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Planning Underground Power Distribution Networks to Minimize Negative Visual Impact in Resilient Smart Cities

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Abstract: This paper presents the application of heuristic methods in conjunction with graph theory in the optimal routing and sizing of underground distribution networks in georeferenced (GIS) scenarios, which are modeled and simulated in the advanced engineering tool CYMDIST. The tool allows the deployment of underground networks to facilitate the design, planning, and implementation of networks, taking into consideration distribution company regulations, thus allowing overview and future planning in the growth of distribution systems. Further, this method is modeled in real georeferenced scenarios, where the coverage of the electric service to all users connected to the network is guaranteed according to population density and energy demand while minimizing the number of distribution transformers used. The applied method considers the location of transformer chambers, the capacity and coverage of the distribution transformers, and the voltage drops over the line section, which should not exceed 5% of the nominal value as described in the ANSI C84.1 standard. Consequently, to verify the efficiency of the applied method, the limitations and restrictions of the mathematical model are considered, as well as the characteristics of the georeferenced system and a comparison with different research studies that address the subject presented here. In addition, supply coverage is guaranteed to be 100%.

Keywords: CYMDIST; heuristic techniques; graph theory; optimization; georeferenced

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1. Introduction

This paper presents a heuristic model based on graph theory for optimal deployment of power distribution grids [1]. In electrical distribution system planning, wire length is the parameter necessary to calculate the voltage loss and the related power losses [2,3]. Moreover, simulation using the advanced engineering tool CYMDIST [4,5] verifies if the deployment achieved with the algorithm complies with the observation of technical criteria related to the maximum voltage loss, which for distribution systems is 5%. Thus, the algorithm developed in MATLAB creates a medium-voltage electrical network and sizes the elements of the network in medium- and low-voltages, which is then evaluated with the specialized software for electrical distribution systems [6].

The objective is to provide an electrical distribution system with reliability and safety through the optimal sizing of electrical equipment in underground distribution systems [7]. Moreover, installing electrical equipment is considered for constructing the underground electrical distribution network [8]. The planning problem is considered NP-complete because of the number of variables included in formulation of the problem [9].

Heuristics are used to solve problems of higher complexity. Thus, the construction of heuristics to find near-optimal solutions is essential. Every optimization problem can be solved using an already-defined heuristic method, such as genetic algorithms (GAs), tabu search (TS), ant colony optimization (ACO), and particle swarm optimization (PSO), among others. The main feature is that graph theory is used to support the algorithm by assigning weights based on the topology of the electrical network [10,11].

The increase in the growth of electricity systems is directly related to the increase in energy demand [12,13]. An unpredictable increase in demand makes current grid design, expansion, and planning of the power distribution system complex [14,15]. Therefore, the topology of a power distribution system is considered a complex network in continuous growth [16–18].

The optimal sizing of electrical distribution networks must consider fundamental technical aspects such as voltage loss and the location of distribution transformers, since these are parameters to determine the safety and quality of electrical service. Therefore, the observance of technical parameters allows the construction of optimal electrical distribution networks with a view to possible expansions in georeferenced scenarios [14,19].

An electrical network must be designed so that the consumer farthest away from the distribution transformer has adequate voltage levels to avoid damage to equipment connected to the electrical network. Moreover, it is essential to verify that the user closest to the distribution transformer does not have electrical overvoltage. These are restrictions considered in this article, since these variables are directly related to the topology of electrical networks [20,21].

Furthermore, the proposed heuristic ensures that demand is covered at the minimum cost and also locates the electrical equipment of the distribution network, seeking to minimize the technical losses that occur in the different topology of electrical distribution networks [22]. In each scenario, the number of users connected to the same transformer station and the population density are varied to evaluate the model's scalability and adaptability to changing demand conditions [23,24].

The method proposed in this article efficiently analyzes critical distribution systems, providing relevant information about the georeferenced scenario. The coordinate system information contributes to the construction of the routing of the underground network. The designed electrical network must ensure safety and reliability in energy dispatch, ensuring voltage reductions within the parameters established in applicable regulations [25–28].

Optimal sizing of buried distribution networks ensures shorter reconnection time in case of power system failure [7,22,29], reducing power supply replacement time [12,20,30]. Moreover, worldwide, there are plans for continuous improvement in the construction of new metropolises, especially in developed and underdeveloped countries [17,31].

Therefore, it is necessary to implement new technologies that intervene in the efficient and optimal solution of daily problems [32] while generating environments with a significantly reduced visual impact [15]. Electric power distribution networks are mainly of overhead construction; in addition to generating a very high visual impact, they are susceptible to many failures, generating more significant interruption to power supply [7,33].

Deploying buried networks minimizes visual impact and generates reliability for the electricity system; however, their deployment is expensive [22]. Thus, to minimize deployment costs, the development of optimization models for deploying distribution networks that contribute to least-cost construction is required [25,30]. These help distribution companies in decision-making for upgrading and building power distribution grids [20,34,34].

The work presented here opens possibilities for future jobs that incorporate evaluation of contingencies and failures, and then the expansion of the electrical distribution network is generated. In addition, it will be possible to integrate hybrid networks that integrate overhead and underground topologies to evaluate scenarios that occur daily in electric utilities and to assess more-efficient management mechanisms.

This article is organized as follows. Section 2 presents related work. Section 3 presents the traditional formulation of the problem, and Section 4 discusses the results. Finally, Section 5 presents the conclusions.

2. Related Works

Conventional electrical systems may experience the need to open a circuit that is part of the leading electrical network. This frequently happens in overhead electrical systems due to the vulnerability to natural disasters and road accidents. As a result, the electrical system is forced to suspend the supply of electrical power to specific sections of the network, which generates costs for energy not supplied. On the other hand, constructing subway electrical networks is of great interest to ensure continuity and service, guaranteeing energy security. Figure 1 shows the requirements to be considered in subway electrical networks.

