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Optimizing Rural Electricity Distribution with Minimum Spanning Tree and Mixed Integer Programming: Evidence from Sungai Mengkuang Village, Indonesia

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Abstract
The increasing demand for PLN electricity connections in line with population growth and rural development necessitates efficient and standardized network planning. This study aims to design a two-stage optimization algorithm that ensures effective customer-to-pole electricity connections, utilizing the Minimum Spanning Tree (MST) and distance-based optimization methods. A case study was conducted in Sungai Mengkuang Village, Bungo Regency, involving 186 customers and 27 PLN electricity poles. The spatial data, comprising latitude and longitude coordinates, were collected using the ARCGIS application. The first optimization stage grouped customers with a maximum of five series connections, in compliance with the SLP (Standard Layak Pelanggan) regulation. The second stage connected these groups to the nearest poles while maintaining a five-connection limit per pole. The algorithm applied a modified Haversine formula to calculate cable distances. The results revealed an optimal configuration with a minimum cable length of approximately 1.028 kilometers and an equitable distribution of connections across poles. The model also identified underutilized poles, suggesting potential for future expansion. This study demonstrates that integrating MST with Mixed Integer Programming (MIP) and spatial data can yield a replicable and efficient model for electricity distribution in rural settings. The approach respects regulatory constraints and minimizes infrastructure costs. For further research, incorporating load balancing, terrain constraints, and dynamic demand forecasting is recommended to enhance model applicability under real-world conditions. This model supports PLN's rural electrification strategy while aligning with sustainable development goals.

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Keywords: Network Optimization, PLN Electricity Connection, Minimum Spanning Tree, Two-Stage Algorithm, SLP

1. Introduction

Access to reliable and equitable electricity is a fundamental pillar for economic development and social welfare, particularly in rural regions [1, 2, 3]. In Indonesia, the national electrification initiative led by PLN aims to extend electricity services to remote areas, in line with the National Energy General Plan (RUEN) and the Sustainable Development Goals (SDGs), particularly Goals 7 and 9 [4, 5]. Recent studies highlight that electrification significantly enhances rural productivity and reduces migration rates by improving living standards [29, 30].

Despite these efforts, disparities remain in planning and executing electricity connections, especially in rural areas where infrastructure and technical compliance are limited [6, 7]. Manual field approaches often neglect spatial and mathematical considerations, resulting in energy losses, voltage drops, and service interruptions [8, 9]. According to recent research, ineffective network planning still contributes to up to 18% of technical losses in some rural grids [31].

To address these challenges, various optimization methods have been proposed. The Minimum Spanning Tree (MST) approach is commonly used to construct the most efficient network structure by minimizing cable lengths without forming cycles [10, 11]. When combined with Mixed Integer Programming (MIP), MST becomes a powerful tool to incorporate technical constraints, such as maximum allowable connections per pole or node [12, 13]

Two-stage optimization is also gaining popularity in energy infrastructure planning, dividing the problem into simpler sub-problems: customer clustering and connection to electricity poles [14, 15, 16] In this context, the application of Geographic Information System (GIS)-based spatial data significantly enhances accuracy and efficiency in network planning [17, 18].

Distance calculations are often performed using a modified Haversine formula to reflect local geographic contexts [19, 20]. This spatially informed approach improves fairness in pole utilization, reduces cable redundancy, and expedites electrification programs [21, 22].

Furthermore, improving network efficiency has a direct impact on connection costs and service reliability for communities [23, 24, 25] confirmed that MST-based models could be adapted to low-voltage distribution networks by integrating local engineering constraints. MST-based models are being increasingly adapted to rural contexts by combining them with regulatory constraints and renewable integration parameters [33].

By combining algorithmic models, spatial data, and PLN's technical parameters, this study aims to provide a replicable, efficient, and regulation-compliant electricity distribution framework. This model supports Indonesia's rural electrification strategy and offers scalability for similar geographic contexts. Future studies should integrate additional variables such as electrical load distribution, terrain complexity, and dynamic demand forecasting to further improve real-world applicability [26, 27, 28].

