

# Optimization of Clean Water Distribution Networks at the Unima FMIPA Campus Using the Minimum Spanning Tree Method

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## Abstract

The availability of clean water within higher education institutions is highly crucial to support the operations and convenience of the academic community. Issues regarding limited access to clean water were identified within the Faculty of Mathematics and Natural Sciences (FMIPA) at the State University of Manado, particularly in the Department of Mathematics Education. This study aims to model the clean water distribution network in FMIPA as a weighted graph and determine the optimal distribution path with minimum total pipe length using the Minimum Spanning Tree (MST) method via Prim's Algorithm. Prim's Algorithm was specifically selected over Kruskal's due to its node-centric growth mechanism; it expands continuously from the primary reservoir root without generating isolated sub-graphs during intermediate computational iterations, thereby accurately replicating the physical constraints of fluid infrastructure development. This operations research-based quantitative study mapped six main nodes encompassing the water tank and departmental buildings. Distance data were obtained through digital map observations and Google Earth based on realistic piping pathways. The results indicate that optimization using Prim's Algorithm produces an efficient single network configuration with the route:  $(S1,S2) + (S2,S3) + (S3,S4) + (S4,S5) + (S5,S6)$ . This network successfully eliminates path redundancy, achieving a minimum total pipe length of 175 meters. Through this modeling, the Mathematics Education Department secures a reliable water supply delivered from the Science Education Building with a distance efficiency of only 25 meters. The implications of this research provide a practical recommendation for the university administration to efficiently optimize the allocation of plumbing material budgets.

**Keywords:** *Water Distribution Network, Minimum Spanning Tree, Prim's Algorithm, Operations Research, Graph Theory.*

## 1. INTRODUCTION

Access to clean water is one of the most crucial elements in supporting operational sustainability and hygiene within higher education institutions. The availability of adequate sanitation infrastructure is directly correlated with academic productivity and the well-being of the academic community (Kafaji & Shiker, 2022). Although meeting the need for clean water is a top priority for campus facility management, challenges in designing an efficient distribution system are often hindered by the high investment costs of piping materials and spatial complexity. Therefore, a strategic approach is needed that can minimize the total length of the piping network without reducing distribution coverage in each building unit.

In the field of *operations research*, this problem of minimizing interconnection paths can be mathematically modeled as a *Minimum Spanning Tree* (MST). The MST problem aims to find a *connected subgraph* without cycles that connects all nodes with the minimum total edge weight (Taha, 2017). In the context of fluid distribution, this weight is represented as the geometric distance between buildings. Two classical algorithms with high computational efficiency in solving the MST problem are Kruskal's Algorithm and Prim's Algorithm (Özkan & Özceylan, 2018; Sari et al., 2023). Prim's Algorithm, in particular, works by growing a spanning tree from a single random node in a nearest-neighbor-oriented manner, making it highly effective for networks with concentrated node density.

Previous research has extensively documented the successful implementation of MST in optimizing pipeline networks across various geographic scales, ranging from macro-regional distribution to residential and village-scale networks (Faizah et al., 2025; Rembulan et al., 2020; Rukmi et al., 2025; Sembiring et al., 2022). Nevertheless, there is a significant literature *gap* when these macro-scale models are directly replicated at the institutional micro-scale, such as within a campus environment. At the macro-scale, route design possesses high spatial flexibility. Conversely, in *the campus built environment*, network planning faces constraints from spatial planning and the rigid structure of existing buildings. Theoretically, this rigidity creates absolute spatial barriers that result in infinite weights ( $\infty$ ) between certain nodes. It is this micro-structural complexity that has not been deeply explored in previous single-graph-based optimization studies.