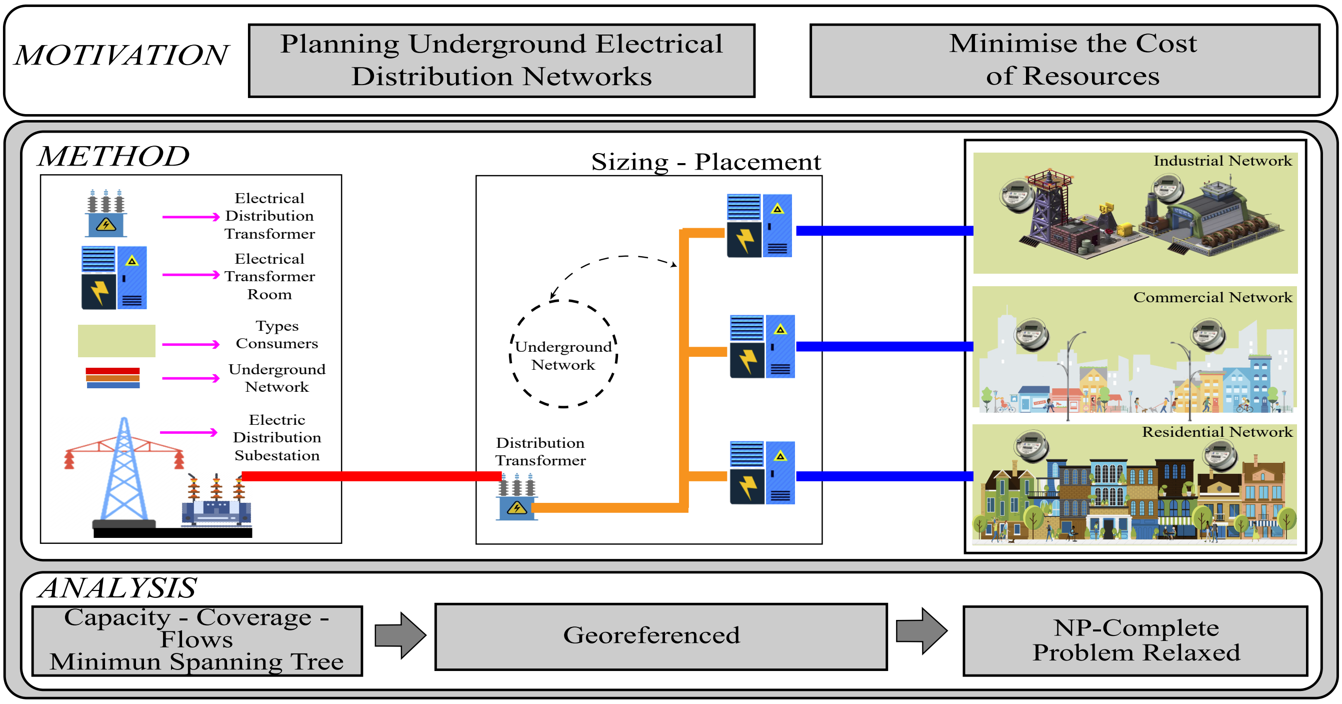

Figure 1. Underground electrical distribution network.

Undoubtedly, the dimensioning of electrical equipment in underground distribution systems increases safety and continuity of service. In addition, this type of underground construction allows the inclusion of generation systems with renewable resources, directly increasing the resilience of the electrical distribution network.

For the deployment and optimal dimensioning of subway electrical distribution networks, it is necessary to implement heuristic models capable of observing restrictions such as voltage drop and technical losses [35]. Consequently, the restrictions have a direct relationship with the cost variable, since the equipment required by the electrical network is to be dimensioned with optimization criteria. The proposed methodology is based on graph theory to analyze the deployment and simulation of electrical networks at minimum cost. Another fundamental characteristic is that it considers the stratification of users according to the energy consumed per time interval. Finally, the proposed mathematical model is validated through simulation in CYMDIST, since this software receives georeferenced data from MATLAB and interprets them to execute load flows of the optimal topology obtained from the planning model.

Subway distribution networks offer benefits that improve the reliability index of the electrical system since they improve the protection indexes against failures [36]. Then, these are implemented in strategic sectors where an aerial network is not feasible due to security problems in the energy supply and reduced general attractiveness due to the negative visual impact it generates. The construction of a subway power grid involves significant investments due to construction requirements, such as civil works, walls, and foundations for the location of the necessary electrical equipment, such as transformer chambers [37,38].

On the other hand, the power quality factor reduces maintenance costs by correctly using the nominal capacity installed to transport electrical power from generation to the final load (users) [39]. Consequently, it is essential to provide the necessary resources to ensure that the deployment of an underground electrical distribution network guarantees operational safety and continuity of electrical service. This is achieved with robust protection systems and adequate insulation levels [40–42].

The proposed optimization algorithm's efficiency directly depends on observance of the constraints to reduce the cost of the objective function. An exhaustive search is executed, and the machine time to solve the problem depends on each case study's initial constraints. In addition, the model allows cost reduction through the optimal sizing of the electrical equipment of the distribution network, taking into consideration the optimal location of the transformation chambers and the minimum required for several distribution transformers to be located in a georeferenced area. Finally, the resulting topology of the electrical system is validated by simulation with the specialized distribution network software CYMDIST.

Table 1 shows a summary of works related to deploying subway power distribution grids and, in addition, the importance and novelty of this article.

Table 1. Summary of related works.

