

OPTIMISATION OF WATER DISTRIBUTION NETWORKS DESIGN BY MINIMIZING THE TOTAL LENGTH

Y. Lahiouel¹, K. Chaoui², L. Khezzar³,
A. Haddad⁴, Z. Azari⁵

¹University of Guelma,
PO Box 401, Guelma, Algeria,
e-mail: ya_lahiouel@yahoo.fr

²University of Annaba,
PO Box 12, Annaba, Algeria,
e-mail: Chaoui_k@yahoo.fr

³The Petroleum Institute, Mechanical Engineering Department,
PO Box 2533, Abu Dhabi, United Arab Emirates,
e-mail: Lkhezzar@pi.ac.ae

⁴School of Technology Makkah,
Kingdom of Saudi Arabia, PO Box 20109, Makkah, KSA,
e-mail: Ak_haddad@hotmail.com

⁵ENIM, L.F.M.,
Ile du Saulcy- 57045 Metz Cédex 01,
e-mail: Azari@sciences.univ-metz.fr

The aim of the present work is to establish a new algorithm for the optimization of the design of water distribution networks. The proposed algorithm makes it possible to connect the nodes and the sources using the shortest path to obtain a final looped configuration. A novel method, the “minimal length algorithm”, is proposed. It uses the advantages of existing methods and exceeds their limitations. Some of the well-known existing methods are the shortest path algorithm, the minimum spanning tree algorithm and a novel method published previously. The developed algorithm is implemented into a user-friendly interactive computer program which allows the design of looped systems with minimal length ensuring least cost, reliability of the network and hence the availability of water.

Key words: water distribution network, least cost network-design, shortest path, minimum spanning tree, genetic algorithms, networks design optimisation.

1. INTRODUCTION

Water distribution networks represent one of the largest infrastructure assets of an industrial society. Design of water distribution networks is often viewed as a least-cost optimisation problem. Water distribution network design is usually achieved in two stages. In the first step, pipe lengths are taken as decision variables. Demand at the nodes, their layout and topology (coordinates) are considered to be known [1]. In the second step, the minimization of the cost is achieved using the pipe diameters as decision variables. The pipe layout, connectivity and imposed minimum head constraints at pipe junctions are also considered to be known.

The focus and emphasis of the present work is directed towards the first stage of water distribution network design, where relatively few works are available. When designing a system rehabilitation or expansion, a designer faces a tedious and difficult task. In the past, pipe network design was for the most based on the experience of the engineers and their perception of the system. More recently, planners constructed mathematical models to replicate the system performance. These models have eased the decision-making process to a great extent by mathematically representing a system under the existing or modified conditions [2].

Through the widespread use and success of the INTERNET and its predecessors, the ARPANET, MILNET, CSNET, etc. [3, 4], interest in the networks and their design has increased. For the Arpanet, researchers have adopted a distributed version of the shortest path algorithm of Bellman-Ford [5], in which a connexion table of paths between adjacent nodes is constructed. The tables of the different nodes are then compared and the shortest paths are chosen [6, 7]. In the same spirit, Dijkstra's algorithm was later adopted for the construction of the shortest path [3, 8]. In the early days of the INTERNET, routing algorithms observed communication latency in links between gateways and attempts were undertaken to minimize communication latency among them. To observe the communication latency adaptively in large networks, it is important to minimize overheads of communications exchanging routing information among nodes. Conventional approaches such as the RIP (Routing Information Protocol), and the OSPF (Open Shortest Path First protocol) incur important communication overheads through communication latency of routes [9] due to the excessive length of the observed path.

Genetic algorithms are techniques based on the natural selection mechanisms of genetics. They draw their power from the theoretical principle of implicit parallelism [10]. These algorithms combine the principles of survival of the more adapted individuals and the exchanges of information. The basic principle of genetic algorithms is to generate an initial arbitrary solution and then try to

optimise it using genetic operators. Hence, genetic algorithms methods have been developed and applied in the design of electricity distribution networks [7, 9]. In previous works, network design has been considered as a grouping problem, where each individual group member represents a group of nodes rather than a node. Since then, grouping genetic algorithms have seen widespread uses [11]. The networks obtained in this case are however not always completely looped. In this situation, if a node is connected to the network by only one branch (pipe), it could become isolated from the entire network in case of failure and therefore, do not receive the fluid. Consequently, a new algorithm has been developed, "the sources-nodes method" [1] which ensures connecting the demand nodes directly to the sources in order to ensure supply of the fluid to all nodes of the network. However, when applied to the case of a network with only one source or with a number of sources considerably lower than the number of demand nodes, this algorithm results in non-attractive network configurations. In particular, the number of the main branches joining the nodes, directly to the sources is relatively high resulting in a more expensive network.