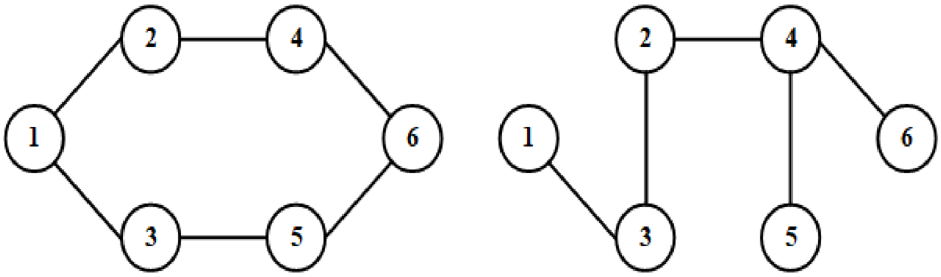
2. Literatur Review

2.1. Theoretical Basis Regarding PLN Electricity Connections and SLP Limitations

PLN sets a maximum limit of 5 SLPs per electricity pole and 5 series connections per SLP to maintain voltage stability and distribution efficiency. The maximum length of a series connection is 150 meters, with a distance of 30 meters between houses. This regulation aims to prevent voltage drops and mechanical failures, as well as facilitate network maintenance.

2.2. Minimum Spanning Tree (MST) Theory

MST is used to find a minimum-weight connection network without cycles, efficiently connecting all nodes. The classical MST was developed by Borůvka, Jarník (Prim), and Kruskal. MST is relevant for optimizing electrical connection networks to minimize the use of cables.



(a) Graph theory image (b) MST image

Fig 1

2.3. Minimum Weight Non-Terminal Spanning Tree (MWNTST)

MWNTST is a variation of MST where non-terminal nodes are required to be internal nodes. It is suitable for network systems with a central hub and customers. This problem is classified as NP-Hard and is solved using approaches such as Genetic Algorithms, Simulated Annealing, and Neighborhood Search.

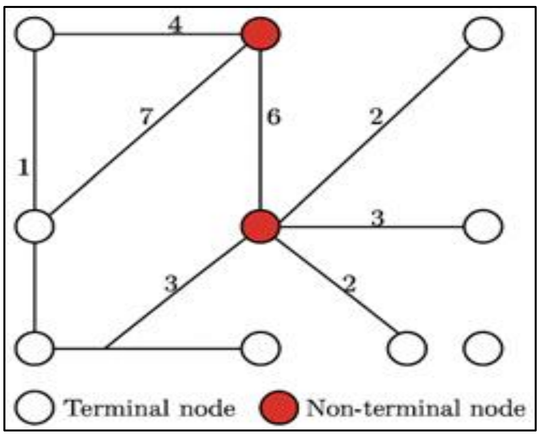


Fig 2: Example of MWNTST network

2.4. Haversine Formula
Used to calculate distances between geographic coordinates (latitude and longitude). This formula takes into account the curvature of the Earth, which is important in calculating cable lengths based on customer and utility pole locations. Haversine is widely used in GIS and distribution network planning.

2.5. Two-Stage Optimization
This model divides decisions into two phases: before and after uncertainty is revealed. It is useful in power grid planning, especially in cases with uncertain variables, such as customer demand or distribution. It is used to simplify and streamline solutions.

2.6. Mixed Integer Programming (MIP)
MIP is used to formulate cable connection optimization problems with integer variables (e.g., the number of connections) and continuous variables (cable length). MIP allows modeling of serial, parallel, or combined connections, taking into account PLN's technical limitations.

2.7. Developments in MST Research
Various studies have developed MST using approaches such as multi-objective, dynamic, artificial intelligence-based, and fuzzy logic. Recent research focuses on connection efficiency with limitations on the number of connections, node capacity, and real-time processing. Table 2.1 shows that this research is novel in combining MST, two-stage optimization, direct and serial connections, and modeling with MIP.