Author, Year	Objectives	Parameters Considered					Thematic	
		Voltage	Capacity	Cost	Georeferenced	Planning	Resilience	Graph Theory
Ciechanowicz, 2016 [43]	Electrical network evaluation and modeling	✓	✓	✓	-	✓	✓	-
Li, 2016 [10]	Reduces active power losses	✓	-	-	-	✓	-	-
Sowmya, 2016 [44]	Use of geographic data in power grids	-	-	-	✓	✓	-	-
Roshanagh, 2016 [45]	Planning new electrical network at minimum cost	✓	✓	✓	-	✓	-	✓
Xie, 2018 [46]	Distribution network planning	✓	✓	✓	-	✓	-	-
Pinzón, 2020 [47]	Location of substations	-	✓	-	✓	✓	-	-
Cresta, 2021 [48]	Management of electrical distribution networks	✓	✓	-	✓	-	✓	✓
Ayalew, 2022 [49]	Expansion of the power grid with distributed generation	✓	✓	✓	-	✓	-	-
Kostelac, 2022 [50]	Planning and operational issues of microgrids	✓	-	✓	-	✓	-	-
Present work	Planning and sizing of electrical distribution network	✓	✓	✓	✓	✓	✓	✓

Regarding works presented with traditional non-scalable models and pre-established parameters, the present work innovates with a model capable of evaluating the reality of an urban, suburban, and/or rural area where it is desired to deploy an underground network. The simulation process of the topology achieved warns of the possibility of becoming a suitable tool for consulting work evaluation of contingencies of previously deployed networks that require expansion from the existing network. The current work does not consider pre-existing overhead networks in the study area, but these will be incorporated in future work by generating a layered solution and integrating them into the electrical system to evaluate efficiency and reliability.

3. Problem Formulation

The design of electrical distribution networks is performed considering different types of consumers, which are associated with the energy consumed over some time. This consideration is necessary to decide if the existing electrical network can satisfy existing and projected demand. End-users may be connected to the primary or secondary electrical networks as long as the additional energy extracted from the distribution system guarantees continuity of service and quality conditions for the end-user.

The topology of the distribution network can be radial or ring. The predominant topology in distribution systems is radial, which implies having complex connection points at low investment costs compared to ring systems. Thus, to guarantee energy security and quality criteria, the timely selection of the electrical distribution network's topology and the electrical equipment's optimal sizing are required.

The sizing of transformers is a fundamental part of the design, since the correct design of this equipment avoids possible problems related to losses of energy not supplied due to power outages. These operating conditions negatively impact energy security and raise costs due to technical losses and unsupplied power.

Furthermore, to select transformers in residential areas, it is essential to know the manufacturer's technical datasheet, the type of transformer, and the rated service power. The standard power ratings for residential transformers are 50, 75, 100, 125, and 150 kVA.

Computation of design demand is classified according to six types of consumers, as indicated in Table 2. This classification is directly related to the monthly consumption level for each type of user. For the case study, the sizing of a subway network of type B is considered, a typical characteristic of a residential system.

Table 2. Strata of electricity consumption.

Strata	Rate of Consumption by Customer (kWh/Month/Customer)
E	0–100
D	101–150
C	151–250
B	251–350
A	351–500
A1	501–900

The optimal planning of a subway network depends on several criteria and information, such as the type of user and the location of the service. This information facilitates the categorization of the service; in the case of a residential load, it can be assumed that the area will be urban or rural, while if the load is commercial or industrial, it is assumed that the area is linked to work areas with high and medium impact loads for the system [51].

Consequently, to design the electrical network, it is essential to use the diversified maximum demand (*DMD*). *DMD* refers to the maximum load projected to be present on the distribution system. Equation (1) indicates the mathematical relationship to be used. The variable M is related to the coincidence factor, and the variable N to the consumption factor. The consumption factor is considered according to the stratum of each user and represents the maximum projected amount of energy consumed by the customer per month. The values of M and N are specified in the local rules and regulations of the distribution companies.

$$DMD = (M * N) \quad (1)$$

A timely power supply study considering demand forecasting ensures electricity supply, reducing unsupplied power rates. Undoubtedly, this allows technological growth to guarantee energy supply and reduce investment costs. Consequently, demand growth analysis is fundamental to designing a distribution system's expansion and its connection to the end-user.

The calculation of the design demand (*DD*) follows the expression of Equation (2). *MDD* is the maximum design demand, *PLD* is the street lighting demand, *RTL* is the resistive technical loss (*RTL*) demand with a value of 3.6% of the *MDD* value, and *PF* is the power factor.

$$DD = \frac{MDD + PLD + RTL}{PF} \quad (2)$$

Planning for the construction of a subway electrical network considers, as a starting point, the position of the electrical substation and the laying of the primary network conductor. In radial electrical networks and for the case study, a voltage level of 13.8 kV is used. Another detail to consider in the present article is that the construction of underground electrical networks is proposed, for which transformation chambers and appropriate equipment must be considered to mobilize the construction of the underground electrical network.

Subway networks have several types of disconnectors and feeders that facilitate the maintenance of this type of system that, due to their construction, have greater resilience than overhead distribution lines. Adequate dimensioning of subway electrical distribution network elements guarantees the system's operation, avoiding overloads in the different branches of circuits and transformers. In addition, load imbalances and technical losses must be minimized to increase reliability and energy security.

It should be noted that subway networks are challenging to access for maintenance. The sizing of system protections and correct identification of conductors facilitate the reconnection of service in case of failure. Consequently, the reliability of the installation increases. In the design of a subway network, it is not enough to know the georeferenced location or the types of loads in the system. It is necessary to size transformers, transformer chambers, protection, electrical conductors, and accessories required to assemble the electrical distribution network.

Another detail is that the voltage level at which the end-users are reached must be verified. The maximum voltage levels allowed, depending on the electrical network, are described in the literature. In addition, any subway electrical installation must be planned and foresee expansion options for an eventual increase in demand [32]. Table 3 describes the *MDD* according to the type of residential user for a subway network, providing the relationship between the maximum diversified demand and the rated load (*RL*).

Table 3. Simulation model parameters.

Residential User	***MDD* (kW)**	***MDD* (kVA)**	***RL* (kW)**	***RL* (kVA)**
B	3.4	3.58	9.8	10.31
A	4.7	4.95	15.82	10.65

In order to plan an underground distribution network, it is essential to rely on maps and geolocalized coordinates. Once this information is known, it is possible to foresee optimal locations to reduce conductor laying distances. This contributes significantly to reducing voltage drops and the increase of Joule losses.

For the correct application of subway network equipment, it is essential to find a tool that calculates the location of such equipment and allows deciding on the variable length and the maximum installed powers. Consequently, the objective is to locate the transformer substations according to the capacity of the network and transformer units. The capacities of the grid and transformation units are designed according to the demand of users connected to the distribution grid.

