



## Research article

## Geographical information system based optimal path routing of distribution networks

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## ABSTRACT

An electric distribution network is a part of a power system that distributes electricity to users with little power loss along its path. Distribution systems suffer from frequent interruptions, high power losses, and low voltage profile which negatively impacts both the utility and the consumers. The major cause of these challenges are unplanned network expansion, improper routing of feeders and branches, untagged transformers, poles, and capacitors, and lack of standard procedures for expansion. In this paper, ArcGIS software was used together with an Analytical Hierarchy Process (AHP) to find the optimal path for distribution feeders, as well as, to find the new transformers, poles, and capacitors placement. ETAP Software was used to model the electric distribution network and also used to compute the power loss in the network and its voltage profile. As a result, after optimal rerouting, the length of the distribution feeder was reduced by 4km. Consequently, the simulation results show that the minimum node voltage is 0.95152 p.u, which is within the IEEE limit of 0.95–1.05. The active and reactive power losses are reduced from 339.49 kW to 222.43kW (by 35%) and from 238.79kVAr to 157.38 kVAr (by 34%), respectively.

## 1. Introduction

The major function of an electric power system is to supply electricity to customers in a reliable and cost-effective manner. An improved system structure and good system planning helps to ensure energy supply continuity [1]. A distribution system is an important part of the overall electric supply system, as it provides the final link between a bulk transmission system and load center. Line losses at the distribution level are well known to waste a significant portion of total power generation. The distribution system must be able to handle the power demand while also offering a high level of service through effective system planning. Because the distribution system is so vital economically, rigorous planning, design, implementation, and operation of the system is capable of supplying ever-increasing growth rates and increased customer satisfaction. The distribution systems planning is required to meet the growing demand for energy in the most efficient manner possible, taking into account the expansion's techno-economic feasibility. In comparison to the generation and transmission systems, the distribution system has a far greater range of voltage levels,

components, loads, and interconnections [2, 3, 4, 5, 6]. With respect to generation and transmission, Ethiopia's current distribution system needs improvement [7, 8, 9]. The main problem that electric power utilities in developing countries face today is that power consumption is high, yet supply expansion is hampered by limited resources, environmental concerns, and other societal considerations. This has necessitated more thorough justifications of system facilities, as well as improvements in electricity production and consumption. Currently, in Bahir Dar City, the power delivered from the distribution systems to the end-users is less reliable than it is expected to be, as there are frequent interruptions that affect both the utility and customer when compared to other developed countries. Some of the major causes of this are: (1) inappropriate routing of distribution feeders, (2) lack of proper planning of networks to monitor and prevent power losses, (3) a significant voltage drop across the lines, (4) untagged transformers, poles, and capacitors, and (5) transformers, poles, and capacitors are not sited according to standards at proper locations. These have led to irregular patterns of network growth, overloading, and ill-proportioned spatial coverage.

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Electric utility companies must have two types of geographic information: (1) a distribution network with critical technical information and the locations of all poles, power lines, circuits, transformers, capacitors, and other equipment; and (2) consumer and billing information with a list of existing customers, their locations, and consumption details to determine the areas for a potential customer, as well as network expansion and equipment additions. With a complete perspective of the entire system represented on a map, GIS cloud technologies assist utilities in managing vital information about consumers and distribution networks. It can assist utility engineers in identifying distribution, demand, and consumption trends in order to determine the energy requirements for developing a profitable distribution system. GIS is unique in its ability to integrate and spatially analyze multisource datasets such as land use, population, topography, hydrology, climate, vegetation, transportation network, and public infrastructure, to name a few. The data is altered and analyzed to obtain information valuable for a specific application, such as circuit routing suitability study. Several authors have worked on the analysis of power distribution systems and GIS-based optimal path routing of its network and other related tools. Kerur *et al.* [10] used graph theory to find the optimal path of distribution feeders. Samui *et al.* [11] and Narasimhulu *et al.* [12] used a direct approach to determine the substation location, size, and its service area, number of feeders, and routes. Leena [13] proposed a bacterial foraging optimization algorithm (BFOA) along with backward-forward sweep (BFS) for distribution network reconfiguration based on load flow method and geographical information system (GIS). Khattak *et al.* [14] utilized GIS and GPS techniques for a radial distribution network that provides high accuracy. An 11kV feeder was mapped to SynerGEE Electric Software to carry out load flow analysis. Bifurcation and load shifting techniques are used for the optimization of the network and the impact on the voltage drop, load profile, and annual energy loss was observed. It is demonstrated that the voltage drop and energy loss can be reduced using the GIS mapping

