Upgrading water distribution networks to work under uncertain conditions

J. Marques and M. Cunha

ABSTRACT

This work presents a multicriteria approach to defining flexible solutions for reinforcing and renewing existing water distribution networks, considering uncertain future working conditions. Criteria related to financial, environmental and pipe failure assessment are proposed to evaluate alternative solutions and to identify the best-placed options to implement. The alternatives are obtained for a phased design scheme that enables midcourse corrections through changes in the network layout. The proposed framework has been demonstrated using a case study based on a water distribution network from the literature.

Key words | flexibility, multicriteria decision analysis, optimization, water distribution networks

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INTRODUCTION

Every country must have reliable water distribution networks (WDNs) whose long-term operation can be secured under a range of circumstances, sometimes adverse. Operators and researchers today have to find ways to design a network that can be modified when conditions change, whether for reasons beyond their control (e.g. climate change) or more or less foreseeably (e.g. urban development, ageing infrastructure). Decision makers will therefore be best served by a flexible design solution that allows them to adapt the system to problems when they arise, under a 'wait-and-see' strategy (de Neufville & Scholtes 2011), such that an efficient supply is effectively maintained. These flexible designs can cope with demand uncertainty (Basupi & Kapelan 2015). According to Creaco *et al.* (2016), a single phase design of WDNs without considering demand uncertainty could result in under- or over-designed systems. This means inefficient networks with deficient or excessive hydraulic capacity. Recently, Pandey *et al.* (2020) state that future demand is the most uncertain parameter of all, and it has a considerable effect on the network's performance. They recommend taking demand uncertainty into account as it has a direct impact on infrastructure costs.

Marques *et al.* (2017) describe a multicriteria decision analysis (MCDA) that ranks possible designs for new WDNs, but it can be even more important to be able to adapt existing infrastructure because it should be less costly. Our work sets out an MCDA in which a phased design can anticipate a need for change through an uncertain future demand. An existing network will require investment in renovation (old pipes replacement) and/or reinforcement (by new parallel pipes). An integrated perspective should also be focused on energy and operating costs, proposing also new pumps to increase the hydraulic capacity of the network.

The MCDA is a powerful technique that has been extensively used for planning of water supply systems. Salehi *et al.* (2018) states that among the water supply activities, the regular rehabilitation of existing WDNs is one of the most important due to the high potential of improving their performance. Those authors expose a comprehensive literature review over the recent decades about the use of MCDA to the rehabilitation of WDNs, and from those references it can be stated that none of them have dealt with the problem of using the phased design approach of WDNs during the life cycle of the infrastructure. In fact, numerous studies

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are oriented to the prioritization of pipe replacements by selecting where the interventions should be made and are not driven by the analysis of specific designs of diameters sizes to be used in particular network pipes. However, in a previous work by the authors (Marques *et al.* 2015a) a phased design of WDNs was proposed to provide the pipe diameter sizes to install in all design phases, but no pumping stations that impose important operation costs were dealt with. In the present work we analyze the situation where pumping stations are considered. This completely changes the intervention logic to renovate and reinforce WDNs. The installation of new pipes increases the investment cost and reduces the operating costs and pollutant emissions related to the electricity consumption. However, the installation of additional pumping capacity can reduce the total initial investment cost by reducing the need to install high capacity pipes, while increasing operating costs and pollutant emissions as more energy is required to power the pumps. The compromise between these kinds of interventions will be addressed in this work.

The proposed MCDA considers the overall cost of reinforcing and improving the WDN using criteria to handle the investment and the carbon emissions that could impact the environment. It also includes criteria to assess pipe failures and help find ways of improving water pipe conditions.