It is equally important to underline that the methods developed for telecommunication networks cannot be applied efficiently to the water distribution systems, since in these, the number of demand nodes is always much larger than the number of sources (reservoirs). In certain situations, the network may even have a unique source covering the entire demand of the nodes.

The present study is a contribution towards water distribution network design. It improves the manner in which the nodes are connected to the sources and to each other. The connectivity of the distribution network obtained must be of minimal length. The method proposed in this work improves and eases the task of the planners of fluid distribution by achieving the optimal connectivity of the nodes in the network. The nature of the fluid (water or otherwise) transported in the network does not have any influence on the proposed method, nor on the result. This method makes use of the distances between the nodes, the rate of flows at demand nodes and the outflows at sources. The experience of the planners, being always necessary, should be rather complementary to the method and confined to reviewing and adapting the results obtained to the specific requirements of each case under study.

This paper describes the development of a new algorithm of minimizing the total length of a network while satisfying the most important constraint that of a looped configuration, necessary to its efficient operation. The looped networks present the advantage of the availability of the transported fluid and the reliability of the network in case of rupture or failing of one pipe. The length minimisation ensures the reduction of the installation cost, the maintenance and operational cost directly related to the losses, which are proportional to the total length [12].

2. PROBLEM DEFINITION

2.1. Network and graph theory

The solution of fluid distribution network problems requires a graph representation of the network that facilitates the necessary calculations. Graph theory permits the representation of the network structure by means of the incidence matrix of the network and allows, therefore, explicit representation.

The nodes represent the points on the pipelines where there exists a discontinuity: intersection of pipes, change of section, fluid injection point (source) and fluid consumption point. The branches represent the pipes that join the nodes together.

The incidence matrix is a compact mathematical concept of the network [13, 14]. The network configuration can be condensed in the incidence matrix that allows to establish the connectivity of the graph, and therefore of the network. The network connection can therefore be described by the node-to-node incidence matrix. This matrix is square and its elements are defined as:

$$(2.1) \quad a_{ij} = \begin{cases} 1, & \text{if node } i \text{ is connected to node } j, \\ 0, & \text{if node } i \text{ is not connected to node } j. \end{cases}$$

The loops of the network can also be deduced from the incidence matrix. While summing the elements on the matrix ranges, the number of connections for each node can be obtained and it allows sorting out the nodes with less than two connections, the floating nodes.

2.2. Mathematical formulation

A set of equations is used to minimize the total length of the network. The most important is the objective function, assumed to be a cost function of the pipe lengths:

$$(2.2) \quad f(L_i) = \sum_{i=1}^N C_i L_i.$$

C_i is the cost per unit length for the pipe i , L_i its length and N the number of pipes constituting the network.

The length of each pipe is defined by the relative positions of its start and end nodes:

$$(2.3) \quad L = \sqrt{(X_{NF} - X_{ND})^2 + (Y_{NF} - Y_{ND})^2},$$

where: X_{ND} , X_{NF} , Y_{ND} , Y_{NF} , are Cartesian coordinates (positions) of the start and end nodes of the pipe.

Since the costs are constant quantities, the decision variables become the pipe lengths. The objective function is hence subjected to the following constraints:

- for each junction node the flow continuity must be satisfied:

$$(2.4) \quad \sum Q_{in} + \sum Q_{out} = Dem,$$

Q_{in} the inflow at the node, Q_{out} is the outflow, Dem is the node demand;

- for each source, the constraint of flow availability is as follows:

$$(2.5) \quad \sum Q_{out} \geq Cap,$$

Cap is the capacity of the source or the quantity of fluid available at the source node;

- for each junction node the reliability constraint must be satisfied:

$$(2.6) \quad NC(i) \geq 2,$$

$NC(i)$ represents the connection degree of the node i , i.e. the number of branches connected to the node:

$$(2.7) \quad NC(i) = \sum_{j=ns+1}^N a_{ij}.$$

This constraint ensures that there exist at least two arc disjoint paths connecting any demand node to its associated source node and is thus a requirement for ensuring sufficient reliability for the network.

3. SOLUTION TECHNIQUES

The problem of the total length optimisation of water distribution networks is here considered as a problem of connectivity. The solution approaches, usually, use one of the three main algorithms: the shortest path algorithm, the minimum spanning tree algorithm [13, 15], and the genetic algorithms [11].

The shortest path and minimum spanning tree are basic algorithms used to develop a general method, since they permit to obtain non-attractive network configurations in comparison to the looped networks that ensure high availability and reliability [16]. System reliability is considered as an important part of the design. The planning process involves consideration of time of the resources available, anticipated demands, location of facilities and accessories, and other economic considerations [17]. The planner can then foresee the recourse to the use of two parallel paths between two nodes in order to increase availability. These are called protected paths. They are not frequently used due to their cost, which is often more penalizing than a possible rupture of pipes.