In this article, OpenStreetMap is used to extract coordinate information in latitude and longitude of the road structure and land distribution of the residential area. In other words, the algorithm knows the topology of the zone or area to intervene in the planning process of underground electrical networks. distribution transformer locations are determined based on the centers of gravity of the loads, which are determined by the demand (S_i) of each system user (i). According to the parameters related to longitude and latitude (Lo_i, La_i), shown in Equations (3) and (4), it should be noted that transformers will be located along the main streets below the sidewalks.

$$Lodt = \frac{\sum_{i=1}^{n}(Lo_i * S_i)}{\sum_{i=1}^{n}(S_i)} \tag{3}$$

$$Ladt = \frac{\sum_{i=1}^{n}(La_i * S_i)}{\sum_{i=1}^{n}(S_i)} \tag{4}$$

Electrical distribution systems represent complex structures due to their number of connections according to topology (radial–ring); therefore, finding the optimal route for subway distribution infrastructure requires combinatorial algorithms of NP-complete complexity. The algorithm must verify constraints specific to the optimization problem, such as: minimizing investment and operation costs, reducing power lines, and meeting quality-of-service parameters. An additional detail is that the proposed heuristic finds the local optimum to the deployment problem of the electrical distribution network and relies on graph theory through definition of the adjacency matrix. The adjacency matrix contains the vertices and edges of the area to be intervened in during the planning process.

The heuristic model proposed in this paper helps find a close-to-optimal answer, where the number and power of the transformers to be placed are determined. In addition, it reduces the voltage drop from transformers to the farthest users of the distribution network. The minimum path required for a radial topology is used to achieve the minimum spanning tree (MST) algorithm. In an actual case study, the topology knowledge allows the designer to evaluate the type of conductor used to construct the subway electrical network.

Graph theory is a combinatorial tool used to determine the relationships between nodes and edges using geolocated coordinates of transformers, intersections, and end-users. The applied model ensures that voltage drops are reduced by the optimal routing of the underground power line, optimal transformer location, and optimal conductor selection based on current and projected power demand. On the other hand, voltage sags in electrical distribution systems represent a problem that affects the quality of electrical power supply to the consumer. Voltage drops are directly related to the length and dimensioning of the conductor, the impedance, and the service voltage level. Therefore, total voltage drop is calculated by summing the voltage drops in each branch.

For the optimal sizing of distribution transformers, the mathematical model uses the modified Prim algorithm, which requires a graph $G = (V, E)$ of order n and size m based on a set of vertices (V) and edges (E), taking into consideration the number of customers connected to the same transformer, and complying with the regulation that voltage drops must not exceed 5%. The distance calculation is made by applying the Haversine equation, which relates the curvature and radius of the earth in terms of latitude and longitude coordinates (Equation (5); results are given in km).

$$D = 2 * R * \arcsin \sqrt{\sin^2\left(\frac{\triangle lat}{2}\right) + \cos(lat1) * \cos(lat2) + \sin^2\left(\frac{\triangle lot}{2}\right)} \quad (5)$$

where:

- D is the distance in km from a point i to a point j;
- $lat1$, $lon2$ are the coordinates of point 2;
- $\triangle lat$ is the difference between the latitude coordinates of point 1 and point 2;
- $\triangle lon$ is the difference between the longitude coordinates of point 1 and point 2;
- R is the earth's radius, with a value of 6372.8 km.

Equation (6) represents the objective function and minimizes the total cost of the distribution network. The capacity constraints of the distribution substation, the existence of georeferenced electrical elements distributed in the area, the reduction of electrical conductor length for the underground network, the sizing of the distribution transformer, and the computation of voltage drops are represented in Equations (7)–(11), respectively.

$$OF = min \sum C_s + \sum Cap_c + \sum Ct_i + \sum Vd \quad (6)$$

Subject to:

$$C_s = \sum_{i=1}^{n} (Cp_i * C_f) \quad (7)$$

$$Cap_c = \sum_{z \in \Re} (z \leqslant m, \forall z, m\Re) \quad (8)$$

$$R_c = \sum_{z \in \Re} (z \leqslant r, \forall z, r\Re) \quad (9)$$

$$Ct_i = \sum_{i=1}^{\alpha}(Cap_c) \tag{10}$$

$$Vd = \frac{2}{\gamma_{20} UnSc} * \sum_{i,j=1}^{n}(P_{i,j} * Lg_{i,j}) \tag{11}$$

A summary of the variables used in this article is presented in Table 4.

Table 4. Variables related to the constraints.

Symbol	Description	Unit
C_s	Restricts the capacity of the substation.	$\mathbb{R}^+$
Cp_i	Partial capacity of residential user.	kVA
n	Number of nodes	$\mathbb{R}^+$
C_f	Multiplication factor projection future growth.	%
Cap_c	Limit of the capacity of each group.	$\mathbb{R}^+$
m	Vector length in the case study.	$\mathbb{R}^+$
z	Verification variable.	$\mathbb{R}^+$
R_c	Restricts the maximum allowable distance.	Meters
r	Maximum allowed distance.	Meters
Ct_i	Restricts the maximum load of the transformers.	kVA
α	Number of clusters.	$\mathbb{R}^+$
Vd	Voltage drop.	V
$\gamma_2 0$	Conductivity according to the type of conductor.	Siemens
Un	Applied voltage of the conductor.	V
Sc	Underground conductor section.	mm^2
Lg	Length of the conductor from the transformer to the user.	Meters
P	Power losses.	kW
i, j	Source and target, respectively.	Index

Figure 2 shows the flowchart of subway power grid deployment. The flowchart shows the methodology used by the underground grid planning algorithm.

The algorithm starts with knowledge of the topology of the scenario for which the underground grid deployment is being executed. Then, the revision boxes are located, observing the regulations, which require a revision box every 40 m. Once the position of the revision boxes is known, the algorithm to determine the minimum spanning tree of the underground electrical network is executed. In addition, a check is performed to reduce the cost of the minimum spanning tree; if the answer is yes, the resulting MST is selected as the local answer.