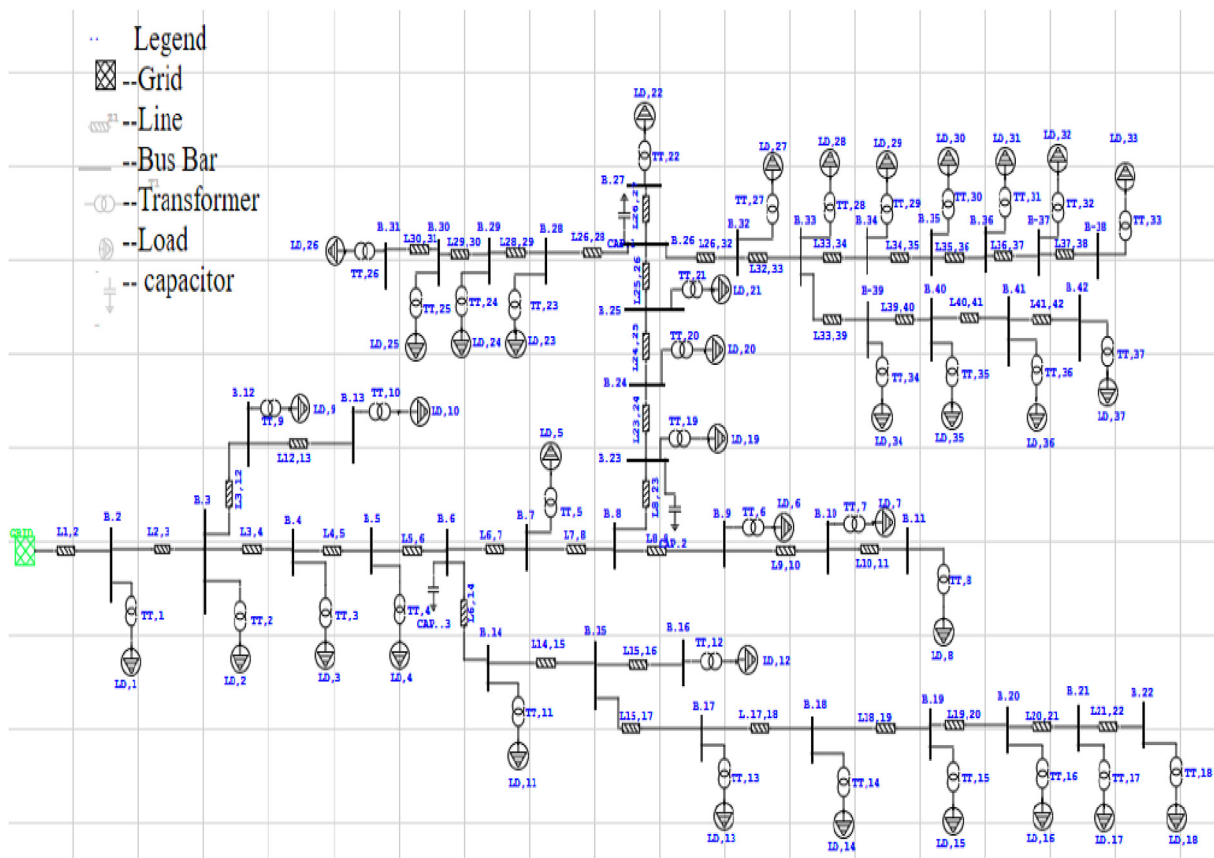
technique. Balamurugan *et al.* [15] proposed a GIS solution for electric power supply network management. GIS was used to quickly segment fault area and isolate it, while power restoration is done for a non-fault segment of the region. Rai [16] developed an electric-GIS application that supports functions such as creating a network of electric utility and analyzing the changes in the electrical asset features.

In this paper, a GIS-based electricity distribution system planning strategy is utilized to determine the optimum path routing that reduces power loss and total voltage drop. Analytic Hierarchy Process (AHP) has been used for making multiobjective decisions regarding the route of a feeder, the location of transformers, poles, and capacitors.

The Analytic Hierarchy Process (AHP) is a decision-making tool that decomposes a complicated problem into a multi-level hierarchical framework comprising objectives, criteria, sub-criteria, and alternatives to better characterize the general choice operation. AHP can be used to make complex, unstructured decisions involving multiple attributes. These criteria define decisions that do not perfectly fit into a linear framework; they consider both physical and psychological elements. AHP presents a connecting mechanism that can quantify the decision-subjective maker's appraisal in a measurable way. The problem is analyzed using a hierarchical framework, with level I indicating the decision's overall aim or focus. Level II comprises of decision factors or criteria, while Level III has sub-factors, and Level IV provides choice options. Prioritization is performed by giving a number from a scale (weight) to each criterion to signify its relevance. A matrix with pairwise comparisons of these attributes provides the means for calculation [17].

## 2. Materials and methods

The 15kV distribution feeder under study presented in Figure 1 is known as the Bahir Dar City Utility and is usually called *Bata* or R3. This



feeder does not have proper information on poles, transformers, and capacitors. From the fieldwork, it was observed that.

- (i) most of the transformers are untagged and they are not sited in a proper location,
- (ii) some of the poles are unnumbered, some of them are in the middle of the houses, which causes so much inconvenience to the public.

For a successful GIS installation, proper GPS surveys and production of an accurate digital base map for the distribution network are required. The survey necessitates the installation of a GPS base station at a pre-determined site, as well as a sufficient number of GPS receivers. Surveyors had to walk beside the feeders to capture the pole, transformer, and feeder's spatial position. The digital base map must include essential landmarks such as highways, buildings, and other features that help identify network assets and plan new distribution networks. For better visualization of the vector map of the network, it is needed to prepare a proper GPS survey and create an accurate digital base map for the distribution network. The load power was obtained from measured data of the secondary line current of 15/0.4kV transformers.

The major steps followed for collecting the required data are (i) fieldwork or GPS survey (ii) downloading images from Google Earth Pro (iii) geo-referencing the image (iv) forming the database, and (v) creating points to a rectified image in Arc Map software.

Thematic layers such as houses, trees, telecom towers, and road networks were extracted and represented in polygons, points, and lines and were digitized using a high spatial resolution satellite picture that was incorporated into the GIS environment. Buildings, roads, telecom towers, and trees are among the features in the personal geodatabase. Using the "add x-y coordinate" functionality in the Arc Map environment, the coordinate points of the transformer, poles, and capacitor were linked together and captured into the geodatabase. High spatial resolution satellite images were acquired and inputted into the GIS environment whereby thematic layers such as buildings and road networks were extracted and represented to determine the optimal location of transformer, pole points, capacitor banks, line lengths of distribution systems. The procedure of data processing using the GIS software is shown in Figure 2.