The algorithm previously developed for the design of looped networks, "sources-nodes method" [1], applied to the case of networks with a number of demand nodes exceeding the number of sources, as well as the case of networks with only one source, results in representations with a large number of main pipes and hence higher cost. Its basic principle is to join the demand nodes directly to the sources of energy in order to ensure a good distribution and availability of the fluid.

The genetic algorithms are stochastic techniques of optimisation in which the solution space is searched by generating arbitrary solutions, which are optimised using genetic operators: the crossover, mutation and reproduction [7, 9, 10, 11, 18]. Because of their stochastic nature, there is no guarantee that the optimal solution will always be reached. The renewal of the solution, at every iteration, offsets any optimality gain. Hence, the final length of the resulting network is sub-optimal and not always entirely looped [1].

3.1. Principle of the proposed method

Using the advantages of the existing methods and aiming to outstrip their disadvantages, a new method of distribution networks design, the algorithm of the minimal length, is proposed which aims at minimizing the total length of the network. The stages of the design by minimizing the total length are enumerated below and are represented in the flowchart of Fig. 1:

1. Given the characteristics of the demand nodes and sources, Cartesian coordinates, demands at nodes and capacities of sources;
2. Calculate the distances between the sources and nodes, and between the nodes;
3. Start with the source of the lowest capacity;
4. Choose the smallest source-node distance and join the node to the source;
5. Choose, among the non-connected nodes, the smallest distance to the last connected node or to the source under study. Then connect this node and constitute a group of nodes in a branched network; the branches are so-called tree branches;
6. Repeat step 5 until the availability at the source under consideration is zero or lower than the demand of the non-connected nodes;
7. Repeat stages 4 to 6 with each source by moving to the source with the next highest capacity, and so on;
8. Generate an incidence matrix, as the groups are formed. Insert "1" in the matrix at the position relative to the formed branch;
9. Mark the nodes having a connection degree lower than 2, Eq. (2.6);
10. Connect the nodes having a degree lower than 2 to each other. Choose the least distant nodes but belonging to two different groups;

11. Join any remaining floating nodes to nodes of the same group. The branches formed at this stage are called the connection branches since they connect the trees to each other.

