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Optimization of installation and energy costs in water distribution systems with unknown flow directions

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ABSTRACT

Water distribution networks (WDNs) are an important part of water distribution systems and are responsible for water transportation from the reservoirs to the demand nodes at adequate pressure and velocity. In the present paper, the synthesis of WDN is treated as an optimization problem with a mixed integer nonlinear programming formulation. The objective function to be minimized is the total network cost, considering installation and energy costs, with unknown flow directions, which is the novelty in the paper. Disjunctive programming and linearization techniques are used in the model formulation to avoid nonlinear and nonconvex problems. Two case studies are used to test the model's applicability. Results show that operational costs can represent a significant part of the total cost in sustainable networks. In the first case study, the total cost was better than the literature results (US$ 2,272,538.85 vs. US$ 2,272,387.49) and the operational costs represent ¼ of the total WDN costs. In the second case study, the operation cost corresponds to almost 2/3 of the total WDN cost. These results show the importance of considering operational costs in the WDN design. Also, the consideration of unknown flow directions can lead to better results for the network topology.

Key words: disjunctive programming, energy pumping costs, installation costs, optimization, unknown flow directions, water distribution networks

HIGHLIGHTS

- Water distribution systems design is treated as an optimization problem.
- The optimization problem has a mixed integer nonlinear programming formulation.
- Installation and energy costs are considered in the objective function.
- Flow directions in node demand loops are considered optimization variables.
- Operational costs can represent a significant part of the total water distribution cost.

INTRODUCTION

Water distribution networks (WDNs) are important systems to serve potable water to demand nodes with adequate pressure and velocity. These networks are composed by one or more reservoirs, consumption nodes, and pipes linking the nodes. Normally, the pipes can form loops in the demand nodes and the water movement can be provided by gravity or by a pumping system when the system elevation is similar to the reservoir elevation.

The design of WDN can be formulated as an optimization problem. The majority of the published papers in the literature consider the installation cost, calculated from a discrete set of available commercial diameters as the objective function to be minimized. The tube length and the flow directions are considered known. The problem constraints are algebraic nonlinear equations and inequalities systems, with possible different solutions.

Different approaches were used in the literature to develop and solve the optimization problems for the synthesis of WDN, involving continuous and discrete variables (Mala-Jetmarova *et al.* 2018).

When loops are present in the node's demand, the nonlinear behaviour of the hydraulic equations can be an additional problem. In the majority of the published papers in the literature, additional software is used to solve the complex system of nonlinear hydraulic equations.

In the present paper, a mixed integer nonlinear programming (MINLP) optimization model is proposed using disjunctive programming and linearization techniques, and a deterministic approach is used to solve it. The objective function to be minimized is the total WDN cost, composed by the installation cost, depending on the available commercial diameters, and by the operational cost, depending on the manometric high of the reservoir and the pumping system. The combination of installation and operational costs in the objective function as well as the consideration of unknown flow directions in the loops are the novelty in the paper. No hydraulic simulators are necessary to solve the problem because the pressure and velocity equations are considered constraints in the model, which is solved in GAMS, using the BARON global optimization solver. Two case studies are used to test the model's applicability.

In the last decades, important stochastic and deterministic approaches have been proposed to solve the WDN design optimization problem. Different models involving linear programming (LP), nonlinear programming (NLP), mixed integer linear programming (MILP), and MINLP formulations were proposed. Obviously, the most realistic and representative models are those that have MINLP formulations and the models are normally nonconvex. Because of this, global optima solutions are not ensured.

Using MINLP models, Bragalli *et al.* (2008, 2012) used a nonconvex continuous relaxation to solve the problem in different solvers in AMPL. D'Ambrosio *et al.* (2015) used mathematical programming to solve the MINLP model by analyzing the modelling aspects in each case, for the dynamics of water in tubes and used spatial branches and linear relaxations.

Cassiolato *et al.* (2019) proposed an MINLP model for the synthesis of WDN. Generalized disjunctive programming (GDP) was used to treat the discrete variables using binary variables. A Big-M reformulation was used and the solver SBB in GAMS was used to solve the problem. The same model was used in Cassiolato *et al.* (2020) with a convex hull reformulation, and GAMS and SBB solvers were used.

Caballero & Ravagnani (2019) presented an MINLP model considering unknown flow directions and a convex hull reformulation was used. The authors also presented an important analysis of the Hazen–Williams equation parameters sensibility.

However, the majority of the published papers in this important field use nondeterministic approaches to solve the problem. Genetic algorithms (GA) were used by Bi *et al.* (2015) and Reca *et al.* (2017). Artificial immune systems (AIS) were used by Eryiğit (2015). Geem (2009) used harmony search (HS). Evolutionary algorithms (EA) were used by Avila-Melgar *et al.* (2016) and Palod *et al.* (2020). Shende & Chau (2019) proposed the simple benchmarking algorithm (SBA) for WDN optimization. With the same objective, an article based on whale optimization algorithm (WOA) was published by Ezzeldin & Djebedjian (2020). Ezzeldin *et al.* (2014), Rao *et al.* (2017), and Surco *et al.* (2017, 2021) used particle swarm optimization (PSO) to solve the optimization problems.

Balekelayi & Tesfamariam (2017) and Mala-Jetmarova *et al.* (2018) presented important reviews considering the distinct approaches used to synthesize WDN and a comparison among them. In the majority of the cited papers, the direction flows are considered known in the network and hydraulic simulators are used to solve the pressure and velocity equations. The most used hydraulic simulator is EPANET (Rossman 2000).

It is given for the WDN of one or more reservoirs and water demand nodes with proper elevations, where loops can exist. It is also given a set of available discrete diameters and pipes linking the demand nodes, with distinct lengths. Each diameter is associated with a cost per length and a specific roughness coefficient. There are upper and lower bounds for the water velocity inside the tubes and the pressure in the node's demand must satisfy a minimum limit. The pumping station considers the hydraulic pumps and the reservoir manometric height for the network water supply.