The next step is to locate the distribution transformers. It is necessary to mention that the applied model is scalable. Therefore, its application in different cases of study is analyzed, determining the number of users connected to a distribution transformer; in addition, the length of the conductor of the low voltage electrical network is determined. Consequently, a multilevel multigraph is constructed and explained in detail in Figure 3. Finally, the flowchart shows the need to lay out the distribution network observing that the location of the distribution transformers complies with the regulatory standards in the literature.

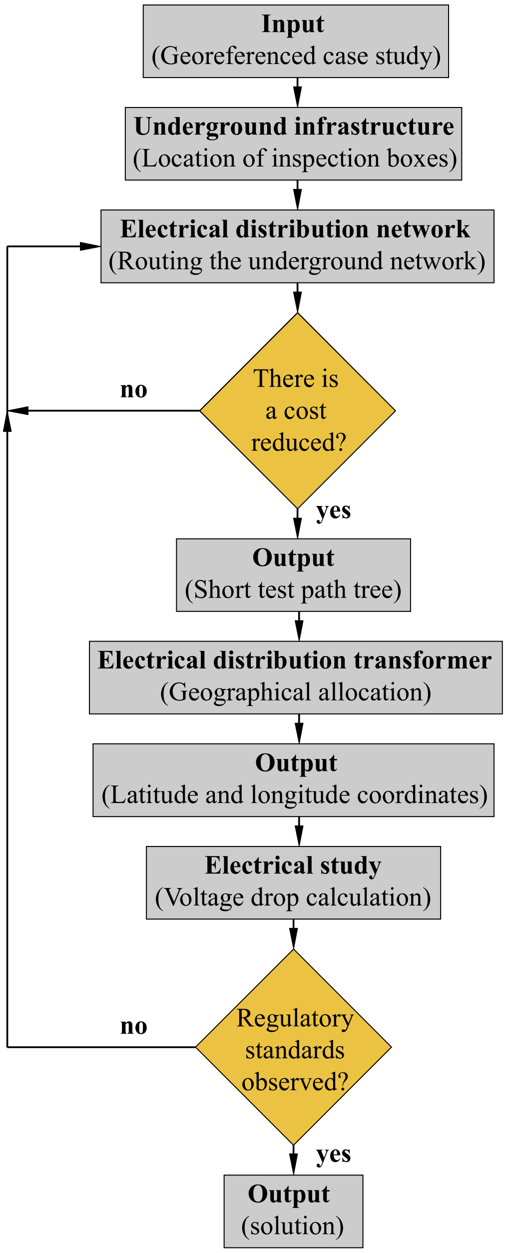

Figure 2. Underground power grid deployment flowchart.

The heuristic model for the optimal deployment of subway networks has been applied in an actual scenario, i.e., georeferenced. The case study is located in the East Dulwich region in southeast London, England, in the London Borough of Southwark, located at the coordinates of longitude −0.0764 to −0.0725 and latitude 51.4555 to 51.452 with an approximate area of 84 square kilometers. The scenario comprises 715 loads with a power demand of 4.9 MW between residential and commercial users. The power demand estimation is based on each type of user's average monthly energy consumption. The K-medoids algorithm divides the scenario into six clusters, as shown in Figure 3. The location of the load centers, number of users, and routes that mark the path to be followed by the subway electrical conductor are verified. Using this information, the heuristic determines how to connect all users with minimum cost and the shortest conductor length.

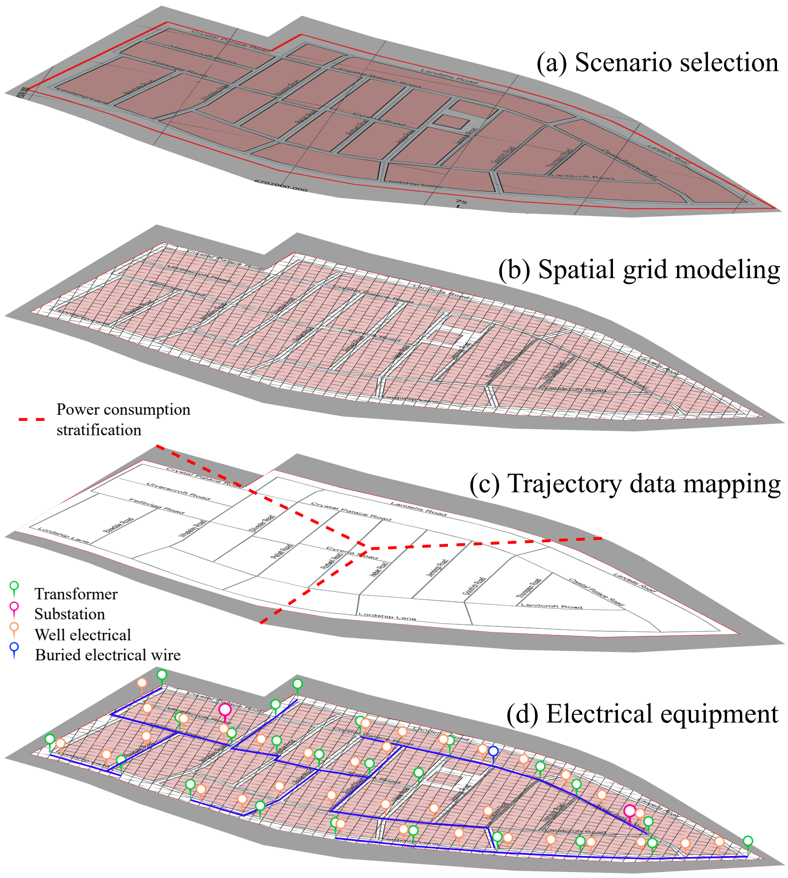

Figure 3. Layered evaluation of the proposed Methodology and Algorithm.

The heuristic is also developed using MATLAB software to achieve the stated objectives. The resulting electrical distribution system is then simulated with CYMDIST software-Version 4.7 to obtain accurate load flow data and to validate the performance of the heuristic.