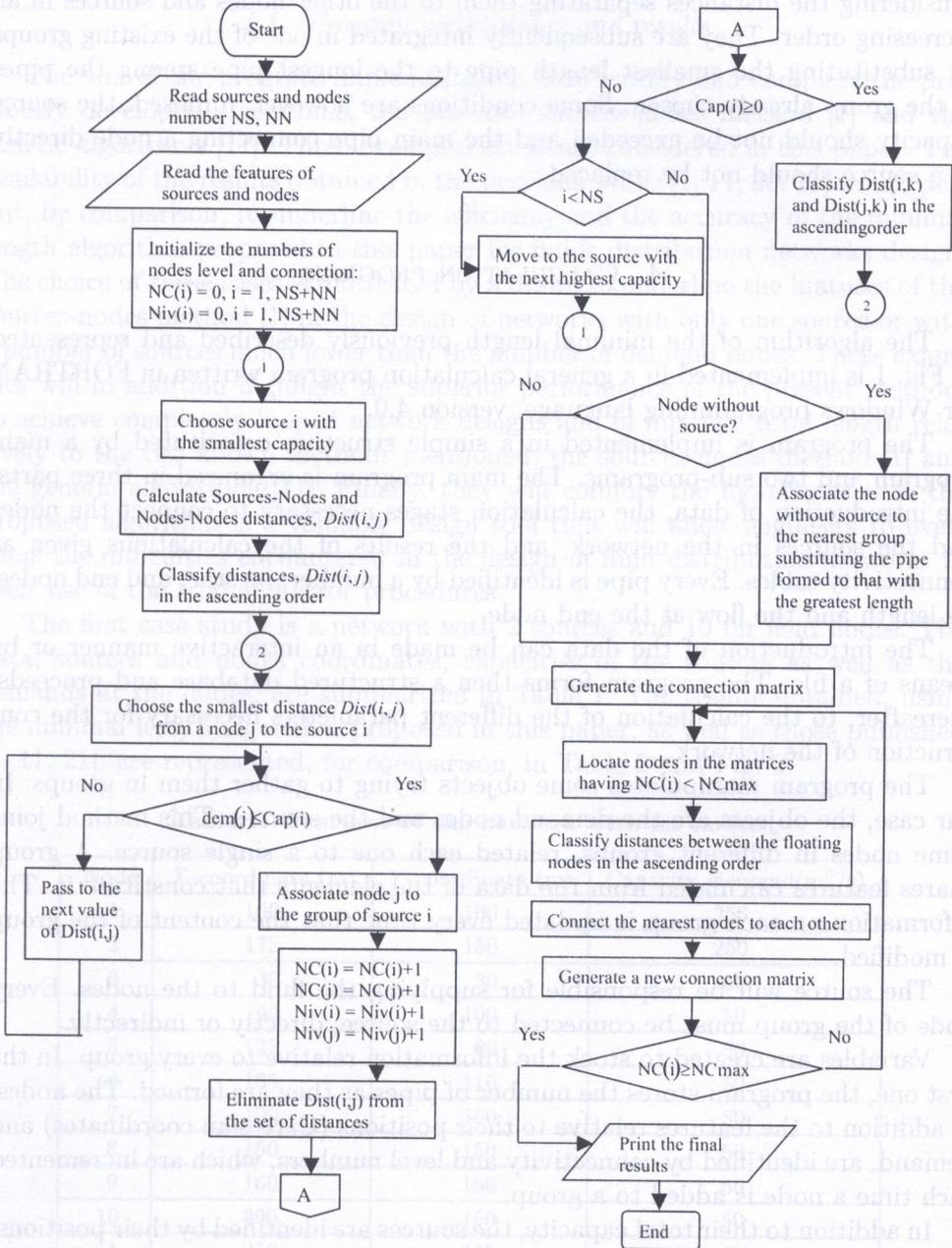


FIG. 1. Flowchart.

3.2. Nodes without source

As the groups of nodes are formed around the sources, if there remain nodes without a source, i.e. not connected to any group, these nodes are addressed considering the distances separating them to the other nodes and sources in an increasing order. They are subsequently integrated in one of the existing groups by substituting the smallest length pipe to the longest pipe among the pipes of the group already chosen. Some conditions are however, imposed: the source capacity should not be exceeded and the main pipe connecting a node directly to a source should not be replaced.

4. CALCULATION PROGRAM

The algorithm of the minimal length previously described and represented in Fig. 1 is implemented in a general calculation program written in FORTRAN for Windows programming language, version 4.0.

The program is implemented in a simple structure constituted by a main program and two sub-programs. The main program is organized in three parts, the introduction of data, the calculation stages necessary to connect the nodes and the sources in the network, and the results of the calculations given as connectivity tables. Every pipe is identified by a number, its start and end nodes, its length and the flow at the end node.

The introduction of the data can be made in an interactive manner or by means of a file. The program forms then a structured database and proceeds, thereafter, to the calculation of the different parameters necessary for the construction of the network.

The program manipulates some objects trying to gather them in groups. In our case, the objects are the demand nodes and the sources. This method joins some nodes in different groups, related each one to a single source. A group shares features calculated from the data of the elements that constitute it. The information on each group is updated every time that the content of the group is modified.

The source will be responsible for supplying the fluid to the nodes. Every node of the group must be connected to the source, directly or indirectly.

Variables are created to stock the information relative to every group. In the first one, the program stores the number of pipes as they are formed. The nodes, in addition to the features relative to their positions (Cartesian coordinates) and demand, are identified by connectivity and level numbers, which are incremented each time a node is added to a group.

In addition to their total capacity, the sources are identified by their positions. The capacity indicates the maximum possible load. This variable is decreased with every new node addition to the group supplied by this source. It represents

the capacity to be used by a group, and its update indicates the capacity that can be allocated again, and the number of nodes to be connected to the group supplied by the source.

4.1. Program applications and results

The aim of the program implementation is to modify and complete the previously developed algorithms, the previous sources-nodes method [1] and the genetic algorithms [11]. Three examples are hence considered in this paper. The availability of the results obtained in the previous works [1, 11, 20, 21] would permit, by comparison, to underline the efficiency and the accuracy of the minimal length algorithm proposed in this paper for fluids distribution networks design. The choice of these cases is motivated by a desire to underline the hiatuses of the sources-nodes method [1] in the design of networks with only one source or with a number of sources much lower than the number of demand nodes. These examples will in addition highlight the superior performance of the present method, to achieve completely looped network designs and of minimal total length relatively to the two known methods mentioned, the sources-nodes method [1] and the genetic algorithms [11]. Finally, they will comfort the hypothesis that the proposed algorithm is a valuable design tool that will allow engineers to overcome the difficulties encountered in the design of fluid distribution networks in their use of the trial-and-error procedures.

The first case study is a network with 2 sources and 10 far field nodes. The data, sources and nodes coordinates, capacities of the sources as well as the demands at the nodes, are summarized in Table 1. The results obtained, using the minimal length algorithm proposed in this paper, as well as those published [1, 11, 21], are represented, for comparison, in Table 2 and Fig. 2.