3. Methods
3.1. Research Object
The research focused on the PLN electricity cable connection network in Sungai Mengkuang Village, Rimbo Tengah District, Bungo Regency, with 186 customers and 27 electricity poles as the objects.

3.2. Data Collection and Processing
Data was obtained from ARCGIS in the form of customer and pole coordinates. Processing was performed by calculating distances using a modified Haversine formula, which ignores the curvature of the Earth due to short distances.

3.3. Two-Stage Optimization
Stage 1: Configure connections between customers, observing a maximum limit of 5 series connections. Connections can be parallel, serial, or a combination. Optimization is performed based on a distance matrix and connection capacity.
Stage 2: Connect groups of customers to the nearest utility pole, also with a maximum limit of 5 SLPs per pole.
Each stage uses shortest-distance selection logic with connection capacity constraints and is illustrated in pseudocode.

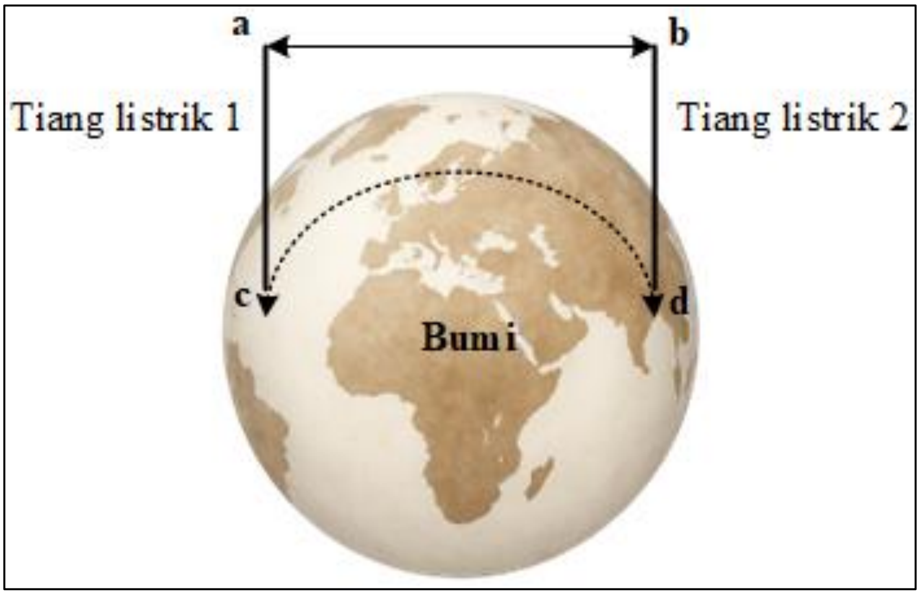


Fig 3: Illustration of distances affected by the curvature of the earth and those not affected by the curvature of the earth

4. Result and Discussion
4.1. Research Object
The object of this research is the electricity connection in Sungai Mengkuang village, Rimbo Tengah sub-district, Bungo district with electricity connection requests of 450, 900, 1200 and 2200 watts.

4.2. Latitude and longitude data
In this study, the data collected were the latitude and longitude of 186 customers who requested electricity connections from PLN as well as 27 electricity poles that had been provided by PLN to supply electricity to customers.