The WDN design can be thought of as an optimization problem formulated with an MINLP formulation, aiming to minimize the network total cost, subject to a set of algebraic nonlinear equality and inequality constraints, given by the mass balance in each node, the pressure difference between two adjacent nodes, considering the existence of loops; the velocities and pressure calculations, given by the Darcy–Weisbach equation or, in some particular cases, with the Hazen–Williams equation.

METHODOLOGY

Disjunctions are used in the model development to define the flow directions and the choice of the tube diameter, roughness, and cost, by using binary variables. The manometric reservoir height is calculated by energy balances in the demand nodes.

The following model sets, indexes, parameters, and variables are defined:

Indexes:

i, j	Demand nodes
k	Available diameter

Sets:

$\mathcal{D}$	Available commercial diameters (k)
$\mathcal{E}_{i,j}$	The existing pipes between nodes i and j ($i - j$)
$\mathcal{N}$	Demand nodes (i, j)

Parameters:

$C_{i,j}$	Hazen–Williams roughness coefficient for pipe $i - j$ (nondimensional)
$Cost(D_k)$	Cost per tube length for diameter D_k (\$/m)
d_i	Node i water demand (L/s)
D_k	Available commercial diameter k (m)
e_1	Interest rate (%)
e_2	Annual rate of increase in the electric energy (%)
E_c	Electricity cost (\$/kWh)
E_h	Cost to pressurize water due to the elevation (\$/m)
$Ep_{i,j}^{\min}$ and $Ep_{i,j}^{\max}$	Pumping energy minimum and maximum values in pipe $i - j$ (m)
F_a	Operational cost actualization factor (nondimensional)
$f_{i,j}^{\min}$ and $f_{i,j}^{\max}$	Minimum and maximum values for the friction factor in pipe $i - j$ (adm)
h_i	Node i elevation (m)
$L_{i,j}$	Pipe $i - j$ length (m)
n_a	Design lifetime (year)
N_{op}	Pumping hours per year (h/year)
$P_i^{\min}$	Minimum pressure in node i (m)
Q	Pump total volumetric flowrate (m^3/s)
$q_{i,j}^{\min}$ and $q_{i,j}^{\max}$	Minimum and maximum volumetric flowrate in pipe $i - j$ (m^3/s)
R_k	Roughness coefficient of pipe with diameter D_k
$v_{i,j}^{\min}$ and $v_{i,j}^{\max}$	Minimum and maximum velocity limits in pipe $i - j$ (m/s)
Z_{ter}	Altimetric height (m)
α	Hazen–Williams conversion factor
β and γ	Hazen–Williams parameters (nondimensional)
$\tau_{i,j}$	Darcy–Weisbach roughness coefficient in pipe $i - j$ (m)
η	Pumps system efficiency (%)
ν	Kinematic viscosity (m^2/s)
$\Delta P_{i,j}^{\min}$ and $\Delta P_{i,j}^{\max}$	Minimum and maximum pressure loss in pipe $i - j$ (m)

Variables:

C_E	Energy cost (\$)
C_T	Installation cost (\$)
$Ep_{i,j}$	Hydraulic head in pipe $i - j$ (m)
$Ep_{i,j}^1$ and $Ep_{i,j}^2$	It is equal to $Ep_{i,j}$ if water goes from the node i (j) to the j (i)
$f_{i,j}$	Darcy–Weisbach friction factor in pipe $i - j$ (nondimensional)
$f_{i,j}^1$ and $f_{i,j}^2$	Refer to $f_{i,j}$, if water flows from node i to node j, and from node j to node i
$\bar{f}_{i,j}$	Logarithm of $f_{i,j}$ in pipe $i - j$
H_{otm}	Manometric head of the pumping system (m)
P_i	Node i pressure (m)
$q_{i,j}$	Volumetric flowrate in pipe $i - j$ (m^3/s)
$q_{i,j}^1$ and $q_{i,j}^2$	Refer to $q_{i,j}$ if water flows from node i to node j and from node j to node i
$\bar{q}_{i,j}$	Logarithm of $q_{i,j}$ in pipe $i - j$
$\mathrm{Re}_{i,j}$	Reynolds number in pipe $i - j$ (nondimensional)
$\mathrm{Re}_{i,j}^1$ and $\mathrm{Re}_{i,j}^2$	Refer to $\mathrm{Re}_{i,j}$ if water flows from node i to node j and from node j to node i
TC	Total WDN cost (\$)
$v_{i,j}$	Water velocity in pipe $i - j$ (m/s)
$v_{i,j}^1$ and $v_{i,j}^2$	Refer to $v_{i,j}$ if water flows from node i to node j and from node j to node i
$\bar{v}_{i,j}$	Logarithm of natural $v_{i,j}$ in pipe $i - j$
$W_{i,j}^1$ and $w_{i,j}^1$	Refer to Boolean variable and binary variable, where equal True and (1) if water flows from node i to node j, or false and (0) if flow from node j to node i
$W_{i,j}^2$ and $w_{i,j}^2$	Refer to Boolean variable and binary variable, where equal True and (1) if water flows from node j to node i, or false and (0) if flow from node i to node j
$x_{i,j}$	Pipe $i - j$ diameter (m)

$Y_{i,j,k}$ ($y_{i,j,k}$)	True (1) if diameter D_k is selected in pipe $i-j$ or false (0), on the contrary
$\lambda_{i,j}$	Pipe $i-j$ cost ($)
$\sigma_{i,j}$	Pipe $i-j$ roughness coefficient
$\Delta P_{i,j}$	Pressure loss in pipe $i-j$ (m)
$\Delta P^1_{i,j}$ and $\Delta P^2_{i,j}$	Refer to $\Delta P_{i,j}$, if water flows from node i to node j, and from node j to node i
$\Delta \bar{P}_{i,j}$	Logarithm of $\Delta P_{i,j}$ in pipe $i-j$

The object function to be minimized is the total WDN cost (TC), composed by the installation cost (C_T), which depends on a set of available commercial diameters plus the energy cost (C_E), which depends on the manometric head of the reservoir ($h_{re} = Z_{ter} + H_{otm}$), given by:

$$TC = C_T + C_E = \sum_{i,j \in \mathcal{E}_{i,j}} \lambda_{i,j} + E_h\, H_{otm} \tag{1}$$

The problem constraints are algebraic equations, from the mass balance in the demand nodes, energy balance in the node loops, hydraulic equations for the pressure loss and velocity calculation, disjunctions to decide the flow directions, disjunctions to decide the pipe diameter, roughness coefficient and cost, and pressure and velocity limits. The problem has an MINLP formulation and is nonconvex.