Table 1. Features of the network with far nodes.

Node	X-coordinate (m)	Y-coordinate (m)	Capacity Demand(m ³ /s)
1	100	100	250
2	175	150	250
3	30	30	50
4	90	100	50
5	125	80	50
6	135	110	50
7	100	150	50
8	150	150	50
9	160	160	50
10	200	150	50
11	250	200	50
12	190	110	50

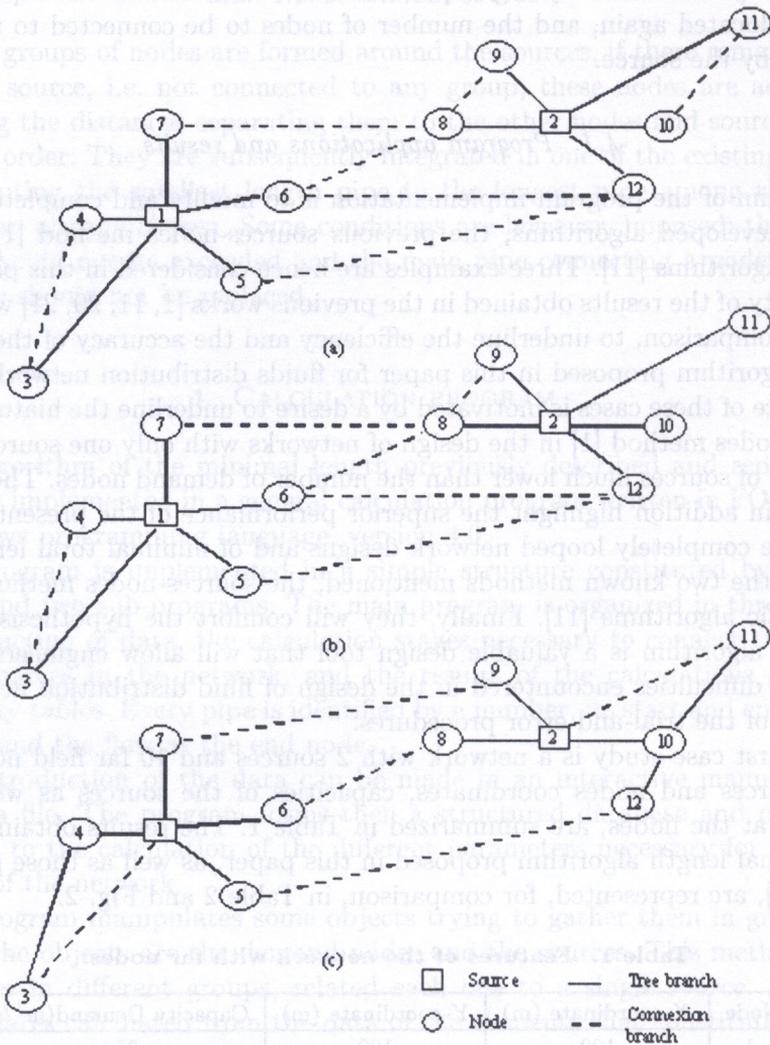


FIG. 2. Network with far modes a) Ref. [1], b) Ref. [11], c) Proposed Method.

The second case of study used in order to test and validate the established algorithm, is a network with only one source and 6 demand nodes. This case is frequently used in most works related to water distribution networks design, and reference is made there to “the two loops network” [19, 21]. It is used, in this work, to put the accent on the excessive number of main pipes when the network possesses a number of sources much lower than the number of nodes. This is the result of the association of demand nodes directly to the source used

Table 2. Results of the network with far nodes.

Pipe	Sources-nodes Method Ref. [1]	Genetic Algorithms Ref. [11]	Proposed Method
1-3	99.00	99.00	99.00
1-4	10.00	10.00	10.00
1-5	32.02	32.02	32.02
1-6	36.40	36.40	36.40
1-7	50.00	50.00	50.00
2-8	25.00	25.00	25.00
2-9	18.03	18.03	18.03
2-10	25.00	25.00	25.00
2-11	90.14	90.14	90.14
2-12	42.72	42.72	
3-4	92.20	92.20	92.20
5-12	71.59	71.59	71.59
6-8	42.72	42.72	42.72
6-12	55.00	55.00	
7-8	50.00	50.00	
7-9			60.83
8-9	14.14	14.14	
10-11	70.71		70.71
10-12			41.23
	Total Length 824.66 m	Total Length 753.95 m	Total Length 764.85 m

by the sources-nodes method [1]. A comparison of the lengths obtained in the two cases reveals striking differences. The data are summarized in Table 3. The results obtained by the two methods are presented, for comparison, in Table 4 and Fig. 3.