METHODOLOGY

In this work, we propose a multicriteria decision analysis to identify the most appropriate reinforcement and renovation interventions (scheduled over a phased planning horizon) required to upgrade a WDN according to a number of different criteria. The criteria (taking into account the phased design) are to reduce the cost, carbon emissions and the number of pipe failures. The total cost and the cost for each time phase, given by Equations (1)–(4), are evaluated for a range of predefined demand scenarios used to represent uncertainty:

$$C_{\mathrm{tot}} = \sum_{t=1}^{NPH} (Cph_t) \tag{1}$$

$$Cph_t = CI_t + CO_t \quad \mathrm{t} \in NPH \tag{2}$$

$$CI_t = \left(\sum_{i=1}^{NPI} (C\mathrm{pipe}_i(Dc_{i,t}) \times L_i) + C\mathrm{pump}_t \right) \frac{1}{(1+IR)^{y_t}} \quad \mathrm{t} \in NPH \tag{3}$$

$$CO_t = \max_s^{NS} \left(\sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,s,t} \cdot HP_{j,s,t}}{\eta_j} \cdot 365 \cdot C\mathrm{energy} \cdot \frac{(1+IR)^{\Delta tph_t} - 1}{IR \cdot (1+IR)^{\Delta tph_t}} \cdot \frac{1}{(1+IR)^{y_t}} \right) t \in NPH \tag{4}$$

where C_{tot} – total cost (USD); NPH – number of phases in the planning horizon; t – time phase; Cph_t – cost for each time phase t (USD); CI_t – present cost of investment for time phase t (USD); CO_t – maximum present cost of operation for the number of scenarios analyzed and for time phase t (USD); NPI – number of pipes; $C\mathrm{pipe}_i(Dc_{i,t})$ – unit cost of pipe i as function of the commercial diameter $Dc_{i,t}$ (USD/m); $Dc_{i,t}$ – commercial diameter of pipe i installed in time phase t (mm); L_i – length of pipe i (m); $C\mathrm{pump}_t$ – cost of the pump installed in time phase t (USD); IR – annual interest rate for updating costs; y_t – starting point of the time phase t (for $t = 1$ the starting point is year 0 $y_1 = 0$) (years); NS – number of scenarios; NPU – number of pumps; γ – specific weight of water (kN/m^3); $QP_{j,s,t}$ – discharge of the pump j in scenario s for time phase t (m^3/h); $HP_{j,s,t}$ – head of the pump j in scenario s for time phase t (m); η_j – efficiency of the pump j; Cenergy – unit cost of energy (USD/KWh) and Δtph_t – duration in years of time phase t (years).

The total cost criterion of Equation (1) is given by the sum of the costs (Cph_t) for all time phases. These costs are assessed in Equation (2) by summing the investment cost of pipes and pumps (Equation (3)) with the maximum energy cost for the NS scenarios analyzed (Equation (4)). In Equation (3) costs are given by the present value for year 0 of the investment cost of pipes added to the investment cost of new pumps. The energy cost is determined in Equation (4) by considering the maximum energy consumption for the NS scenarios analyzed.

The criteria of Equation (5) include the carbon emissions arising from pipe construction plus the emissions related to maximum energy consumption for the NS scenarios:

$$EC_t = \sum_{i=1}^{NPI} (EC\text{pipe}_i(Dc_{i,t}) \times L_i) + \max_s^{NS} \left(\sum_{j=1}^{NPU} \frac{\gamma \cdot QP_{j,s,t} \cdot HP_{j,s,t}}{\eta_j} \cdot 365 \cdot ECop \cdot \Delta tph_t \right) \quad t \in NPH \tag{5}$$

where EC_t – carbon emissions due to pipe installation and maximum energy consumption for the NS scenarios analyzed for time phase t (tonnesCO$_2$); $EC\text{pipe}_i(Dc_{i,t})$ – unit carbon emission of pipe i as a function of the commercial diameter $Dc_{i,t}$ installed (tonnesCO$_2$/m) and $ECop$ – unit carbon emissions of operation due to energy (tonnesCO$_2$/KWh).

These carbon emissions are computed using the procedure described in Marques *et al.* (2015b). The carbon emissions related to new pump installation are not evaluated because they are considered to be negligible when compared with emissions related to pipe constructions and energy use.