The electrical equipment is selected based on technical requirements such as primary and secondary network voltage and design demand. The distribution transformers are oil-immersed type, and the voltage level of the medium-voltage network is 11 kV, while the voltage level of the low-voltage network is 0.22 kV.

The simulation parameters are detailed in Table 5. The primary feeder follows the typology proposed in the connectivity or adjacency matrix obtained as a near-optimal solution. Additional detail is that the heuristic achieves 100% coverage for electricity supply to users. Demand depends on a selected cluster and the number of users, so the demand is identified for each cluster. The location of the substation is arbitrary.

On the other hand, the proposed method applies the Prim algorithm to determine the optimal number of transformers to be placed, identifying the characteristics of the streets of the scenario and a stretch from the transformer greater than 40 m in conjunction with the calculation of the connectivity matrix, which is responsible for determining the shortest distance between the houses, the transformers, and the substation. Table 6 illustrates initial considerations for running the proposed optimization model.

Table 5. Characteristics of the final scenario for analysis of the method.

Item	Parameters	Description
Scenario	Final user Residential users Commercial users Total demand Connections associated with each transformer	715 f.p. 0.95 f.p. 0.85 variable (4.2 MW) 15, 20, 25, 30
Medium-voltage network	Primary feeder Voltage level Type of installation Network settings Type of conductor	1 11 kV Underground Radial Insulated power cord TCLPE 15 kV
Low voltage network	Distribution transformer Voltage level Network settings Type of conductor	11/0.22 kV immersed in oil 220 V Radial Insulated power cord TCLPE 2 kV

Table 6. Simulation model parameters.

Scenarios	Transformer Demand (kW)	Transformer Power without Tap (kVA)
Scenario A	124	150
Scenario B	106	112.5
Scenario C	88	112.5
Scenario D	71	75

4. Analysis of Results

For deploying the subway distribution network, conductor routing has been considered using the georeferenced scenario database with the osm file extension. The heuristic model has been built in MATLAB software, while the power flow study has been analyzed with CYMDIST software. Furthermore, it is noted that the heuristic has been evaluated on a balanced power network. In order to verify the versatility of the proposed heuristic and its easy adaptability, four case studies are carried out. The close-to-optimal solution for each case study is shown in Table 7, where the length of the primary feeder conductor, the optimal number of transformers, the maximum length of the conductor in the medium-voltage power network, and the percentage of voltage drop are shown. A detail that can be appreciated with Table 7 is that as the distance increases, so does the voltage drop; consequently, it can be inferred that the voltage drop is directly proportional to the length. Furthermore, the number of transformers required in the underground distribution network increases as the length of the topology increases. Topology length is defined as the length of the road network.

Consequently, it is verified that the proposed heuristic model is scalable, i.e., it can be applied to any case study. A maximum capacity of links in each transformer has been determined for each scenario.

The heuristic algorithm can estimate the optimal number of transformers to be placed in each case study to guarantee 100% coverage. The optimal number of transformers is directly related to the design demand of each user. Knowing the optimum number of transformers, the demand for street lighting, and the demand for technical losses allows for determining the minimum power required at the power transformer to supply electricity while observing safety and service continuity criteria.

Table 7. Near-optimal solution for each case study.

Description	Scenario A	Scenario B	Scenario C	Scenario D
Length from source (m)	490	495	500	610
No. of transformers	35	40	49	60
Network length MV (km)	30	43	55	58
Voltage drop	2.1%	2.4%	2.7%	3%

Figure 4 shows the algorithm's results applied to the four base scenarios, where each base scenario must cover the power demand of the entire scenario, estimated at 5.4 MVA. The model suggests that Case Study D requires the highest number of transformers, reaching 60 with the sizing power of 79 kVA. On the other hand, Case Study A requires a maximum number of 35 transformers of 137 kVA to cover demand. As explained in previous paragraphs, the solutions responded to local optimums since they depend on the initial conditions of the problem to be solved. Another detail revealed in Figure 4 is that as the length increases, it is necessary to place more transformers.

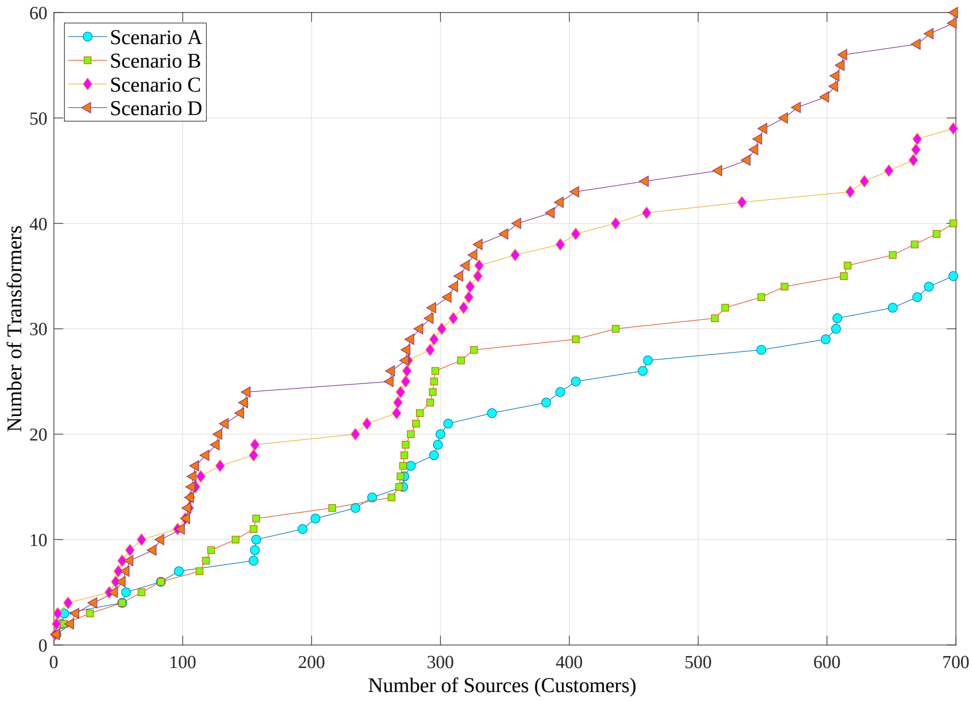

Figure 4. Number of transformers required related to the distance from the source to the load.