Table 3. Features of the network with a unique source.

Node	X-coordinate (m)	Y-coordinate (m)	Capacity/ Demand (m ³ /s)
1	3 100	100	1 120
2	2 100	100	100
3	1 100	100	100
4	2 100	1100	120
5	1 100	1 100	270
6	2 100	2 100	330
7	1 100	2 100	200

Table 4. Results of the network with a unique source.

Pipe	Sources-nodes Method Ref.[1]	Proposed Method
1-2	1 000.00	1 000.00
1-3	2 000.00	
1-4	1 414.21	
1-5	2 236.07	
1-6	2 236.07	
1-7	2 828.43	
2-3		1 000.00
2-4		1 000.00
3-5	1 000.00	1 000.00
4-5	1 000.00	1 000.00
5-7		1 000.00
4-6		1 000.00
6-7	1 000.00	1 000.00
	Total Length 14 714.78 m	Total Length 8 000.00 m

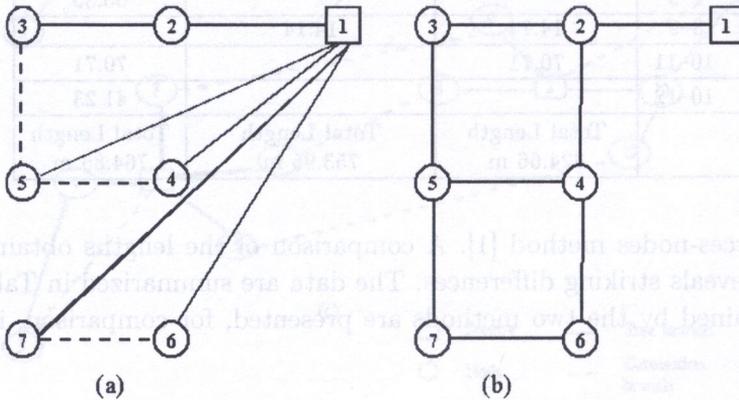


FIG. 3. Network with a unique source a) Ref. [1], b) Proposed Method.

The third case used in order to test and to validate the proposed algorithm, is a network with only one source and 20 demand nodes. This example is purposefully chosen for its relatively large size. The number of demand nodes is relatively important to the unique source. It would permit to underline the behaviour of the method proposed in such a case, while comparing it to the network of reference. A comparison of the lengths obtained in the two cases is very encouraging. The data are summarized in Table 5. The obtained results as well as those published are represented in Table 6 and Fig. 4.

Table 5. Features of the network with a unique source and 20 nodes.

Node	X-coordinate (m)	Y-coordinate (m)	Capacity/Demand (m ³ /s)
1	50	1 650	1 680
2	650	1 650	120
3	1 950	1 650	120
4	2 350	1 650	60
5	2 650	1 650	60
6	3 050	1 650	60
7	650	1 250	120
8	1 150	1 250	120
9	1 950	1 250	120
10	2 350	1 250	60
11	2 650	1 250	60
12	650	850	120
13	1 150	850	120
14	1 950	850	120
15	1 150	550	60
16	1 450	550	60
17	1 950	550	60
18	1 150	250	60
19	1 450	250	60
20	1 150	50	60
21	1 450	50	60

Table 6. Results of the network with a unique source and 20 nodes.

Pipe	Ref. [20]	Proposed Method	Pipe	Ref. [20]	Proposed Method
1-2	600.00	600.00	10-11	300.00	300.00
2-3	1 300.00		12-13	500.00	500.00
2-7	400.00	400.00	13-14	800.00	
2-8		640.31	13-15	300.00	300.00
3-4	400.00	400.00	13-16		424.26
3-9	400.00	400.00	14-17	300.00	300.00
4-5	300.00	300.00	15-16	300.00	300.00
4-10	400.00	400.00	15-18	300.00	300.00
5-6	400.00	400.00	16-17	500.00	
5-11	400.00		16-19	300.00	300.00
6-11		565.69	17-21		707.11
7-8	500.00	500.00	18-19	300.00	300.00
7-12	400.00	400.00	18-20	200.00	200.00
8-9	800.00		19-21	200.00	200.00
8-13	400.00	400.00	20-21	300.00	300.00
9-10	400.00			Total Length	Total Length
9-14	400.00	400.00		12 100.00 m	10 237.37