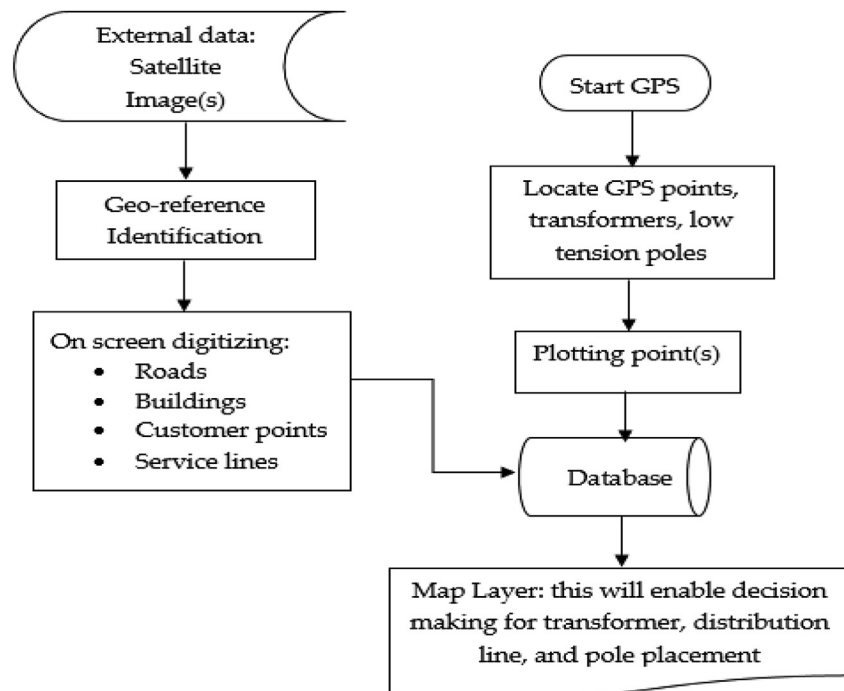


Figure 2. Flow chart of procedure of data processing using the GIS software.

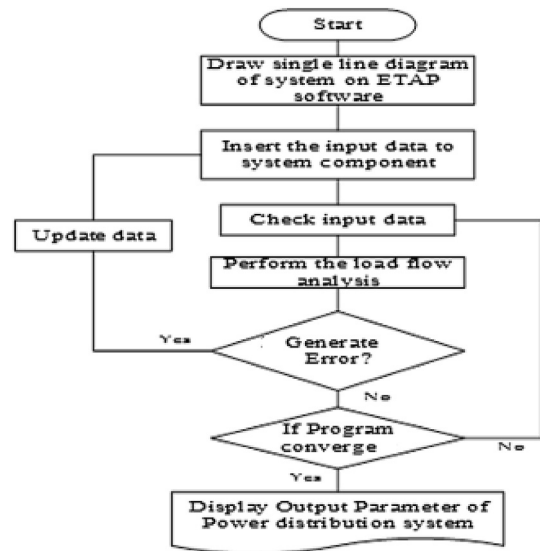


Figure 3. Procedure for modelling of distribution system ETAP software.

### 2.1. Distribution system modelling using ETAP software

The single line diagram of the Bata feeder is shown in Figure 1. The overhead distribution line is simulated by the power system simulator called ETAP software. ETAP is one of the foremost-integrated databases for electrical power system simulation with the proper information of system components. The distribution system has standard conductors type such as AAC-25, AAC-50, AAC-95 with a total length of 22km (existing system) which is reduced to 18 km after improving the system by using Analytical Hierarchy Process (AHP) optimization techniques.

The electrical design of the distribution line was achieved by computing the various parameters such as resistance, inductance, capacitance, and conductance etc. after reducing the total length of the path. These overhead lines (feeder) are used to distribute medium voltage (15 kV) from Bahir Dar substation-II to the distribution

**Table 1.** Fundamental scale.

Importance level	Degree of Importance	Aij	Aji
1	Equal importance	1	1
2	Intermediate values	2	1/2
3	More important	3	1/3
4	Intermediate values	4	1/4
5	Strong importance	5	1/5
6	Intermediate values	6	1/6
7	Very strong importance	7	1/7
8	Intermediate values	8	1/8
9	Extremely important	9	1/9

**Table 2.** Important criteria coefficients.

	Telecom tower	Road	Tree	Building
Telecom tower	1	3	2	5
Road	1/3	1	3	7
Tree	1/2	1/3	1	3
Building	1/5	1/7	1/3	1
sum	2.03	4.473	6.33	16

**Table 3.** Normalized value and final weight of criteria.

	Telecom tower	Road	Tree	Building	Average weight
Telecom tower	0.5	0.67	0.32	0.31	0.45
Road	0.163	0.22	0.474	0.44	0.32
Tree	0.25	0.074	0.16	0.19	0.17
Building	0.1	0.032	0.052	0.063	0.06

transformer. Therefore, the single line modelling of Bata feeder is obtained by using ETAP Software. Figure 3 shows the flowchart of the steps taken to model the distribution system using ETAP software.

## 2.2. Impedance calculation

The line impedance for each section of the line is calculated from the line data using Eq. (1).

$$Z = (r + jx)L \quad (1)$$

where  $r$  is the resistance of the line in ohms per km,  $x$  is the reactance of the line in ohms per km and  $L$  is the line length in km.

The impedance standard data per kilometer (km) as collected from Bahir Dar City Utility are:

- I. AAC-95:  $0.3085 + j0.2147 \Omega/\text{km}$
- II. AAC-50:  $0.5787 + j0.4362 \Omega/\text{km}$
- III. AAC-25:  $1.1810 + j0.8345 \Omega/\text{km}$

## 2.3. Load/power calculation

Since it is not possible to measure the load power at each transformer directly, the power of the loads connected to all transformers is

obtained from the measured current and nominal voltage using Eq. (2) [17].

$$S = \sqrt{3} VI^* = P + jQ \quad (2)$$

The line voltage is  $V = 0.4\text{kV}$  for all transformer points.