The mass balance in each demand node is given by (Caballero & Ravagnani 2019):

$$\sum_{j \in \mathcal{E}_{j,i}} (q^1_{j,i} - q^2_{j,i}) - \sum_{j \in \mathcal{E}_{i,j}} (q^1_{i,j} - q^2_{i,j}) = d_i, \qquad \forall\, i \in \mathcal{N} \tag{2}$$

The volumetric flowrate is $q^1_{i,j}$ if in the pipe $i-j$ water flows from node i to node j and is $q^2_{i,j}$ if water flows from node j to node i. The pumping energy of a hydraulic pump in the pipe $i-j$ is $Ep^1_{i,j}$ if water flows from node i to node j, or is $Ep^2_{i,j}$ if water flows from node j to node i.

The energy balance in the demand nodes is given by:

$$P_i + h_i + Ep^1_{i,j} - Ep^2_{i,j} = P_j + h_j + \Delta P^1_{i,j} - \Delta P^2_{i,j}, \qquad \forall\, i, j \in \mathcal{E}_{i,j} \tag{3}$$

The pressure loss in pipe $i-j$ is $\Delta P^1_{i,j}$ if water flows from node i to node j, or is $\Delta P^2_{i,j}$ if water flows from node j to node i. In each node, a minimum pressure exists and in the reservoir the pressure is considered to be zero.

The term $Z_{ter} + H_{otm}$ is the piezometric high of the reservoir. It is defined as a demand node and:

$$Z_{ter} + H_{otm} + Ep^1_{i,j} - Ep^2_{i,j} = P_j + h_j + \Delta P^1_{i,j} - \Delta P^2_{i,j}, \qquad \forall\, i, j \in \mathcal{E}_{i,j} \tag{4}$$

The pressure loss in each pipe $i-j$ is calculated by the Darcy–Weisbach equation, where $f_{i,j}$ is the friction factor in the pipe and depends on the Reynolds number (Surco *et al.* 2017):

$$\Delta P_{i,j} = \frac{0.0827\, f_{i,j}\, q^2_{i,j}\, L_{i,j}}{x^5_{i,j}}, \qquad \forall\, i, j \in \mathcal{E}_{i,j} \tag{5}$$

$$f_{i,j} = \frac{1.325}{\left[\ln\left(\dfrac{\tau_{i,j}}{3.7\, x_{i,j}} + \dfrac{5.74}{\mathrm{Re}^{0.9}_{i,j}}\right)\right]^2}, \qquad \forall\, i, j \in \mathcal{E}_{i,j} \tag{6}$$

$$\mathrm{Re}_{i,j} = \frac{v_{i,j}\, x_{i,j}}{\nu}, \qquad \forall\, i, j \in \mathcal{E}_{i,j} \tag{7}$$

In particular situations, if only water is the fluid used in the network, the Hazen–Williams equation can be used, being α the conversion factor, which depends on the unities system used and $\beta = 1/0.54$ and $\gamma = 2.63/0.54$ are the equation parameters (Surco *et al.* 2017):

$$\Delta P_{i,j} = \frac{\alpha\, L_{i,j}\, q^{\beta}_{i,j}}{C^{\beta}_{i,j}\, x^{\gamma}_{i,j}}, \qquad \forall\, i, j \in \mathcal{E}_{i,j} \tag{8}$$

The velocity in the pipe $i-j$ is given by:

$$v_{i,j} = \frac{4\, q_{i,j}}{\pi\, x^2_{i,j}}, \qquad \forall\, i, j \in \mathcal{E}_{i,j} \tag{9}$$

These equations are nonlinear. Logarithms can be applied to linearize them:

$$\ln \Delta P_{i,j} = \ln(0.0827 L_{i,j}) + \ln f_{i,j} + 2\ln q_{i,j} - \ln x_{i,j}^5, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{10}$$

$$\ln\ \mathrm{Re}_{i,j} = \ln v_{i,j} + \ln\frac{x_{i,j}}{\nu}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{11}$$

$$\ln \Delta P_{i,j} = \ln(\alpha L_{i,j}) + \beta \ln q_{i,j} - \ln(C_{i,j}^{\beta} x_{i,j}^{\gamma}), \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{12}$$

$$\ln v_{i,j} = \ln q_{i,j} - \ln\left(\frac{\pi}{4} x_{i,j}^2\right), \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{13}$$

New variables must be defined for all $i, j \in \mathcal{E}_{i,j}$:

$\bar{v}_{i,j} = \ln v_{i,j}$, $\bar{q}_{i,j} = \ln q_{i,j}$, $\Delta\bar{P}_{i,j} = \ln \Delta P_{i,j}$, $\bar{f}_{i,j} = \ln f_{i,j}$, and $\overline{\mathrm{Re}}_{i,j} = \ln\ \mathrm{Re}_{i,j}$
The linearized equations are:

$$\Delta\bar{P}_{i,j} = \ln(0.0827 L_{i,j}) + \bar{f}_{i,j} + 2\bar{q}_{i,j} - \ln x_{i,j}^5, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{14}$$

$$\overline{\mathrm{Re}}_{i,j} = \bar{v}_{i,j} + \ln\frac{x_{i,j}}{\nu}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{15}$$

$$\Delta\bar{P}_{i,j} = \ln(\alpha L_{i,j}) + \beta\bar{q}_{i,j} - \ln(C_{i,j}^{\beta} x_{i,j}^{\gamma}), \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{16}$$

$$\bar{v}_{i,j} = \bar{q}_{i,j} - \ln\left(\frac{\pi}{4} x_{i,j}^2\right), \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{17}$$