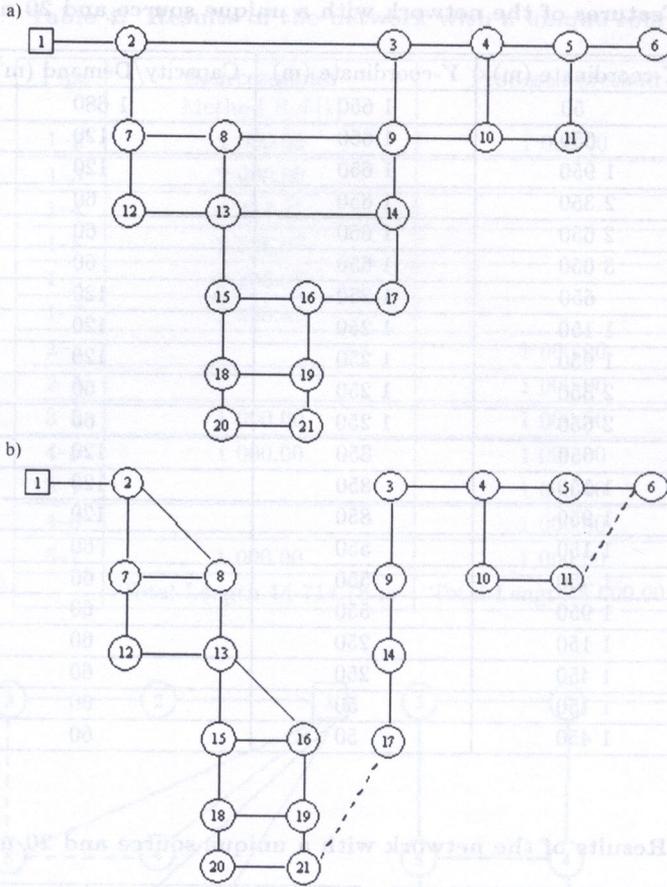


FIG. 4. Network with a unique source and 20 nodes a) Ref. [20], b) Proposed Method.

4.2. Illustration of the design stages

As mentioned above, different modifications are made to the incidence matrix during the different stages of the method. These stages are illustrated in the case of the network in Fig. 2.

First stage: Construction of the groups.

The first stage of the method is the formation of the groups of nodes around every source. For this case study, two branched networks are therefore formed, each one identified by its supply source. The groups are built using the minimal distances between elements.

Group 1: Identified by source 1, contains after searching the following elements:
Source: 1

Nodes: 4, 5, 6, respectively. The pipes formed are then (1, 4), (1, 5), (5, 6), (1, 6) and (4, 5), respectively, since these distances are the smallest among the set of the calculated ones. Thus, these pipes are identified as tree branches.

Group 2: Identified by source 2, contains after searching the following elements:

Source: 2

Nodes: 9, 8, 10, respectively. The formed pipes are then (2, 9), (9, 8), (2, 8), (2, 10) and (9, 10), respectively. These represent the smallest distances calculated.

The incidence matrix is then established. Its elements are:

$$A = \begin{array}{c|cccccccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ \hline 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 6 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 8 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 9 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 10 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 11 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \hline \text{Total} & 3 & 3 & 0 & 2 & 3 & 2 & 0 & 2 & 3 & 2 & 0 & 0 \end{array}$$

Second stage: Location of the nodes without source.

In this stage of the calculations, one can notice that nodes 3, 7, 11 and 12 are left unconnected to any source group, since their connection degree is equal to 0 (zero). Hence a review of the pipes already formed and a substitution by other pipes is made in order to join the nodes without source to the least distant groups.

In this way pipes (4, 3), (1, 7), (10, 11) and (10, 12) are substituted to pipes (4, 5), (5, 6), (9, 10) and (9, 8), respectively.

The new connexion matrix is therefore as follows:

$$A = \begin{array}{c|cccccccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 \\ \hline 1 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 0 \\ 3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 4 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 6 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 7 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 8 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 9 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 10 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \\ 11 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ \hline \text{Total} & 4 & 3 & 1 & 2 & 3 & 1 & 1 & 1 & 3 & 3 & 1 & 1 \end{array}$$

Third stage: Location of the floating nodes.

In this stage of the design, the nodes of degree 1, say having only one connection and belonging to different groups are connected to each other. The nodes marked in this case are those numbered 3, 5, 6, 7, 8, 9, 11 and 12.

After interconnection of the marked floating nodes, the connexion matrix is established once again according to the newly formed pipes. It is given below:

$$\mathbf{A} = \begin{array}{c|cccccccccccc|c}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & \text{Total} \\
 \hline
 1 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 5 \\
 2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 4 \\
 3 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \\
 4 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \\
 5 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 2 \\
 6 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 2 \\
 7 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 2 \\
 8 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 2 \\
 9 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 2 \\
 10 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 3 \\
 11 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 2 \\
 12 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 2
 \end{array}$$

At this stage of the calculations, all nodes have a degree at least equal to 2. Therefore, the iterative process is terminated since the network obtained as a result of the application of the method, is completely looped.