## 2.4. Choice of weighting values by using AHP optimization

In AHP Optimization, sharing of the different weights in a certain multi-objective function differs based on the interest of the responsible engineer. To weigh each of the map layers, a weighing mechanism was designed. The weighting system forms the backbone of the methodology. All of the weighted layers are added together to make an appropriate layer. This layer serves as the foundation for the GIS analysis. Weights for thematic layers were calculated using the Analytical Hierarchy Process (AHP) [18]. A decision matrix assesses and ranks a set of decision-making tools. The first step is to create a list of weighted criteria and then compare each choice to those criteria. This is a variation of the L-shaped matrix which is given by Eq. (3) [18].

$$\begin{bmatrix} 1 & b_{12} & b_{13} \dots b_{1m} \\ b_{21} & 1 & b_{23} \dots b_{2m} \\ \dots & \dots & \dots \\ b_{m1} & b_{m2} & b_{m3} \dots 1 \end{bmatrix} \quad (3)$$

Place all the criteria in a  $n \times n$  square matrix and enter the degree of importance of relevant elements if the criteria is  $n$ . If  $A_{ij}$  is the relative relevance of element  $i$  (criterion) to element  $j$ , then  $A_{ji}$  is the inverse of  $A_{ij}$ . Technical requirements, for example, are far more essential than environmental factors. As a result, its corresponding value is 5, and the amount of its corresponding element in reversed row and column is  $1/5$  [17,19]. The fundamental scale parameters and their importance levels are presented in Table 1, while Table 2 presents the important criteria coefficients. The Normalized value and final weight of criteria is presented in Table 3 and it is used in the calculation of the consistency of the distribution network as presented in Table 4.

The next step is to obtain the lambda value of each of the elements by dividing the weighted sum value by the final weight.

Telecom tower:  $\lambda_{\max 1} = 2.06/0.45 = 4.578$

Road:  $\lambda_{\max 2} = 1.4125/0.32 = 4.414$

Tree:  $\lambda_{\max 3} = 0.6866/0.17 = 4.04$

Building:  $\lambda_{\max 4} = 0.25386/0.062 = 4.09$

The mean value will be:  $\lambda_{\max} = (4.578 + 4.414 + 4.04 + 4.09)/4 = 4.2805$ .

Now the consistency index (C.I.) is obtained by using Eq. (4) [20]:

$$C.I. = (\lambda_{\max} - n)/(n-1) \quad (4)$$

where  $\lambda_{\max}$  is the biggest characteristic value of the comparison matrix,  $n$  is the matrix order. The smaller the CI value is, the closer the judgment matrix will be. On the other hand, the degree of the judgment matrix will be greater in this instance.

Therefore,  $CI = (4.2805 - 4)/3 = 0.09$

The consistency ratio is given by Eq. (5) [20]:

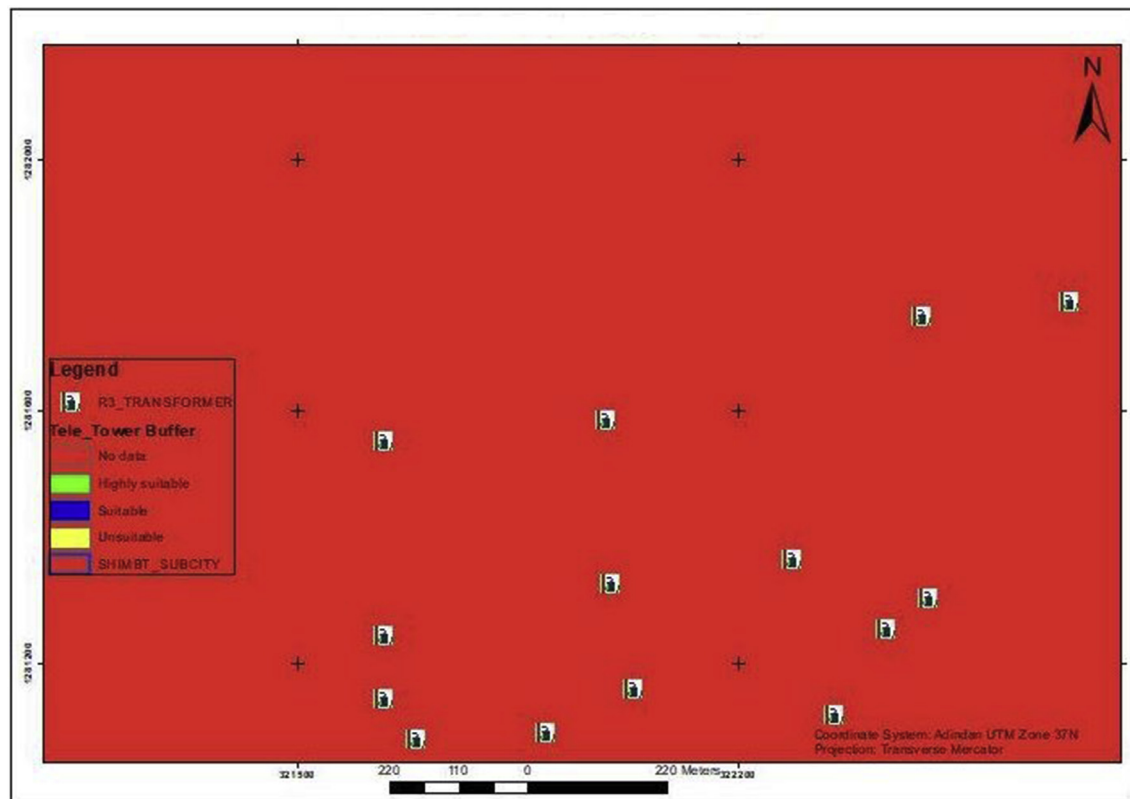
$$CR = (C.I./R.I) \quad (5)$$

**Table 4.** Calculation of consistency.

Weight criteria	0.45	0.32	0.17	0.062	Weighted sum value
	Telecom tower	Road	Tree	Building	
Telecom tower	$1 \times 0.45 = 0.45$	$3 \times 0.32 = 0.96$	$2 \times 0.17 = 0.34$	$5 \times 0.062 = 0.31$	2.06
Road	$0.33 \times 0.45 = 0.1485$	$1 \times 0.32 = 0.32$	$3 \times 0.17 = 0.51$	$7 \times 0.062 = 0.434$	1.4125
Tree	$0.5 \times 0.45 = 0.225$	$0.33 \times 0.32 = 0.1056$	$1 \times 0.17 = 0.17$	$3 \times 0.062 = 0.0186$	0.6866
Building	$0.2 \times 0.45 = 0.09$	$0.143 \times 0.32 = 0.04576$	$0.33 \times 0.17 = 0.0561$	$1 \times 0.062 = 0.062$	0.25386

**Table 5.** Random Index (RI) values.

Attribute	1	2	3	4	5	6	7	8	9	10
RI	0.0	0.0	0.52	0.9	1.11	1.25	1.35	1.4	1.45	1.49

**Figure 4.** Buffering of telecom tower with transformer.

where RI = random index.