Table 1: Customer latitude and longitude data

ID	Lintang	Bujur	ID	Lintang	Bujur	ID	Lintang	Bujur
1	-1.57008	102.10707	63	-1.56955	102.10486	125	-1.57475	102.10854
2	-1.57034	102.10715	64	-1.56950	102.10445	126	-1.57323	102.10805
3	-1.57020	102.10711	65	-1.57407	102.10937	127	-1.57441	102.10642
4	-1.57443	102.10797	66	-1.57414	102.10795	128	-1.56580	102.10437
5	-1.56901	102.10596	67	-1.56927	102.10525	129	-1.57452	102.10694
6	-1.57391	102.10863	68	-1.57451	102.10842	130	-1.57423	102.10788
7	-1.57015	102.10636	69	-1.57409	102.10725	131	-1.56844	102.10577
8	-1.57497	102.10870	70	-1.57267	102.10827	132	-1.57435	102.10708
9	-1.57374	102.10758	71	-1.57456	102.10654	133	-1.57509	102.10694
10	-1.57231	102.10921	72	-1.57376	102.10923	134	-1.57315	102.10733
11	-1.57193	102.10784	73	-1.57423	102.10698	135	-1.56617	102.10516
12	-1.57194	102.10935	74	-1.57262	102.10868	136	-1.56942	102.10668
13	-1.57465	102.10725	75	-1.57391	102.10826	137	-1.57514	102.10883
14	-1.57521	102.10899	76	-1.57449	102.10909	138	-1.57537	102.10662
15	-1.57480	102.10913	77	-1.57425	102.10799	139	-1.57487	102.10686
16	-1.56950	102.10513	78	-1.57425	102.10654	140	-1.57363	102.10764
17	-1.56937	102.10551	79	-1.57337	102.10722	141	-1.57345	102.10807
18	-1.57431	102.10630	80	-1.57138	102.10718	142	-1.57043	102.10689
19	-1.57417	102.10664	81	-1.57472	102.10862	143	-1.57382	102.10860
20	-1.57426	102.10756	82	-1.57322	102.10987	144	-1.57298	102.10877
21	-1.57388	102.10776	83	-1.57479	102.10946	145	-1.57353	102.10753
22	-1.57438	102.10877	84	-1.57504	102.10928	146	-1.57463	102.10862
23	-1.57444	102.10883	85	-1.57337	102.10804	147	-1.57459	102.10887
24	-1.57239	102.10812	86	-1.57367	102.10889	148	-1.57467	102.10876
25	-1.57515	102.10857	87	-1.57473	102.10694	149	-1.57054	102.10721
26	-1.57489	102.10882	88	-1.57076	102.10702	150	-1.57492	102.10670
27	-1.57217	102.10913	89	-1.57477	102.10933	151	-1.57087	102.10642
28	-1.56953	102.10497	90	-1.57204	102.10971	152	-1.57308	102.10895
29	-1.57288	102.11025	91	-1.57121	102.10727	153	-1.56675	102.10547
30	-1.57321	102.10833	92	-1.56924	102.10561	154	-1.56558	102.10475
31	-1.56899	102.10697	93	-1.57304	102.10745	155	-1.57302	102.10916
32	-1.57268	102.10991	94	-1.57547	102.10665	156	-1.57266	102.11014
33	-1.57274	102.11006	95	-1.57033	102.10685	157	-1.57411	102.10648
34	-1.57511	102.10930	96	-1.56949	102.10543	158	-1.57356	102.10759
35	-1.56936	102.10692	97	-1.57524	102.10706	159	-1.56946	102.10530
36	-1.57495	102.10797	98	-1.57348	102.10747	160	-1.57324	102.10720
37	-1.57452	102.10642	99	-1.57465	102.10675	161	-1.57296	102.10839
38	-1.57506	102.10854	100	-1.57521	102.10665	162	-1.57354	102.10873
39	-1.56640	102.10539	101	-1.57395	102.10725	163	-1.57506	102.10770
40	-1.57371	102.10736	102	-1.57430	102.10663	164	-1.57157	102.10767
41	-1.57347	102.10843	103	-1.57397	102.10846	165	-1.57255	102.10958
42	-1.57340	102.10873	104	-1.56948	102.10522	166	-1.57333	102.10990
43	-1.57429	102.10939	105	-1.57254	102.10823	167	-1.57331	102.10855
44	-1.57155	102.10731	106	-1.57360	102.10886	168	-1.57310	102.10804
45	-1.57402	102.10883	107	-1.57305	102.10904	169	-1.57360	102.10811
46	-1.57401	102.10779	108	-1.57219	102.10942	170	-1.57411	102.10800
47	-1.57278	102.10783	109	-1.57490	102.10946	171	-1.57112	102.10745
48	-1.57462	102.10923	110	-1.57113	102.10712	172	-1.57324	102.10869
49	-1.57445	102.10674	111	-1.57347	102.10763	173	-1.57275	102.10832
50	-1.57342	102.10729	112	-1.57266	102.11031	174	-1.57164	102.10773
51	-1.57292	102.10745	113	-1.57498	102.10683	175	-1.56938	102.10515
52	-1.57476	102.10879	114	-1.57465	102.10644	176	-1.57589	102.10850
53	-1.57215	102.10956	115	-1.57753	102.10888	177	-1.56982	102.10616
54	-1.57263	102.10801	116	-1.57482	102.10813	178	-1.57407	102.10891
55	-1.57328	102.10835	117	-1.57327	102.10757	179	-1.57416	102.10892
56	-1.57275	102.10773	118	-1.56653	102.10533	180	-1.57067	102.10736
57	-1.56886	102.10577	119	-1.57439	102.10665	181	-1.57160	102.10625
58	-1.56954	102.10469	120	-1.57248	102.10817	182	-1.57336	102.10765
59	-1.56921	102.10571	121	-1.57416	102.10937	183	-1.57432	102.10846
60	-1.56912	102.10601	122	-1.57385	102.10817	184	-1.57331	102.10738
61	-1.57399	102.10867	123	-1.57396	102.10927	185	-1.57364	102.10871
62	-1.57254	102.10883	124	-1.57468	102.10898	186	-1.57350	102.10858