A reformulation in the model can be proposed, by using disjunctions (Balas 2018). A Boolean variable $Y_{i,j,k}$ will be associated to the pipe $i - j$ with diameter D_k, for all $k \in \mathcal{D}$. It will be true if in the pipe $i - j$ the diameter D_k is selected of false on the contrary. The same is valid for the cost $\lambda_{i,j}$ and for the roughness coefficient $\sigma_{i,j}$. Considering the use of the Darcy–Weisbach equation, the exclusive disjunction is:

$$\underset{k \in \mathcal{D}}{\underline{\vee}} \begin{bmatrix} Y_{i,j,k} \\ x_{i,j} = D_k \\ \lambda_{i,j} = L_{i,j}\ Cost(D_k) \\ \sigma_{i,j} = R_k \\ \bar{v}_{i,j} = \bar{q}_{i,j} - \ln\left(\frac{\pi}{4} D_k^2\right) \\ \Delta\bar{P}_{i,j} = \ln(0.0827 L_{i,j}) + \bar{f}_{i,j} + 2\bar{q}_{i,j} - \ln D_k^5 \\ f_{i,j} = \dfrac{1.325}{\left[\ln\left(\dfrac{R_k}{3.7\ D_k} + \dfrac{5.74}{\mathrm{Re}_{i,j}^{0.9}}\right)\right]^2} \\ \overline{\mathrm{Re}}_{i,j} = \bar{v}_{i,j} + \ln\dfrac{D_k}{\nu} \end{bmatrix}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{18}$$

A convex hull reformulation (Grossmann & Lee 2003) can be used and a binary variable $y_{i,j,k}$ associated to the pipe $i - j$ with diameter D_k, for all $k \in \mathcal{D}$, which is equal to 1 if in the pipe $i - j$ the diameter D_k is selected and is equal to 0 on the contrary. The reformulated equations are:

$$x_{i,j} = \sum_{k \in \mathcal{D}} D_k\, y_{i,j,k}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{19}$$

$$\lambda_{i,j} = \sum_{k \in \mathcal{D}} L_{i,j}\ Cost(D_k)\, y_{i,j,k}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{20}$$

$$\sigma_{i,j} = \sum_{k \in \mathcal{D}} R_k\, y_{i,j,k}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{21}$$

$$\bar{v}_{i,j} = \bar{q}_{i,j} - \sum_{k\in\mathcal{D}} \ln\left(\frac{\pi}{4}D_k^2\right)y_{i,j,k}, \quad \forall\, i,j \in \mathcal{E}_{i,j} \tag{22}$$

$$\Delta\bar{P}_{i,j} = \ln(0.0827L_{i,j}) + \bar{f}_{i,j} + 2\bar{q}_{i,j} - \sum_{k\in\mathcal{D}} \ln D_k^5 y_{i,j,k}, \quad \forall\, i,j \in \mathcal{E}_{i,j} \tag{23}$$

$$f_{i,j} = \frac{1.325}{\left[\ln\left(\sum_{k\in\mathcal{D}} \frac{R_k}{3.7\,D_k} y_{i,j,k} + \frac{5.74}{\mathrm{Re}_{i,j}^{0.9}}\right)\right]^2}, \quad \forall\, i,j \in \mathcal{E}_{i,j} \tag{24}$$

$$\overline{\mathrm{Re}}_{i,j} = \bar{v}_{i,j} + \sum_{k\in\mathcal{D}} \ln\frac{D_k}{\nu} y_{i,j,k}, \quad \forall\, i,j \in \mathcal{E}_{i,j} \tag{25}$$

$$\sum_{k\in\mathcal{D}} y_{i,j,k} = 1, \quad \forall\, i,j \in \mathcal{E}_{i,j} \tag{26}$$

If the Hazen–Williams equation is used, the exclusive disjunction is given by:

$$\underset{k\in\mathcal{D}}{\veebar}\left[\begin{array}{c} Y_{i,j,k} \\ x_{i,j} = D_k \\ \lambda_{i,j} = L_{i,j}\,Cost(D_k) \\ \sigma_{i,j} = R_k \\ \bar{v}_{i,j} = \bar{q}_{i,j} - \ln\left(\frac{\pi}{4}D_k^2\right) \\ \Delta\bar{P}_{i,j} = \ln(\alpha L_{i,j}) + \beta\bar{q}_{i,j} - \ln(R_k^\beta D_k^\gamma) \end{array}\right], \quad \forall\, i,j \in \mathcal{E}_{i,j} \tag{27}$$

Reformulating with a convex hull:

$$\Delta\bar{P}_{i,j} = \ln(\alpha L_{i,j}) + \beta\bar{q}_{i,j} - \sum_{k\in\mathcal{D}} \ln(R_k^\beta D_k^\gamma) y_{i,j,k}, \quad \forall\, i,j \in \mathcal{E}_{i,j} \tag{28}$$

Now, $v_{i,j}^1$ assumes the value of $v_{i,j}$ if water flows from node i to node j. On the contrary, $v_{i,j}^2$ assumes the value of $v_{i,j}$ if water flows from node j to node i. For the variables $q_{i,j}^1$, $q_{i,j}^2$, $\Delta P_{i,j}^1$, $\Delta P_{i,j}^2$, $Ep_{i,j}^1$, $Ep_{i,j}^2$, $v_{i,j}^1$, and $v_{i,j}^2$, it is necessary to define upper and lower bounds. The lower bounds are defined as $q_{i,j}^{\min}$, $\Delta P_{i,j}^{\min}$, $Ep_{i,j}^{\min}$, and $v_{i,j}^{\min}$, for all $i,j \in \mathcal{E}_{i,j}$. Analogously, $q_{i,j}^{\max}$, $\Delta P_{i,j}^{\max}$, $Ep_{i,j}^{\max}$, and $v_{i,j}^{\max}$ are the upper limits.