Then, the random index (RI) is obtained for the number of attributes used in decision making as presented in Table 5.

Since the number of attributes is 4,  $RI = 0.9$ .

Therefore,

$$CR = (C.I)/RI = (0.09)/0.9 = 0.1$$

Since  $CR \leq 0.1$ , it is considered acceptable, and it helps in giving an informed judgment attributable to the knowledge of the analyst based on the problem under study. After the overlay, the optimum path of the feeder is shown Figure 4. From the GIS result, the optimum length of the feeder and the optimum location of the transformer, pole, and capacitor are obtained. The total optimum feeder length is reduced from 22 km to 18 km.

## 2.5. Standardization

The evaluation of options can be expressed using various scales (ordinal, interval, and ratio). Standardizing the criteria facilitates the rescaling of all evaluations, allowing for comparison across and within the criteria [21]. At this stage, the possible location of transformers and feeder routes are selected based on the standards set by the Utility. Table 6 shows the overhead electric lines and quality of supply standard parameters, while Table 7 shows the elements and criteria of power Distribution network line routing suitability parameters.

## 2.6. Buffering of transformers, poles, and capacitor banks

Because voltage loss may be permitted due to long-distance covered in power distribution, the buffering analysis aids in determining the

minimum possible length of connection. Four factors affect the distribution system of the study area. These are road buffering, tree buffering, building buffering and telecom tower buffering. The GIS simulation shows that some transformers and poles are placed in no data (nothing is

**Table 6.** Overhead electric lines and quality of supply standards.

Parameter	Vertical clearance [m]	Horizontal clearance [m]
Road	6.1	2
Building	2.5	1.2
High voltage	2.5	1.2
Telecom tower	1.83	1.2
Tree	3	4
River	—	3

**Table 7.** Elements and criteria of power distribution network line routing suitability in meters.

No.1	No data*	Highly suitable	Suitable	Unsuitable
Road	0–2	2–2.2	2.2–2.5	2.5–3
Building	0–1.2	1.2–1.5	1.5–2	2–2.5
Telecom tower	0–1.2	1.2–1.5	1.5–2	2–2.5
Tree	—	5–5.5	4.2–5	4–4.2

\* There is no transformer or pole located in this range. The classification or range depends on the actual suitability of the city.



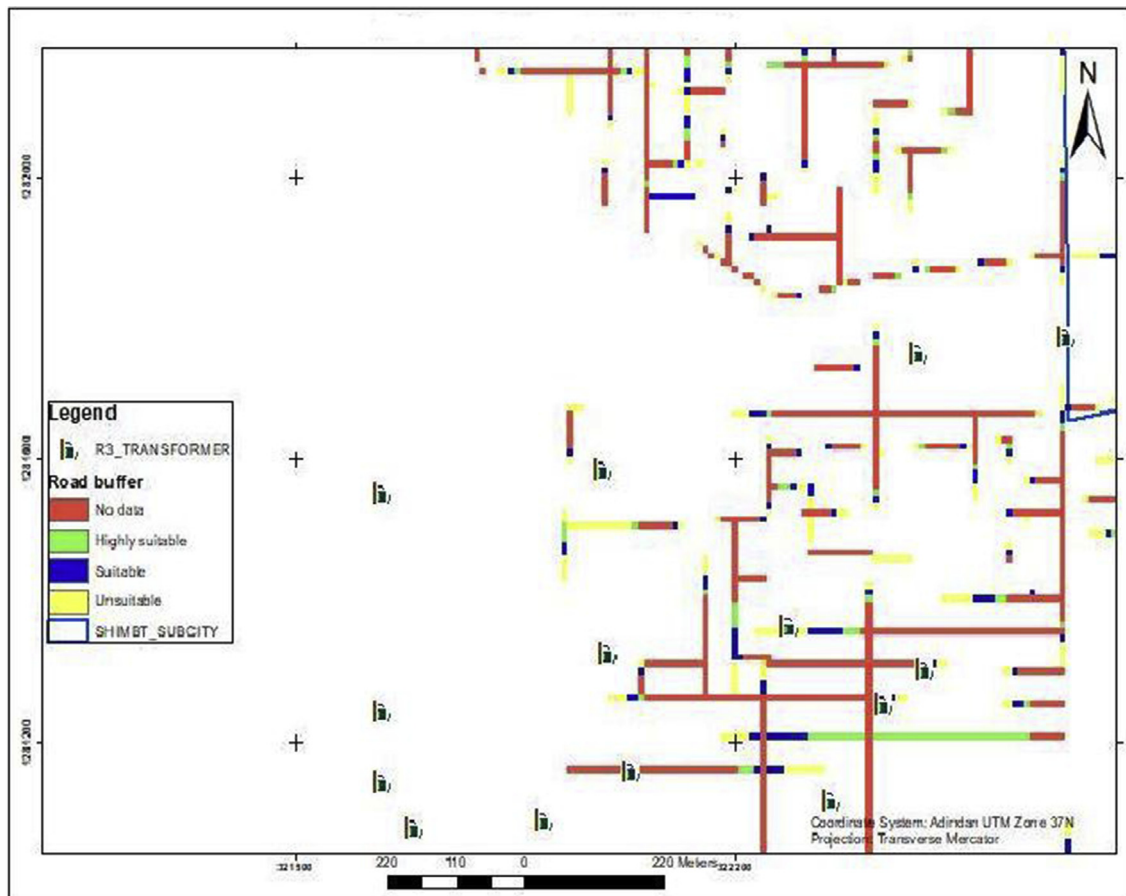


Figure 5. Buffering of road with transformer map.

placed in the position indicated), unsuitable, highly suitable, suitable, between suitable and unsuitable, between suitable and highly suitable, and out of the range from the classification of each factor as shown in Figures 4, 5, 6, and 7.