Real-world issues related to this water distribution rigidity have been identified at the Faculty of Mathematics and Natural Sciences (FMIPA), Manado State University. Based on data from initial observations and an inventory of sanitation facilities conducted in March 2026, the clean water distribution system within the faculty has not been optimally integrated. This phenomenon directly impacts the Department of Mathematics Education, where, out of a total of 4 main sanitation facilities (student and faculty restrooms), the average daily water flow continuity reaches only 25%, equivalent to 2 hours of service per day. This limited access is caused by the absence of direct piping from the central reservoir (Node 1), forcing the department to rely on an unstable secondary seepage. The potential economic losses resulting from an uncalculated network expansion plan are also very high; initial estimates indicate that a non-optimized conventional pipe installation (star topology) would require over 350 meters of material. The topographical characteristics and building distribution at the Faculty of Mathematics and Natural Sciences (FMIPA) of the State University of Manado ( $\infty$ ) necessitate a precise distribution network model to achieve inter-building connectivity with minimal material costs. To bridge this theoretical and practical gap, this study aims to model the clean water distribution network at the FMIPA campus of the State University of Manado as an undirected weighted graph and solve it using Prim's Algorithm. The novelty of this research lies in the modeling of realistic micro-scale

pipeline routes that integrate real-world spatial constraints as deterministic boundaries within the distance matrix, rather than merely relying on abstract Euclidean distance assumptions (Kafaji & Shiker, 2022). The results of this study are expected to provide a dual contribution: as a foundation for tactical policy-making by university management in optimizing the budget for pipeline installation, and to enrich empirical operations research studies on the application of MST in networks with high spatial constraints.

## 2. RESEARCH METHOD

This study employs a quantitative approach using *operations research* methods to optimize the clean water distribution network within the FMIPA campus of the State University of Manado. The primary focus is to determine the distribution route with the minimum total length using the *Minimum Spanning Tree* (MST) algorithm

### 1. Network Model (Graph Representation)

The water distribution network is modeled as a weighted undirected graph:

$$G = (V, E)$$

where:

- $V$  is the set of *nodes* representing water tanks and buildings in the FMIPA campus
- $E$  is a set of *edges* representing possible pipeline routes between nodes
- Each edge  $e \in E$  has a weight  $w(e)$  that indicates the physical distance between locations (meters)

Operationally:

- Each building in the FMIPA (e.g., Physics, Chemistry, Biology, Science Education, and Mathematics Education buildings) is represented as a node
- Possible routes for pipe installation are connected as edges
- Edge weights are obtained from direct distance measurements or campus map estimates

This model assumes that:

- All nodes must be connected (connected graph)

- Installation costs are proportional to pipe length
- Flow capacity is not considered (focus on network structure)

## 2. Data Collection

The data used in this study includes:

- Location data for buildings and water tanks in the FMIPA area
- Distances between buildings (measured using digital maps)
- Possible connectivity structures (realistic pipeline routes)

Data collection techniques were carried out through:

- Observations using Google Earth
- Documentation of the FMIPA campus map
- Distance estimation using tools (Google Maps and Google Earth)

## 3. *Minimum Spanning Tree* (MST) Algorithm

To determine the minimum spanning tree of the water distribution network graph in the FMIPA environment, this study applied Prim's Algorithm. The selection of Prim's Algorithm over other MST algorithms, such as Kruskal's Algorithm and Borůvka's Algorithm, was based on three primary considerations. First, regarding graph characteristics, the FMIPA water distribution network constitutes a dense graph with only six nodes ( $V = 6$ ). Under these conditions, Prim's Algorithm operates with a time complexity of  $O(V^2)$ , which is more computationally efficient than Kruskal's Algorithm with a complexity of  $O(E \log E)$  the latter being more suitable for sparse graphs where the number of edges is substantially smaller than  $V^2$  (Cormen et al., 2009; Chen, 2023). Second, Prim's Algorithm employs a vertex-centric approach by expanding the spanning tree from a designated source node, which is conceptually consistent with pressurized water distribution systems that operate from a single source in this case, the water storage tank. By contrast, Kruskal's Algorithm follows an edge-centric approach that does not account for the presence of a source node, making it less representative of the physical logic of water flow from a source to multiple endpoints (Girsang et al., 2019). Third, from a physical implementation perspective, the incremental construction of Prim's Algorithm from the source node outward mirrors the sequential nature of pipeline installation in real

infrastructure projects, yielding results that are more directly interpretable for technical planning purposes (Ahmed et al., 2018). On these grounds, Prim's Algorithm is considered the most appropriate method for optimizing the clean water distribution network in this study. Mathematically, the steps of Prim's Algorithm are as follows:

- 1) Initialization: Select a random node  $v \in V$  as the starting node of the spanning tree  $T$ . Define the set of tree nodes  $V_T = v$  and the set of tree edges  $E_T = \emptyset$ .
- 2) Iteration: Find the edge with the minimum weight  $w(u, v)$  such that  $u \in V_T$  and  $v \notin V_T$ .
- 3) Update: Add the node  $v$  to  $V_T$  and the edge  $(u, v)$  to  $E_T$ .

Termination Condition: Repeat steps 2 and 3 until all nodes in the graph have been added to the set  $V_T$  (or when  $|V_T| = |V|$ ).

### 3. RESULTS AND DISCUSSION

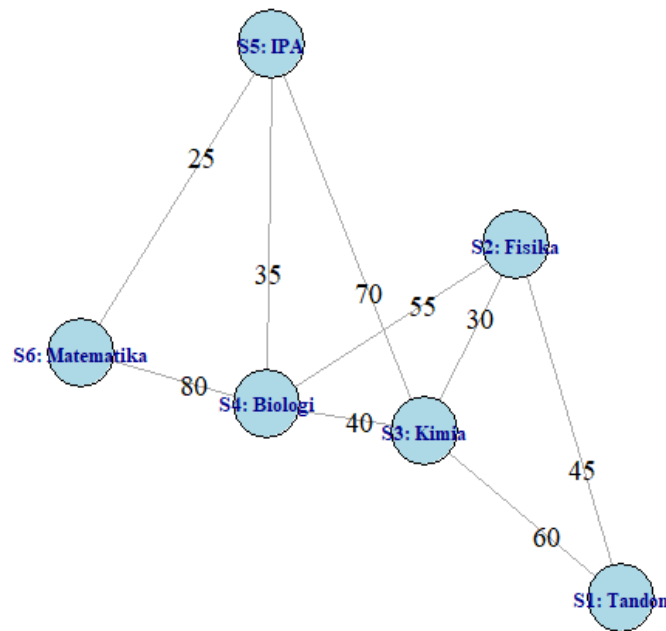
#### 3.1 Representation and Modeling of the FMIPA Network Graph

Based on observations using Google Earth and the environmental map documentation of the FMIPA at the State University of Manado, 6 main nodes ( $|V| = 6$ ) were identified, representing the water reservoir as the primary source and the department buildings as distribution points. These nodes are defined as follows:

- Node 1 (S1): Main Water Reservoir
- Node 2 (S2): Physics Building
- Node 3 (S3): Chemistry Building
- Node 4 (S4): Biology Building
- Node 5 (S5): Science Education Building
- Node 6 (S6): Mathematics Education Building

Before optimization, all geographically realistic piping route possibilities were modeled as an initial graph (Figure 1).

Figure 1. Initial Graph of the FMIPA Clean Water Distribution Network Before Optimization



The inter-node distance matrix (in meters), which represents the edge weights ( $w(e)$ ) based on Google Maps estimates and realistic piping installation routes, is presented in Table 1 below:

Table 1. Matrix of Distances Between Buildings in the FMIPA Area (Meters)

Node	S1	S2	S3	S4	S5	S6
<b>S1 (Reservoir)</b>	-	45	60	$\infty$	$\infty$	$\infty$
<b>Master's (Physics)</b>	45	-	30	55	$\infty$	$\infty$
<b>Ph.D. (Chemistry)</b>	60	30	-	40	70	$\infty$
<b>S4 (Biology)</b>	$\infty$	55	40	-	35	80
<b>S5 (Science)</b>	$\infty$	$\infty$	70	35	-	25
<b>S6 (Mathematics)</b>	$\infty$	$\infty$	$\infty$	80	25	-

*Note: The symbol  $\infty$  indicates that there is no realistic direct route for pipe installation between the two nodes due to geographical obstacles or building structures.*

### 3.2 Optimization Using Prim's Algorithm

The Prim's algorithm iteration process begins by designating Node 1 (Water Tank) as the initial root ( $V_T = \{S1\}$ ).