Given $i,j \in \mathcal{E}_{i,j}$, $W_{i,j}^1$ is the Boolean variable which is true if water flows from node i to node j and false, on the contrary, and $W_{i,j}^2$ is the Boolean variable which is true if water flows from node j to node i and false, on the contrary. If the Darcy–Weisbach equation is used, the exclusive disjunction which defines the flow direction in each pipe is given by:

$$\left[\begin{array}{c} W_{i,j}^1 \\ v_{i,j} = v_{i,j}^1 \\ q_{i,j} = q_{i,j}^1 \\ \Delta P_{i,j} = \Delta P_{i,j}^1 \\ Ep_{i,j} = Ep_{i,j}^1 \\ f_{i,j} = f_{i,j}^1 \\ \mathrm{Re}_{i,j} = \mathrm{Re}_{i,j}^1 \\ v_{i,j}^{\min} \le v_{i,j} \le v_{i,j}^{\max} \\ q_{i,j}^{\min} \le q_{i,j} \le q_{i,j}^{\max} \\ \Delta P_{i,j}^{\min} \le \Delta P_{i,j} \le \Delta P_{i,j}^{\max} \\ Ep_{i,j}^{\min} \le Ep_{i,j} \le Ep_{i,j}^{\max} \\ f_{i,j}^{\min} \le f_{i,j} \le f_{i,j}^{\max} \\ \mathrm{Re}_{i,j}^{\min} \le \mathrm{Re}_{i,j} \le \mathrm{Re}_{i,j}^{\max} \end{array}\right], \veebar \left[\begin{array}{c} W_{i,j}^2 \\ v_{i,j} = v_{i,j}^2 \\ q_{i,j} = q_{i,j}^2 \\ \Delta P_{i,j} = \Delta P_{i,j}^2 \\ Ep_{i,j} = Ep_{i,j}^2 \\ f_{i,j} = f_{i,j}^2 \\ \mathrm{Re}_{i,j} = \mathrm{Re}_{i,j}^2 \\ v_{i,j}^{\min} \le v_{i,j} \le v_{i,j}^{\max} \\ q_{i,j}^{\min} \le q_{i,j} \le q_{i,j}^{\max} \\ \Delta P_{i,j}^{\min} \le \Delta P_{i,j} \le \Delta P_{i,j}^{\max} \\ Ep_{i,j}^{\min} \le Ep_{i,j} \le Ep_{i,j}^{\max} \\ f_{i,j}^{\min} \le f_{i,j} \le f_{i,j}^{\max} \\ \mathrm{Re}_{i,j}^{\min} \le \mathrm{Re}_{i,j} \le \mathrm{Re}_{i,j}^{\max} \end{array}\right], \quad \forall\, i,j \in \mathcal{E}_{i,j} \tag{29}$$

where $f^1_{i,j}$ and $\mathrm{Re}^1_{i,j}$ are equal to $f_{i,j}$ and $\mathrm{Re}_{i,j}$, respectively, if water flows from node i to node j, and $f^2_{i,j}$ and $\mathrm{Re}^2_{i,j}$ are equal to $f_{i,j}$ and $\mathrm{Re}_{i,j}$, respectively, if water flows from node j to node i. Moreover, $f^{\min}_{i,j}$ and $\mathrm{Re}^{\min}_{i,j}$ are the inferior limits and $f^{\max}_{i,j}$ and $\mathrm{Re}^{\max}_{i,j}$ are the superior limits, for all $i, j \in \mathcal{E}_{i,j}$.

These disjunctions can be written using a convex hull reformulation. The binary variable $w^1_{i,j}$ is equal to 1 if water flows from node i to node j and equal to 0, on the contrary, and the binary variable $w^2_{i,j}$ is equal to 1 if water flows from node j to node i and is equal to 0, on the contrary. The reformulated equations are:

$$v_{i,j} = v^1_{i,j} + v^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{30}$$

$$v^{\min}_{i,j}\, w^1_{i,j} \le v^1_{i,j} \le v^{\max}_{i,j}\, w^1_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{31}$$

$$v^{\min}_{i,j}\, w^2_{i,j} \le v^2_{i,j} \le v^{\max}_{i,j}\, w^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{32}$$

$$q_{i,j} = q^1_{i,j} + q^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{33}$$

$$q^{\min}_{i,j}\, w^1_{i,j} \le q^1_{i,j} \le q^{\max}_{i,j}\, w^1_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{34}$$

$$q^{\min}_{i,j}\, w^2_{i,j} \le q^2_{i,j} \le q^{\max}_{i,j}\, w^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{35}$$

$$\Delta P_{i,j} = \Delta P^1_{i,j} + \Delta P^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{36}$$

$$\Delta P^{\min}_{i,j}\, w^1_{i,j} \le \Delta P^1_{i,j} \le \Delta P^{\max}_{i,j}\, w^1_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{37}$$

$$\Delta P^{\min}_{i,j}\, w^2_{i,j} \le \Delta P^2_{i,j} \le \Delta P^{\max}_{i,j}\, w^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{38}$$

$$Ep_{i,j} = Ep^1_{i,j} + Ep^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{39}$$

$$Ep^{\min}_{i,j}\, w^1_{i,j} \le Ep^1_{i,j} \le Ep^{\max}_{i,j}\, w^1_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{40}$$

$$Ep^{\min}_{i,j}\, w^2_{i,j} \le Ep^2_{i,j} \le Ep^{\max}_{i,j}\, w^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{41}$$

$$f_{i,j} = f^1_{i,j} + f^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{42}$$

$$f^{\min}_{i,j}\, w^1_{i,j} \le f^1_{i,j} \le f^{\max}_{i,j}\, w^1_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{43}$$

$$f^{\min}_{i,j}\, w^2_{i,j} \le f^2_{i,j} \le f^{\max}_{i,j}\, w^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{44}$$

$$\mathrm{Re}_{i,j} = \mathrm{Re}^1_{i,j} + \mathrm{Re}^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{45}$$

$$\mathrm{Re}^{\min}_{i,j}\, w^1_{i,j} \le \mathrm{Re}^1_{i,j} \le \mathrm{Re}^{\max}_{i,j}\, w^1_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{46}$$

$$\mathrm{Re}^{\min}_{i,j}\, w^2_{i,j} \le \mathrm{Re}^2_{i,j} \le \mathrm{Re}^{\max}_{i,j}\, w^2_{i,j}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{47}$$

$$w^1_{i,j} + w^2_{i,j} = 1, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{48}$$