Figure 5 shows the maximum conductor length required for each case study. Length is recorded from the main feeder and the total number of supplies for the 715 loads in the scenario. The results show a minimum required length of 58 km of conductor for the MV underground grid assembly for Case Study D, with a maximum capacity of 15 subscribers per transformer. Scenario A has a minimum length of 30 km of underground MV network with a maximum capacity of 30 subscribers per transformer.

As previously mentioned, the electrical distribution system has been modeled with CYMDIST software. This allows different studies such as load flow, voltage drops, and power profile of the electrical system, among others. Figure 6 illustrates the implementation of the case study A distribution system. The blue lines indicate the underground electrical network and its topology. The primary feeder, 35 transformers with delta-grounded star connection, and the number of concentrated loads deployed in the area of interest can be identified.

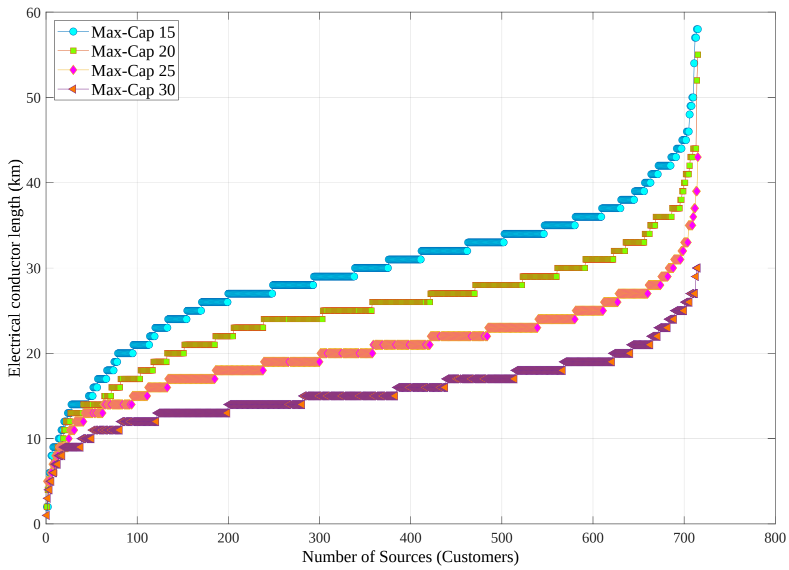

Figure 5. Length of the conductor related to the distance from the source to the load.

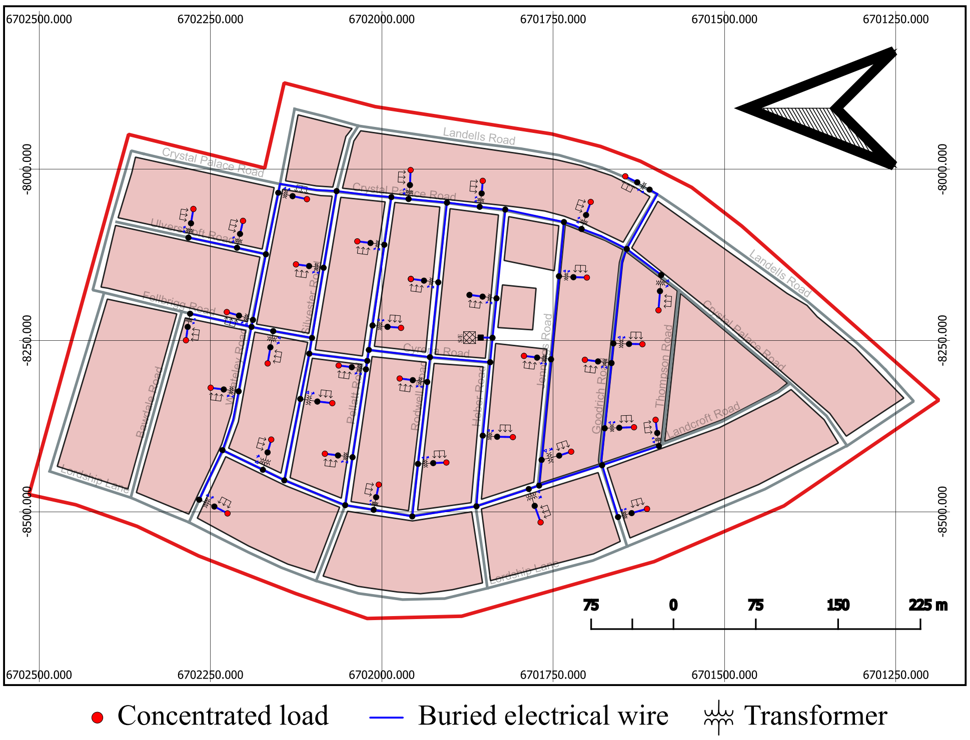

Figure 6. Medium- voltage network of scenario A.

An electrical system in optimal operation is established through reliability and power supply quality indicators. These can increase due to problems in the system's operation due to different abnormal operating conditions; these conditions are considered voltage drops due to technical losses in the MV electrical network.

It is essential to verify the maximum voltage drop from the transformer to the farthest load, since compliance with the maximum acceptable 5% for voltage variation in the transformer secondaries must be guaranteed. Figure 7 shows the voltage drop in each study case. From the graph in Figure 7, it can be identified that the distance with the highest voltage drop is 120 m from the main feeder; therefore, Scenario D shows a voltage drop of approximately 4.1%, which is the highest voltage drop of the different case studies. In addition, Case Study A shows a voltage drop of approximately 1.55%. Consequently, when analyzing the voltage drops in each case study. The voltage drops are within the acceptable limits in the literature and do not exceed 5.5%.