4.3. Distance matrix creation

The first data processing step is to calculate the distance between customers, the distance between electricity poles, and the distance between electricity poles and customers. An example of the calculation results for the distance between customers using the modified Haversine formula, as explained above.

Table 2: Example of a distance matrix between electricity poles and customers that is formed

Dar/Ke	1	2	3	4	5	6	7	8	9	10
1	0	10.963	33.955	63.345	24.250	46.376	62.996	65.150	39.783	9.7719
2	10.963	0	24.705	54.293	13.291	36.226	52.467	55.409	28.820	20.707
3	33.955	24.705	0	29.599	16.126	13.486	30.701	31.241	18.455	43.211
4	63.345	54.293	29.599	0	44.132	20.373	18.360	7.4275	36.287	72.28
5	24.250	13.291	16.125	44.132	0	24.572	39.832	44.076	15.558	33.998
6	46.376	36.226	13.486	20.373	24.572	0	17.218	19.503	16.288	55.921
7	62.996	52.467	30.701	18.360	39.832	17.218	0	11.679	26.724	72.668
8	65.150	55.409	31.241	7.4275	44.076	19.503	11.679	0	33.877	74.452
9	39.783	28.820	18.455	36.287	15.558	16.288	26.724	33.877	0	49.506
10	9.7719	20.707	43.211	72.285	33.998	55.921	72.668	74.452	49.506	0

4.4. Two-Stage Optimization of Power Grid Connections

This section describes the results of implementing a two-stage optimization algorithm to design PLN customer grid connections in Sungai Mengkuang Village. The primary goal of the optimization is to ensure all customers can connect to the PLN grid efficiently, comply with PLN's technical limitations, and minimize the total length of cable used.

- **First Stage:** Direct Connection to the Electric Pole
  In the first stage, customers are connected directly to the electricity poles based on the shortest distance, with a maximum of five customer connections per pole in accordance with the Customer Eligibility Standards (SLP) from PLN. The results of this stage show that:
  1. A total of 27 electricity poles were used in the connection process.
  2. Each pole was utilized to its full potential, connecting five customers.
  3. A total of 135 of the 186 customers were successfully connected directly to the poles.
  4. The total length of cable required for this phase was approximately 1,027 kilometers.