4.3. Results and discussions

The first case of study, network with nodes in far field, is used in order to show the power of the method developed in this work to design completely looped networks, and with the sum of the network pipe lengths lower to the one obtained by the previously developed algorithm [1]. In the cases studied, the network obtained by the program, Fig. 2c and the network of reference [1], Fig. 2a, it can be seen that they are completely looped. Furthermore the total length obtained by the present program is smaller, and therefore of least cost.

The difference between the total lengths obtained by the genetic algorithms [11], Fig. 2b, and the present method can be explained by the fact that the latter is not completely looped. It can easily be seen that nodes 10 and 11 have only one pipe; each one is supplied by only one main pipe, reaching it directly from source 2. Hence, the network obtained by our program presents the advantage of availability of the fluid. Whereas, the difference between the total length of the network in Fig. 2c and the one in Fig. 2b is only of 10.91 m. This value

represents 1.43% of the total length, which is 764.85 m. The difference between the length of the network of Fig. 2c and the one of the network of Fig. 2a is 59.80 m. It represents 7.25% of the total length.

The second case studied, the network with only one source, was chosen in order to underline the difficulties in designing a network with only one source or with a number of sources lower relatively than the number of demand nodes, by joining the nodes directly to the sources [1]. The network obtained by the sources-nodes method, Fig. 3a, is not very convenient or acceptable, since the number of main pipes is large and the lengths of these conducts are considerable. It resulted in a network with a length nearly twice the one of Fig. 3b, which was obtained by the minimal length algorithm. The difference is 6714.78 m, which represents 45.63% of the total length of 14714.78 m.

The third case of study would sustain the same theory concerning the fluid distribution networks design with only one source. Here again, one underlines the hiatuses of the sources-nodes method [1] that would give a network with a number of main pipes equal to the number of nodes, either 20 main pipes, relating the source 1 to all other demand nodes. Then, they would be completed by connection branches that should join the 20 floating nodes to each other. Whereas the network obtained by our method, the minimal length algorithm, Fig. 4b, is an entirely looped network and of length much lower than the length of the network in [20], Fig. 4a. The difference between the two lengths is 1862.63 m, which represents 15.39% of the total length of 12100.00 m.

One can notice, on the other hand, that the network obtained in our case, Fig. 4b, is under a structure with two sub-graphs or sub-trees related by the unique pipe [11-17] called also a bridge. This can affect the assessment of the reliability rate of the network. The final decision would be taken thereafter by the planner in order to increase the rate of reliability using his experience and common sense to possibly add, one or two pipes that would reinforce the link between the two sub-trees. This would not, however, appreciably alter the total length of the network obtained.

Fluid distribution networks design is usually a very complex task. Rather than using a trial-and-error approach, an optimisation procedure is preferred. Still, due to a number of reasons it is not reasonable to expect that in general, the problem will be solved using a completely automated procedure, i.e. optimisation should be viewed as a decision support tool rather than a decision making tool.

The development, in the present paper, of the minimal length algorithm permits to ease the difficulties met when using the trial-and-error approach in the optimization of fluid distribution networks design. The resulting network would also allow a decision-maker to visualize the trade-offs between different benefits and costs. Thus, the decision matrix would certainly be more complete.

5. CONCLUSION

In many optimisation problems, the analysts are often confronted with multi-objective decision problems. However, many optimisation studies are formulated as a problem whose goal is to find the "best" solution, which corresponds to the minimum or maximum value of a single objective function that lumps all the different objectives into one. Fluid distribution system design is a multi-objective problem for which it is difficult to identify the true benefits and constraints due to the uncertainty in future demands.

The design of the connectivity between nodes and sources for the fluid networks design is a key component in the design of the networks at least cost. This paper aims to bring a contribution to the existing methods while proposing a new method of cost minimization in networks design, using the conceptual advantages of available methods. The method proposed, the minimal length algorithm, is conceived in a simple manner that responds to the needs imposed by the constraints relative to the design of fluid distribution looped networks.

The algorithm implemented into a user-friendly interactive computer program provides facilities to the user. The main objective of the present work is to design looped networks with minimal length, in order to guarantee the economy of the total cost, and ensure the reliability of the network and availability of the supplied fluid.

The results obtained by the model developed in this paper, compared to those already published, are very satisfactory. The networks obtained are completely looped. Under the requirement that all nodes must have at least two connections to the branches, the program developed in this work, achieves this condition and allows free choice of the number of connections for the demand nodes in order to facilitate the construction of multiple paths. The obtained total length is minimal and thus achieves the objective of least cost.

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