### 3. Results and discussion

The reduction in active and reactive power loss, as well as an improvement in node voltage profile, have been used to evaluate the efficacy of the GIS-based optimum path routing approach. ETAP 16.0 has been used to model the electric distribution system. The simulation result shown in Figure 4 shows that there is no telecom tower placed in the network. Buffering of the pole and capacitor banks is similar to that of buffering of the transformer. The combination of buffering of transformers, poles, and capacitor banks forms the optimal path of the network. The overlay system with routing path is shown in Figure 8.

#### 3.1. Voltage profile

The simulation results show that the voltage profile of the network is significantly improved after the network route is optimized. The minimum voltage before network reconfiguration was 0.928 p.u., and this was improved to 0.95152 p.u after the network is reconfigured. The results of the improvement in voltage profile is shown in Figure 9. The voltage profile represented with blue is for the base case system while the one represented with red is the voltage profile of the

distribution system after rerouting. All the bus voltages were seen to be above 0.95 p.u.

#### 3.2. Voltage drop reduction

As shown in Figure 10, the voltage drop across all branches of the feeder is reduced significantly. The maximum voltage drop is seen to reduce from 7.2% to 4.848%.

#### 3.3. Power loss reduction

The summary of the network parameters such as feeder length, active and reactive power losses are presented in Table 8. After rerouting the network optimally, the total feeder active power loss is reduced from 339.49kW (base case) to 222.43kW whereas the reactive power loss is reduced to 157.38 kVar from 238.79 kVar. In other words, the active and reactive power loss reductions due to the optimal network rerouting are 35% and 34%, respectively. In addition to the reduction in active and reactive power losses and voltage drop, optimal routing of the feeder reduces the line length from 22km to 18km which saves additional cost of line installation. The authors of this paper strongly recommend the use of GIS based path routing methods for optimal expansion of distribution feeders as it is effective in reducing line length, power losses, and voltage drop of a distribution system. GIS based optimum path routing among all the feeders can be used to study, analyze and enhance the reliability of the entire distribution system and reduce feeder overloading.

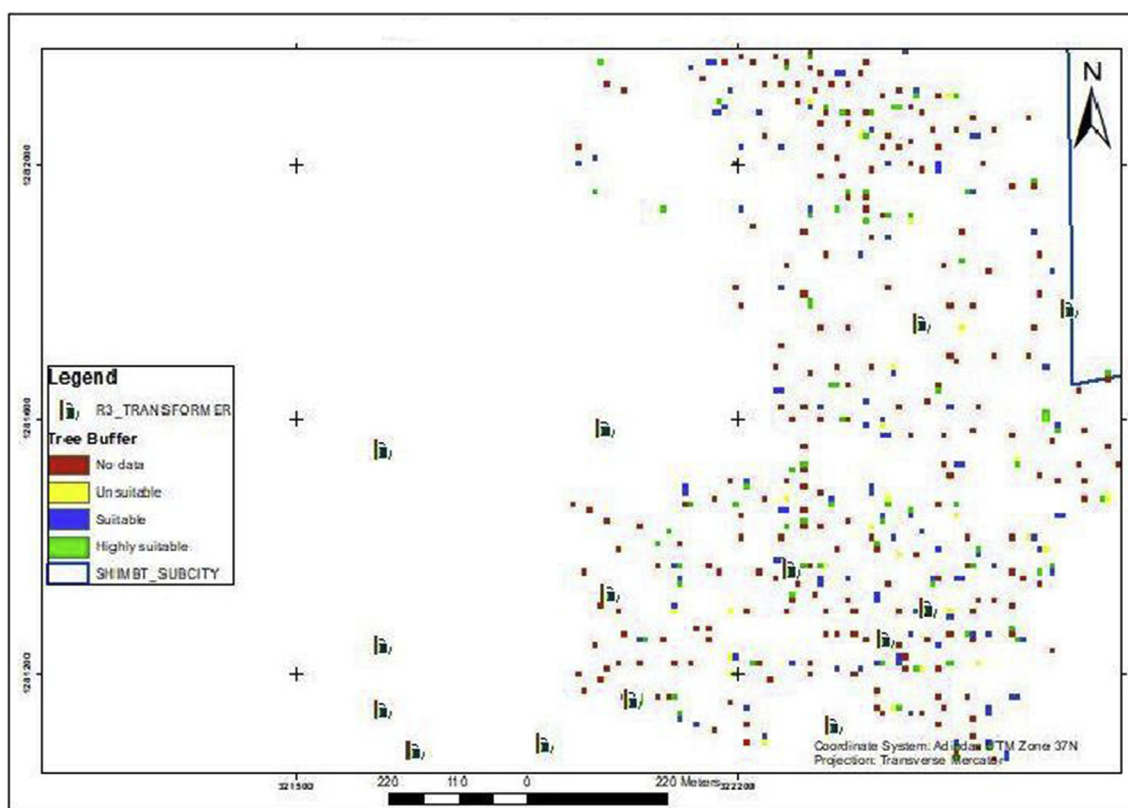


Figure 6. Buffering of trees with transformer.