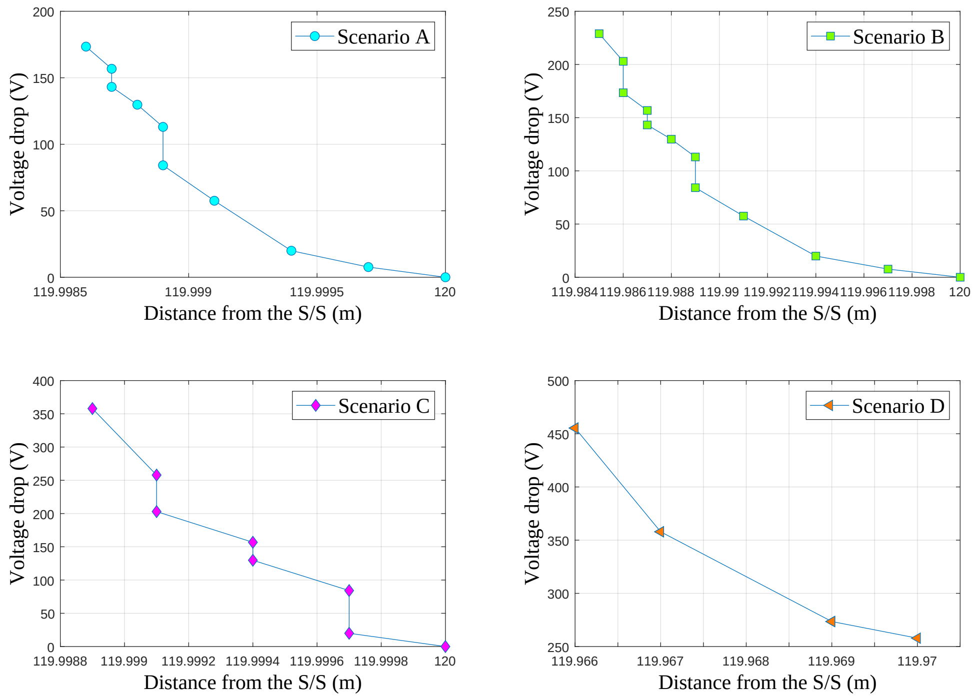

Figure 7. Stress drop in study scenarios.

Figure 8 shows the apparent power profile for each case study. The apparent power profile is recorded from the power source to the user. It can be identified from Figure 8 that as the distance increases, the apparent power profile decreases.

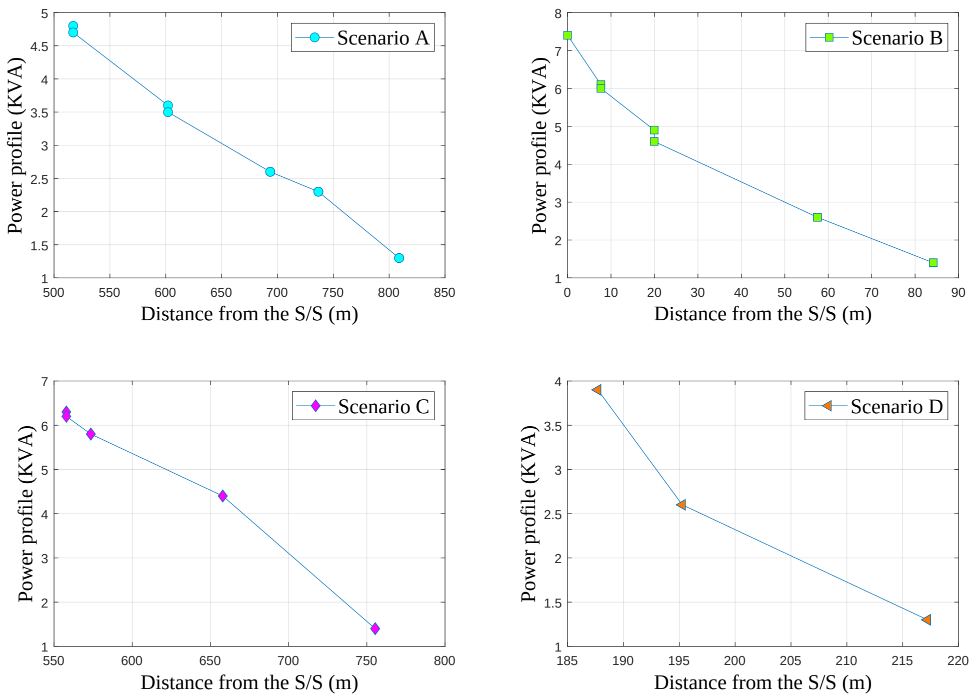

Figure 8. Power profile in (kVA) of the study scenarios.

5. Conclusions

The model proposed in this paper shows that a close-to-optimal response is provided for each case study. It demonstrates the scalability of the model and its easily adaptability to any case of study. In addition, it is possible to verify the maximum conductor lengths required in underground electrical networks. Knowing the power to be installed in distribution transformers, it is possible to plan the dimensioning of conductors, protection, and civil works. Consequently, the proposed heuristic helps designers make decisions by observing technical criteria with reduced costs.

The heuristic method has allowed the optimal deployment of the subway network, considering reduced investment costs. The significant contribution of this article is that it allows electric distribution companies to make expansion plans and project demand by generating different case studies.

Electricity supply is susceptible to interruptions or failures, especially in overhead networks, which causes economic losses. Thus, a robust algorithm for subway distribution networks has been proposed to increase the security and reliability of the electricity supply from the distribution system to the end-user.

The efficiency of the proposed mathematical model has been verified through a georeferenced system. By analyzing load flows for each case study, we verified that the electrical network does not exceed 5% voltage drop from the secondary of the transformers to the users farthest from the source. In future research, the proposed model will integrate distributed generation.

The work presented opens possibilities for future works that incorporate evaluation of contingencies and failures, and then the expansion of the electrical distribution network is generated. In addition, it will be possible to incorporate hybrid networks that contemplate overhead and underground topologies to evaluate scenarios that occur daily in electric utilities and thus evaluate more-efficient management mechanisms.

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