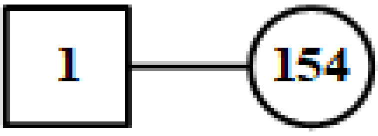


Fig 4: Connection of electricity poles to customers, result of iteration 1

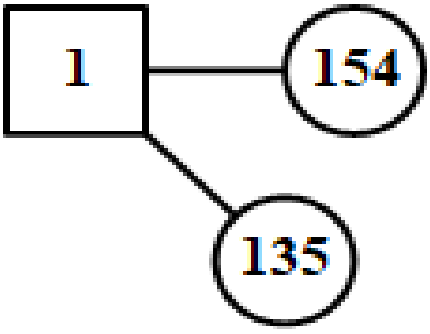


Fig 5: Connection of electricity poles to customers, result of iteration 2

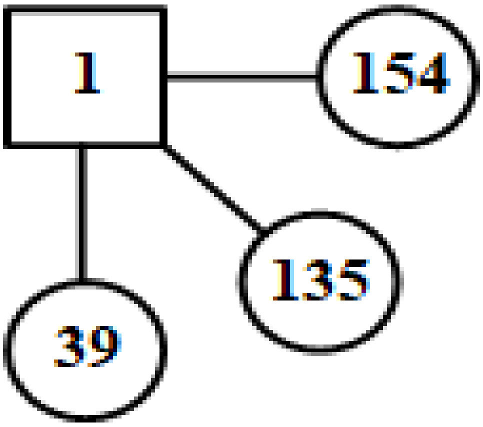


Fig 6: Connection of electricity poles to customers, result of iteration 3

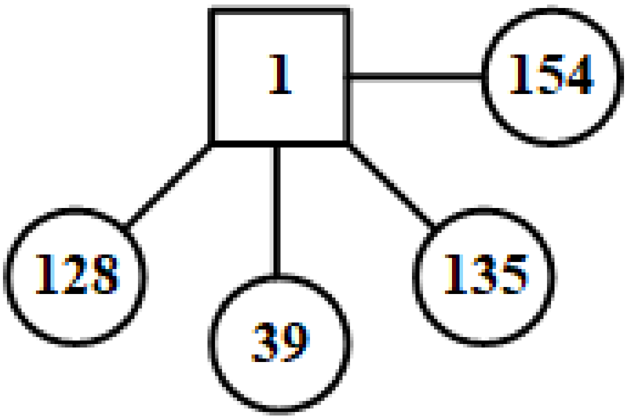


Fig 7: Connection of electricity poles to customers, result of iteration 4

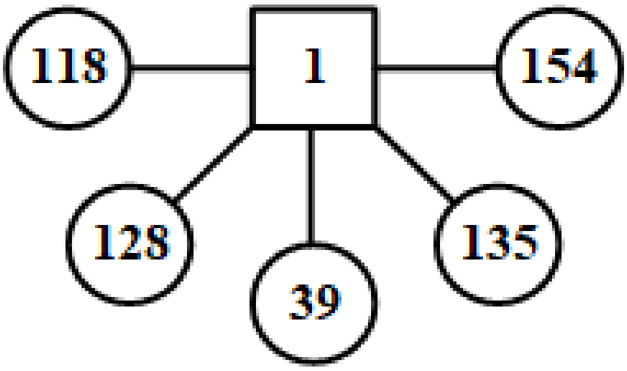


Fig 8: Connection of electricity poles to customers, result of iteration 5

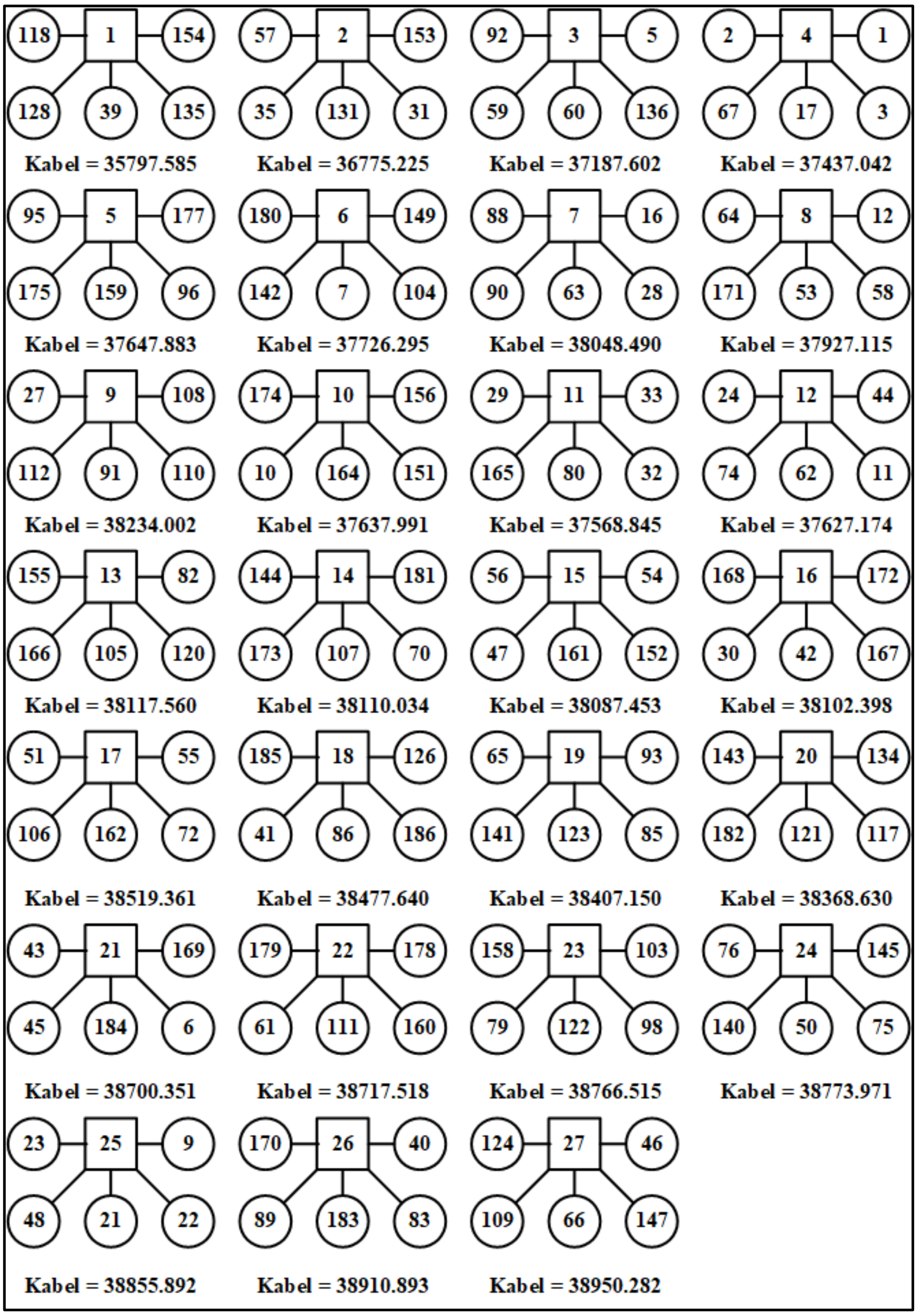


Fig 9: Customer connection to electricity poles as a result of phase 1 optimization

- Stage Two: Customer Connection

The second phase was carried out to connect the remaining 51 customers who had not been connected to the electricity poles in the first phase. The strategy used was to connect these customers to other customers already connected to the poles, while still adhering to the following restrictions:

1. A maximum of five tiered (series) connections are allowed on a single connection line.
2. Destination customers are selected based on the shortest distance and remaining connection capacity.

Connection patterns generated in this stage include parallel, series, and combination connections, tailored to the geographic distribution of customers and the capacity of each node. For example, poles 24 through 27 have a full tiered connection configuration (five customers in series).

