. Res. 199 (2021) 107392, https://doi.org/10.1016/j.epsr.2021.107392.

[40] C. Zhang, J. Li, Y.J. Zhang, Z. Xu, Optimal location planning of renewable distributed generation units in distribution networks: an analytical approach, IEEE Trans. Power Syst. 33 (2018) 2742–2753, https://doi.org/10.1109/TPWRS.2017.2749410.