If the Hazen–Williams equation is used, the exclusive disjunction to define the flow direction is given by:

$$\begin{bmatrix} W^1_{i,j} \\ v_{i,j} = v^1_{i,j} \\ q_{i,j} = q^1_{i,j} \\ \Delta P_{i,j} = \Delta P^1_{i,j} \\ Ep_{i,j} = Ep^1_{i,j} \\ v^{\min}_{i,j} \le v_{i,j} \le v^{\max}_{i,j} \\ q^{\min}_{i,j} \le q_{i,j} \le q^{\max}_{i,j} \\ \Delta P^{\min}_{i,j} \le \Delta P_{i,j} \le \Delta P^{\max}_{i,j} \\ Ep^{\min}_{i,j} \le Ep_{i,j} \le Ep^{\max}_{i,j} \end{bmatrix} \veebar \begin{bmatrix} W^2_{i,j} \\ v_{i,j} = v^2_{i,j} \\ q_{i,j} = q^2_{i,j} \\ \Delta P_{i,j} = \Delta P^2_{i,j} \\ Ep_{i,j} = Ep^2_{i,j} \\ v^{\min}_{i,j} \le v_{i,j} \le v^{\max}_{i,j} \\ q^{\min}_{i,j} \le q_{i,j} \le q^{\max}_{i,j} \\ \Delta P^{\min}_{i,j} \le \Delta P_{i,j} \le \Delta P^{\max}_{i,j} \\ Ep^{\min}_{i,j} \le Ep_{i,j} \le Ep^{\max}_{i,j} \end{bmatrix}, \quad \forall\, i, j \in \mathcal{E}_{i,j} \tag{49}$$

Considering the topological diversity that can exist in WDN, some demand nodes, sometimes, do not have adequate pressure and it is necessary to use pumping stations to solve the problem. Considering n_a years, a set of annual costs can be actualized, by using an interest rate and a unitary rate of increase in the energy costs, given by (Surco *et al.* 2021):

$$F_a = \begin{cases} \dfrac{1-(1+e_2)^{n_a}(1+e_1)^{-n_a}}{e_1 - e_2}, & \text{if } e_1 \neq e_2 \\ \dfrac{n_a}{1+e_1}, & \text{if } e_1 = e_2 \end{cases} \tag{50}$$

The actualized energy cost is given by:

$$E_h = \frac{9.81\,Q}{\eta} E_c\, N_{op}\, F_a \tag{51}$$

Finally, the optimization problem for the synthesis of WDN considering installation and energy costs, with unknown flow directions, is given by:

Minimize Equation (1)

Subject to Equations (2)–(4), (19)–(26), (30)–(48), and (50)–(51).

The same optimization problem can be redefined if the Hazen–Williams equation is used. In this case, the Darcy–Weisbach equation must be replaced by the Hazen–Williams equation and proper equations and inequalities.

Model application

To test the applicability of the developed model, two examples from the literature were used. In both cases, the pipes diameter, the reservoir manometric head, and the flow directions were the optimization variables to minimize the WDN total cost, and the problems were solved using the global solver BARON in GAMS.

Case study 1

This case study is a real problem which consists of designing a part of the water distribution system of the city of João Pessoa, in Brazil, known as Grande Setor WDN, and was first used by Gomes *et al.* (2009). Figure 1 presents the network topology. There are one reservoir, eight pipes linking six demand nodes, two loops, and a hydraulic pump with a water catchment level of 30 m, responsible for pumping water to the reservoir. Table 1 presents the nodes and pipe elevation, demand, and pipe lengths. Table 2 presents 10 commercial available diameters, costs, and the Hazen–Williams roughness coefficients. The costs were provided by Gomes *et al.* (2009) in R$ and converted to USD (USD 1 = R$ 2). For comparison effects, we used the same cost values as used in the paper. Lower and upper bounds for the water velocity are 0.2 and 3 m/s and the minimum required pressure in the nodes demand is 25 m. The pump efficiency is considered 75% in the pump stations and the number of operation hours is 7,300 h/year. The energy cost is 0.1 US$/kWh, the annual interest rate is 12%, and the annual increase

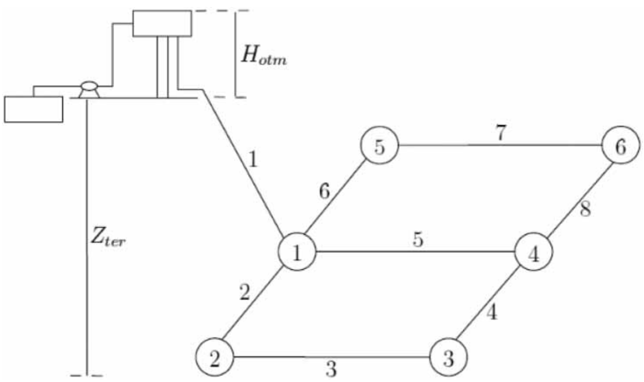

Figure 1 | Grande Setor WDN.