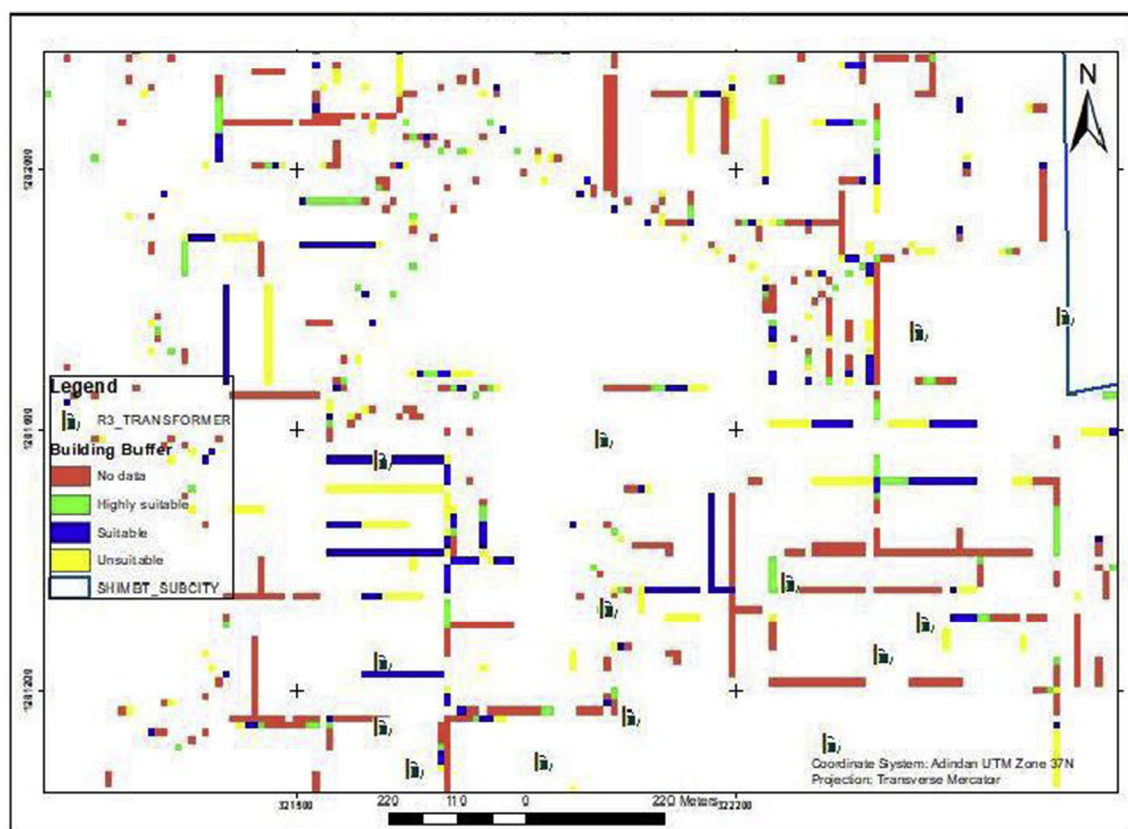


Figure 7. Buffering of building with transformer.

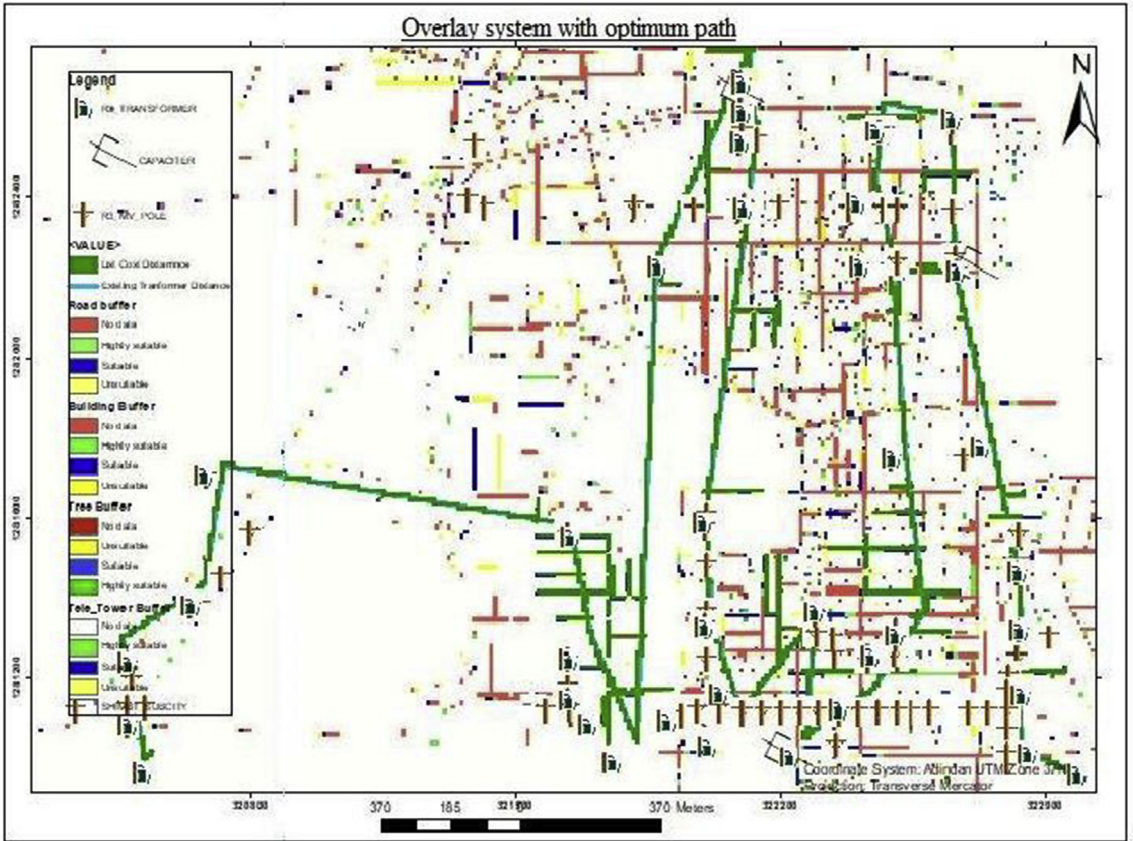


Figure 8. Overlay system with optimum path.