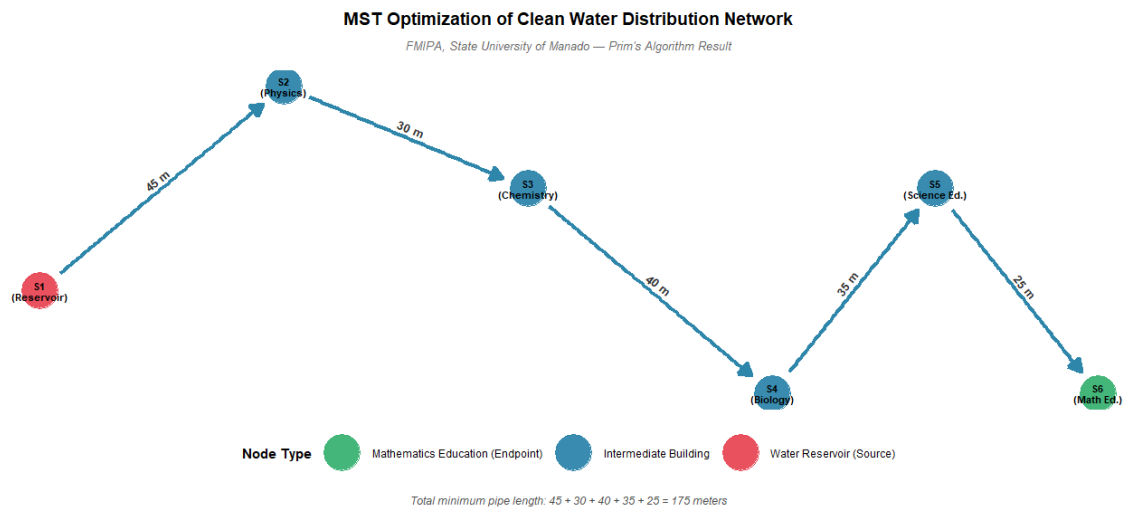
- Iteration 1: The edge with the minimum weight connected to  $V_T$  is  $(S1, S2)$  with a weight of 45. Therefore,  $V_T = \{S1, S2\}$ .
- Iteration 2: The minimum edge connected to  $V_T$  leading to a node outside  $V_T$  is  $(S2, S3)$  with weight 30. Therefore,  $V_T = \{S1, S2, S3\}$ .
- Iteration 3: The next valid minimum edge is  $(S3, S4)$  with weight 40. Therefore,  $V_T = \{S1, S2, S3, S4\}$ .
- Iteration 4: The next minimum edge is  $(S4, S5)$  with a weight of 35. Therefore,  $V_T = \{S1, S2, S3, S4, S5\}$ .
- Iteration 5: The last minimum edge to connect the Department of Mathematics Education is  $(S5, S6)$  with a weight of 25. Therefore,  $V_T = \{S1, S2, S3, S4, S5, S6\}$ .

All nodes have been connected ( $|V_T| = 6$ ), so the iteration is terminated.

### 3.3 Analysis of Distribution Path Efficiency

Based on the final iteration results, a minimum spanning tree with the most efficient total weight (pipe length) is obtained. The elimination of inefficient paths leaves the final network structure as shown in Figure 2.