Table 1 | Nodes and pipes for the Grande Setor WDN

Node/Pipe	Elevation (m)	Demand (L/s)	Pipe length (m)
1	6.0	0.00	2,540
2	5.5	47.78	1,230
3	5.5	80.32	1,430
4	6.0	208.60	1,300
5	4.5	43.44	1,490
6	4.0	40.29	1,210
7			1,460
8			1,190

Table 2 | Available diameters for the Grande Setor WDN

Diameter (m)	Cost (US$/m)	Roughness coefficient	Diameter (m)	Cost (US$/m)	Roughness coefficient
0.1084	23.55	145	0.3662	158.93	130
0.1564	31.90	145	0.4164	187.50	130
0.2042	43.81	145	0.4666	218.12	130
0.2520	59.30	145	0.5180	257.80	130
0.2998	76.12	145	0.6196	320.15	130

rate in the energy is 6%, for a lifetime of 20 years. The Hazen–Williams equation is used and two distinct values for the parameter α were used:

$$\alpha = 10.67 \text{ and } \alpha = 10.667, \ \beta = 1.852 \text{ and } \gamma = 4.871$$

The problem was solved using the global optimizer solver BARON, in GAMS. Table 3 presents the velocities in the pipes, the pressure in the demand nodes, and flow directions. As can be seen, these values are the same when using $\alpha = 10.67$ or $\alpha = 10.667$. However, costs are different, being US$ 2,272,538.85, when $\alpha = 10.67$, and US$ 2,272,387.49, when $\alpha = 10.667$. These values correspond to the global optima in the considered situations. In both cases, operation costs correspond to approximately ¼ of the total WDN costs. Table 4 presents a comparison with the literature results. Different approaches were used in the works of Gomes *et al.* (2009), who used an iterative approach and $\alpha = 10.67$, $\beta = 1.852$, and $\gamma = 4.871$, and Surco *et al.* (2021), who used PSO to solve the problem with the aid of hydraulic simulators and $\alpha = 10.667$, and the same values for β and γ.

When $\alpha = 10.667$, there is a difference in the total cost between the present paper and Surco *et al.* (2021) results, due to the operation cost. Although the solutions are the same, this difference is caused due to the

Table 3 | Hydraulic variables calculated for the Grande Setor WDN

Pipe/Node	Velocity (m/s)	Flow direction	Pressure (m)
1	1.39	R-1	30.84
2	1.13	1-2	27.10
3	0.64	2-3	25.00
4	0.69	4-3	26.30
5	1.33	1-4	26.62
6	1.20	1-5	25.40
7	0.50	5-6	
8	0.73	4-6	

Table 4 | Diameter, manometric head, and costs for the Grande Setor WDN

Pipe	Gomes *et al.* (2009) $\alpha = 10.67$	Present paper $\alpha = 10.67$ Diameters	Surco *et al.* (2021) $\alpha = 10.667$	Present paper $\alpha = 10.667$
1	0.6196	0.6196	0.6196	0.6196
2	0.2998	0.2998	0.2998	0.2998
3	0.2998	0.2520	0.2520	0.2520
4	0.2042	0.2998	0.2998	0.2998
5	0.5180	0.5180	0.5180	0.5180
6	0.2520	0.2520	0.2520	0.2520
7	0.2042	0.2042	0.2042	0.2042
8	0.1564	0.2042	0.2042	0.2042
H_{otm} (m)	15.79	13.658	13.655	13.655
C_T (US$)	1,630,405.75	1,662,535.10	1,662,535.10	1,662,535.10
C_E (US$)	705,244.20	610,003.75	609,796.65	609,852.39
$C_T + C_E$ (US$)	2,335,649.95	2,272,538.85	2,272,331.75	2,272,387.49

parameters associated with the pumping system. In the present paper, no numerical approximations were used in the pumping calculation. Besides, the calculated installation costs were the same for distinct values of α. The little difference in the operation costs caused distinct values for the manometric head of the reservoir.

In this case study, the operation costs correspond to approximately ¼ of the total network cost. Considering the case with $\alpha = 10.667$ is possible to see how the operational costs in percentage of the total cost for the 20 years used as the lifetime for the pumping system in the network. These results are presented in Table 5. It can be noted that in the first year the operation costs correspond to 2.86% of the total costs and in the 20th year, this percentage corresponds to 26.84%.

Case study 2

The second case study is also a real problem, in the city of Itororó, Brazil. Figure 2 presents the WDN topology, with 1 reservoir, 20 pipes linking 17 demand nodes, 3 loops, and a hydraulic pump with a water catchment level of 222 m, responsible to pump water to the reservoir. Table 6 presents the nodes and pipes characteristic. Available set of seven distinct commercial diameters are presented in Table 7, with the respective costs. In this case, the costs in R$ were converted from USD (USD 1 = R$ 4). The water velocity must be bounded between 0.2 and 3.5 m/s and the minimum required pressure is 15 m for all demand nodes. The Darcy–Weisbach equation is used and a roughness coefficient equal to 2×10^{-5} m for all pipes was considered. The water kinematic viscosity at 20 °C is $\nu = 1.004 \times 10^{-6}$ m^2/s. The pump efficiency is 75% and 7,300 h/year is considered as the operation time. The

Table 5 | Contribution of the operation costs in the total WDN cost

Year	C_E (US$)	Percentage (%)	Year	C_E (US$)	Percentage (%)
1	48,942.86	2.86	11	415,034.38	19.98
2	95,263.78	5.42	12	441,743.25	20.99
3	139,103.23	7.72	13	467,021.30	21.93
4	180,594.13	9.80	14	490,945.16	22.80
5	219,862.30	11.68	15	513,587.39	23.60
6	257,026.83	13.39	16	535,016.64	24.35
7	292,200.39	14.95	17	555,297.89	25.04
8	325,489.66	16.37	18	574,492.65	25.68
9	356,995.58	17.68	19	592,659.12	26.28
10	386,813.68	18.87	20	609,852.39	26.84

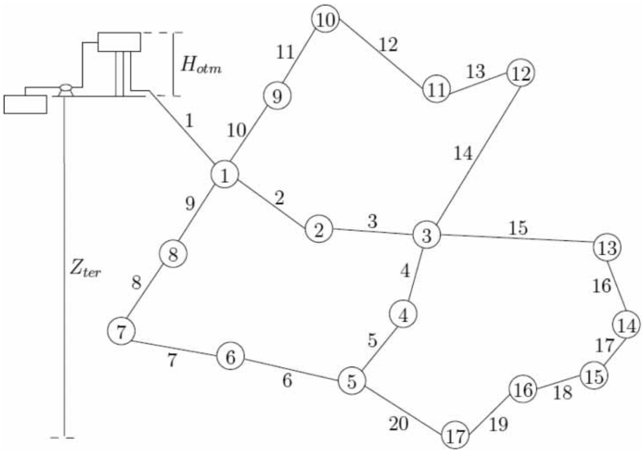

Figure 2 | Itororó WDN.