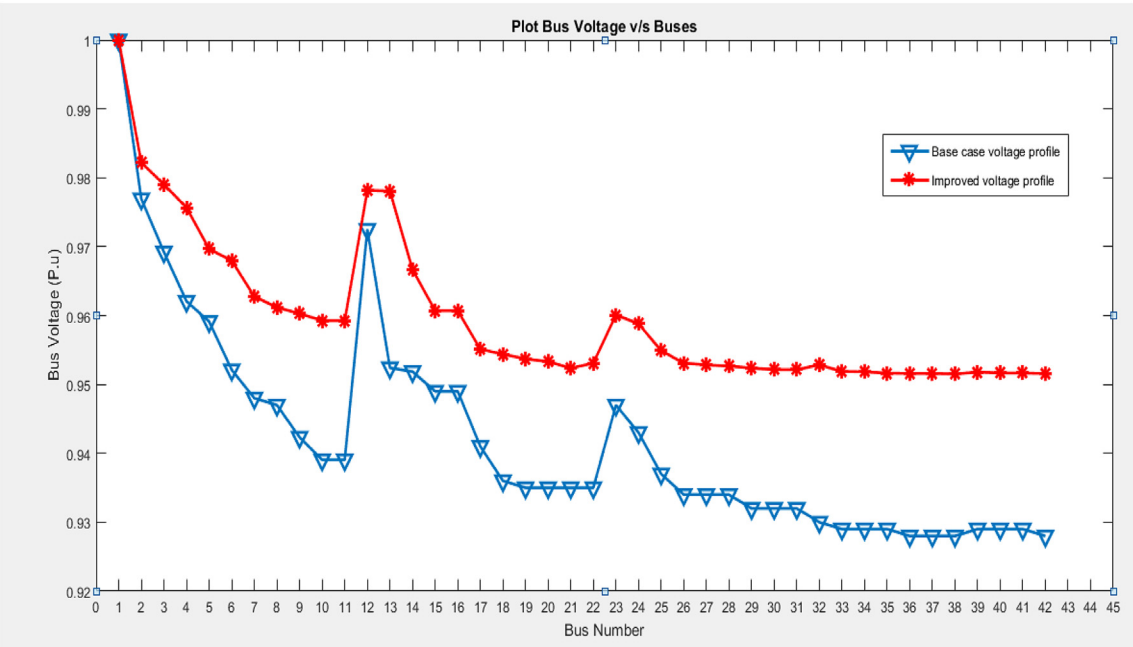


Figure 9. Improved voltage profile due to optimum feeder length.



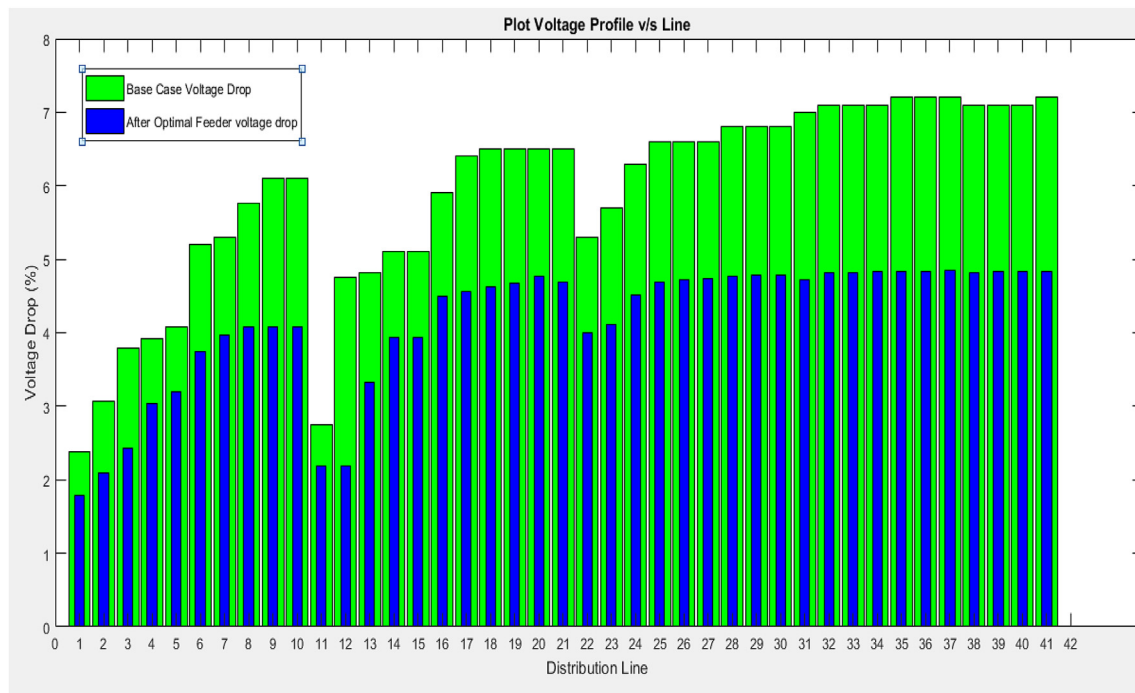


Figure 10. Voltage drop reduction of the case study.

Table 8. Network performance before and after re-routing.

Scenarios	Performance measurement	
Existing network (scenario 1)	Total feeder length	22km
	Active power loss	339.49 kW
	Reactive power loss	238.79 kVAr
Optimal network path (scenario 2)	Optimal feeder length	18 km
	Active power loss	222.43kW
	Reactive power loss	157.38 kVAr

#### 4. Conclusion

In this paper, the *Bata* Feeder radial distribution network was mapped using GIS and GPS techniques based on distribution system planning. Routing the distribution path of distribution networks is important to reduce losses and to enhance voltage profile. Route optimization was performed in this work to shorten the feeder length to a feasible route based on site suitability. An analytical hierarchy process (AHP) was utilized for decision-making. After the simulation using ARCGIS10.4.1 software, the optimum locations of transformers, support poles and capacitors was obtained. As a result, the feeder length was reduced by 4km, improving the network's voltage profile and lowering active and reactive power losses. Active and reactive power losses have been reduced by 35% and 34%, respectively. The minimum bus voltage has been increased to 0.95152 p.u., which is higher than the IEEE minimum bus voltage of 0.95 p.u. In the future, authors recommend that further researches can be done to focus on GIS based Optimum path routing for transmission lines.

#### Declarations

##### Author contribution statement

Lidiya Bitew Techane: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data.

Ayodeji Olalekan Salau: Analyzed and interpreted the data; Wrote the paper.

Yalew Werkie Gebru, Engidaw Abel Hailu: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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##### Data availability statement

Data will be made available on request.

##### Declaration of interests statement

The authors declare no conflict of interest.

##### Additional information

No additional information is available for this paper.

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