Figure 2. Final Graph of the FMIPA Clean Water Distribution Network Resulting from MST Optimization



Mathematically, the pipeline network configuration in Figure 2 is expressed as:

$$\text{Optimal line} = (S1, S2) + (S2, S3) + (S3, S4) + (S4, S5) + (S5, S6)$$

The minimum total pipe length required to build an integrated clean water distribution network in the FMIPA environment is:

$$\text{total length} = 45 + 30 + 40 + 35 + 25 = 175 \text{ meter}$$

Critically, these results demonstrate that solving institutional-scale water distribution problems using the MST approach can eliminate route redundancy. If the network were built without optimization modeling (e.g., using a star topology where each building is connected directly to the main reservoir), the total pipe length would increase significantly and be economically inefficient because some nodes are geographically very far from the main reservoir.

Through this modeling, the Department of Mathematics Education (S6), which previously faced limited access to clean water, now has guaranteed connectivity via a distribution route flowing from the Science Education Building (S5 → S6) with a pipe distance efficiency of just 25 meters from the nearest node.

The implications of this minimization of geometric length are directly proportional to the efficiency of the budget for procuring piping materials at the university, reinforcing the theory that network optimization at the scale of educational institutions can be effectively solved using graph-based algorithms (Wirakusuma & Diatmika, 2025; Özkan & Özceylan, 2018; Rukmi et al., 2025). Furthermore, this geometric minimization is highly congruent with recent empirical benchmarks at the residential level by Sembiring et al. (2022) and the village level by Faizah et al. (2025), which consistently

demonstrated pipeline length reductions of approximately 25.6% to 26% through the elimination of loop redundancies.

#### 4. CONCLUSION

Based on the results of the analysis and discussion regarding the optimization of the clean water distribution network in the FMIPA campus of Manado State University using the *Minimum Spanning Tree* (MST) method with Prim's algorithm, the following academic conclusions can be drawn:

1. Modeling the clean water distribution network into a weighted undirected graph successfully represented the geographical connectivity between buildings within the FMIPA campus with precision through 6 main nodes and realistic pipeline routes connecting them.
2. The application of Prim's Algorithm resulted in an optimal linear pipeline network configuration, connecting the Main Reservoir (S1) to the Physics Building (S2) , the Chemistry Building (S3) , the Biology Building (S4) , the Science Education Building (S5) , and ending at the Mathematics Education Department (S6) .
3. This final network structure successfully minimized the total length of the pipe installation to the most efficient point of 175 meters. The MST approach has been critically proven to eliminate pipe route redundancy when compared to conventional, non-optimized structures.

The problem of limited access to clean water in the Department of Mathematics Education (S6) can be effectively and economically resolved through a direct interconnection from the nearest node, namely the Science Education Building (S5 → S6), requiring a minimum of 25 meters of piping material. This geometric minimization has a direct implication on the efficiency of the institution's budget for procuring piping materials.

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operations research model. May the intellectual contributions in this article yield tangible impacts on the development of campus facilities and infrastructure.

## 6. RECOMMENDATIONS

Based on the results of network optimization analysis using the *Minimum Spanning Tree* (MST) approach, several theoretical and practical recommendations can be proposed as follows:

- For Campus Authorities and Infrastructure Managers: It is hoped that they will adopt the pipeline network configuration results from this study, particularly when installing piping from the Science Education Building (S5) to the Mathematics Education Department (S6). This approach has been proven to minimize material procurement costs due to the efficiency of the pipeline length, which requires only 25 meters.
- For Budget Policymakers: It is necessary to apply mathematical modeling or operations research before undertaking similar infrastructure development projects within the university environment. This is important to avoid budget waste resulting from redundant routes or the use of inefficient network topologies.

For Future Researchers: This study is still limited to optimizing geometric aspects (pipe length) without considering pipe diameter, water flow rate, water pressure (*head loss*), and terrain slope topography. Therefore, future researchers are advised to develop this model into a *Capacitated Minimum Spanning Tree* (CMST) or integrate it with fluid mechanics laws (such as the Hazen-Williams equation) to obtain a piping network design that is not only minimal in length but also functionally optimal.

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