Table 6 | Nodes elevation and demands and pipe lengths

Node/Pipe	Elevation (m)	Demand (L/s)	Pipe length (m)
1	220.5	5.05	324
2	215.6	1.91	124
3	210.4	3.81	184
4	210.5	1.40	206
5	209.5	4.35	103
6	213.2	3.51	202
7	218.5	3.44	134
8	230.7	2.48	227
9	211.5	3.06	167
10	213.5	1.85	166
11	205.5	2.86	152
12	208.8	6.11	168
13	215.5	5.09	177
14	212.6	4.06	225
15	207.5	8.05	254
16	219.4	4.26	263
17	220.5	1.21	133
18			321
19			105
20			169

Table 7 | Costs for the commercial available diameters for the Itororó WDN

Diameter (m)	Cost ($/m)	Diameter (m)	Cost ($/m)
0.0534	24.16	0.2042	87.62
0.0756	32.12	0.2520	118.59
0.1084	47.09	0.2998	152.24
0.1564	63.80		

energy cost is 0.134 $/kWh and the annual interest rate is 10%. The lifetime considered is 25 years and the annual increase in the energy is 6%.

The problem was solved using the solver SBB in GAMS and Table 8 presents the calculated hydraulic variables and the flow directions. The optimized total cost for the WDN was $ 487,254.78. In this case, it can be noted that the operation cost corresponds to almost 2/3 of the total WDN cost. Table 9 presents the pipes diameter, manometric head of the pumping system, and the network costs.

Table 8 | Hydraulic variables calculated for the Itororó WDN

Pipe/Node	Velocity (m/s)	Flow direction	Pressure (m)
1	1.25	R-1	25.41
2	2.13	1-2	27.48
3	2.03	2-3	28.84
4	0.75	3-4	28.05
5	0.68	4-5	28.77
6	0.46	5-6	24.01
7	1.10	7-6	22.06
8	1.32	8-7	15.00
9	0.44	1-8	33.23
10	0.89	1-9	28.54
11	1.15	9-10	29.28
12	1.48	10-11	25.76
13	0.21	11-12	18.24
14	1.26	3-12	18.50
15	1.63	3-13	20.61
16	1.08	13-14	15.05
17	1.31	14-15	16.72
18	0.97	16-15	
19	1.43	17-16	
20	0.83	5-17	

Table 9 | Diameters, manometric high, and costs for the Itororó WDN

Pipe	Diameter (m)	Pipe	Diameter (m)
1	0.2520	11	0.0756
2	0.1564	12	0.0534
3	0.1564	13	0.0534
4	0.1564	14	0.0756
5	0.1564	15	0.1084
6	0.0534	16	0.1084
7	0.0534	17	0.0756
8	0.0756	18	0.0534
9	0.1564	19	0.0756
10	0.1084	20	0.1084
H_{otm} (m)	C_T (\$)	C_E (\$)	$C_T + C_E$ (\$)
25.466	179,816.40	307,438.38	487,254.78

Table 10 | Contribution of the operation costs in the total Itororó WDN cost

Year	C_E ($)	Percentage (%)	Year	C_E ($)	Percentage (%)
1	18,512.99	9.33	14	206,001.73	53.39
2	36,352.78	16.82	15	217,023.75	54.69
3	53,543.85	22.94	16	227,644.96	55.87
4	70,109.79	28.05	17	237,879.95	56.95
5	86,073.33	32.37	18	247,742.76	57.94
6	101,456.38	36.07	19	257,246.92	58.86
7	116,280.04	39.27	20	266,405.48	59.70
8	130,564.67	42.07	21	275,231.00	60.48
9	144,329.85	44.53	22	283,735.58	61.21
10	157,594.48	46.71	23	291,930.91	61.88
11	170,376.76	48.65	24	299,828.23	62.51
12	182,694.23	50.40	25	307,438.38	63.10
13	194563,79	51.97			

Table 10 presents the contribution of the operation costs to the total WDN cost during the 25 years considered as the lifetime of the pumping system. It can be noted that in the first year this contribution represents 9.33% and in the last year, 63.1%.

CONCLUSION

In the present paper, an MINLP optimization model for the synthesis of WDN was presented. In the model, the flow directions are considered unknown and binary variables were used to define them in the demand node loops. Also, operation costs are considered in the objective function. The model constraints consider the pressure and velocity limits and hydraulic equations to calculate pressures and velocities and no additional software is needed to calculate them. Both, unknown flow directions and operation costs in the objective function are the novelties in the paper. Some linearization strategies were used to avoid nonlinearities in the model and the environment GAMS was used to solve the problems. Two real case studies were used to test the model applicability.

The objective function to be minimized is the total WDN cost, considering operation and installation costs, depending on a set of available commercial diameters. The operation cost depends on the manometric head of the reservoir. In the first case study, the papers used in the results comparison used known flow directions. Hazen–Williams and Darcy–Weisbach equations were used in the case studies. In both cases, the operation costs represent ¼ and 2/3 of the total cost, which means that it represents an important percentage of the total cost in the WDN.

The linearization techniques used decreased the degree of complexity of the model. It is very useful, considering that the binary variables inserted in the model to consider the flow directions unknown increase the complexity degree. Nevertheless, the solution of the problem becomes more realistic, once the operation costs represent a significant part of the WDN total cost.

For future studies, aiming to improve the current optimization model, uncertainties in the water nodes demand and different operation conditions, and multi-periods of operation could be considered.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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