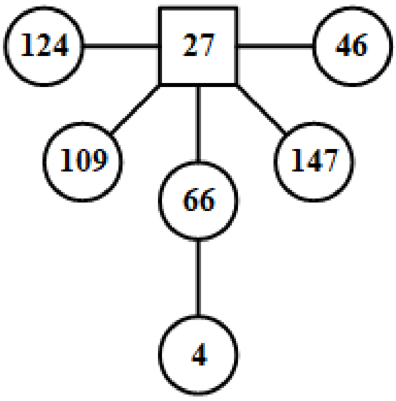


Fig 10: Connection between customers and to electricity poles, results of optimization iteration 1

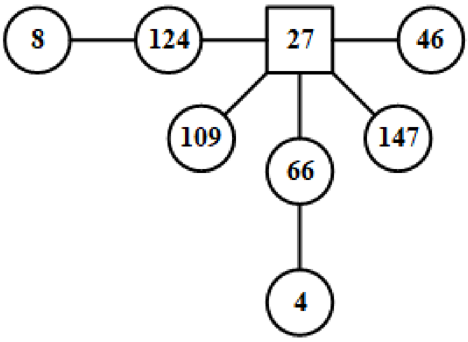


Fig 11: Connection between customers and to electricity poles, results of optimization iteration 3

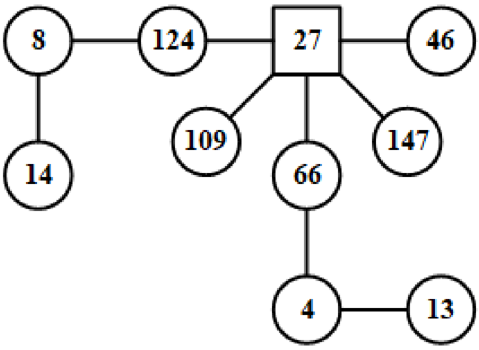


Fig 12: Connection between customers and to electricity poles, results of optimization iteration 4

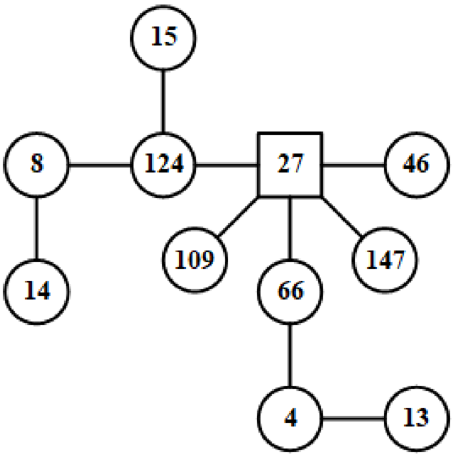


Fig 13: Connection between customers and to electricity poles, results of optimization iteration 5

Table 3: The number of SLP from each electric pole is the result of 2-stage optimization

Tiang Listrik	SLP	Tiang Listrik	SLP	Tiang Listrik	SLP
1	5	10	5	19	5
2	5	11	5	20	5
3	5	12	5	21	5
4	5	13	5	22	5
5	5	14	5	23	5
6	5	15	5	24	5
7	5	16	5	25	5
8	5	17	5	26	5
9	5	18	5	27	5

5. Conclusion

This study concludes that the implementation of a two-stage optimization algorithm—integrating the Minimum Spanning Tree (MST) method and capacity-constrained pole assignment—can effectively produce an electricity connection configuration that is both technically feasible and spatially efficient. The algorithm successfully addressed real-world constraints, such as the maximum number of serial connections among customers and the limited number of connections allowed per electricity pole. The resulting configuration minimized total cable length while ensuring an equitable distribution of loads across the available infrastructure.

The use of spatial coordinate data and a modified Haversine formula proved essential in enhancing the geographic accuracy of the network design. In practice, the model supports PLN and similar utility providers in planning low-voltage electricity connections more systematically,
particularly in rural and remote areas. Furthermore, the algorithm's modular structure and replicability make it a valuable tool for scaling up rural electrification programs in diverse geographic contexts.

This research contributes not only to technical planning but also to the broader goal of achieving sustainable and inclusive energy access. Future development of the model is recommended to include additional parameters such as customer electricity load profiles, land topography, and projected future demand. Incorporating these dynamic factors will enhance the model's robustness and adaptability under real field conditions.

In summary, this study provides a practical, algorithm-based solution for electricity network design that bridges spatial optimization and engineering constraints, paving the way for more effective and equitable rural electrification strategies.

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