Finally, the criteria in Equation (6) are used to evaluate the number of breaks in the network for each time phase and are function of the age, length and diameter of the pipe:

$$NB_t = \sum_{i=1}^{NPI} 4.976 \cdot \frac{AP_{i,t}^2 \cdot (L_i \cdot 10^{-3})}{Dc_{i,t}^2} t \in NPH \tag{6}$$

where NB_t – number of pipe breaks for time phase t and $AP_{i,t}$ – age of the pipe i at the end of time phase t (years).

In this work, a hypothetical case study is used to demonstrate the applicability of the approach. As there is no historic data of pipe failures an expression determined by Xu *et al.* (2011) is used that is appropriate to the commercial pipe diameter range and material of the pipes proposed here. These criteria, defined through Equations (1)–(6) for the different phases, are used to evaluate the alternative designs. This means that priority can be given to particular time phases of the planning horizon. For the MCDA application, this is handled by giving different weights to criteria for each time phase.

The alternatives to be evaluated are stated according to different strategies to reinforce and renovate the WDN by using parallel pipes, adding new pumps and replacing old pipes with new ones. These alternatives are obtained by using an optimization model with a cost minimization as objective function, subject to constraints to verify minimum pressure at the nodes, to check the nodal flow continuity equations, to compute the head loss in pipes and to use a set of commercial diameters. This model is solved with an algorithm based on the simulated annealing heuristic (Kirkpatrick *et al.* 1983), which is linked to the EPANET (Rossman 2000) hydraulic simulator to verify the hydraulic constraints.

Once the criteria, weights and alternatives have been defined, PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations) (Brans & Vincke 1985) is used to rank the alternatives and identify the best intervention strategy for the network. Not only is this method particularly user friendly, but its mathematical properties are favourable and it is widely applied in MCDA problems.

In PROMETHEE, a number of alternatives (NA) are ranked according to a preference ranking index $\phi(a_i)$ (Equation (7)) of an alternative a_i and varies between -1 and 1. This index is given by the balance between the strengths $\phi^+(a_i)$ and weaknesses $\phi^-(a_i)$ of one alternative a_i relative to the others. For positive $\phi(a_i) > 0$ the alternative a_i outranks all the alternatives in all criteria, and for negative $\phi(a_i) < 0$ the alternative a_i is outranked by all the alternatives, in all criteria:

$$\phi(a_i) = \phi^+(a_i) - \phi^-(a_i) \tag{7}$$

with

$$\phi^+(a_i) = \frac{1}{NA - 1} \sum_{j \in NA, j \neq i} \pi(a_i, a_j) \tag{8}$$

$$\phi^-(a_i) = \frac{1}{NA - 1} \sum_{j \in NA, j \neq i} \pi(a_j, a_i) \tag{9}$$

The strength value $\phi^+(a_i)$ expresses how an alternative a_i is outranking all the other (Equation (8)). The higher $\phi^+(a_i)$, the better the alternative. The weaknesses value $\phi^-(a_i)$ expresses how an alternative a_i is outranked by all the others (Equation (9)). The lower $\phi^-(a_i)$, the better the alternative. In Equation (8) the preference index $\pi(a_i, a_j)$ expresses the degree by which a_i is preferred to a_j over all the criteria, and in Equation (9), the preference index $\pi(a_j, a_i)$ expresses how a_j is preferred to a_i. If $\pi(a_i, a_j)$ is close to 0, this indicates a weak global preference of a_i over a_j, whereas if $\pi(a_i, a_j)$ is close to 1, this implies a strong global preference of a_i over a_j. These preference indexes are computed by considering all criteria and weights of the problem.

The alternatives with high values of ϕ (close to 1) should be selected and the alternatives with low values of ϕ (close to -1) should be discarded. A detailed description of the method can be found in Brans & Vincke (1985) and an extended literature review of the application of PROMETHEE in several areas can be found in Behzadian *et al.* (2010).

CASE STUDY AND RESULTS

Water supply

The MCDA described in the previous section is applied to a case study based on the network used by Jowitt & Xu (1990) and Gupta *et al.* (2017). This case study was modified so that the applicability of the proposed approach could be demonstrated. This network has a single reservoir with a constant level (2 m), three pumps, 37 pipes and 22 nodes. The layout of the network can be found in Gupta *et al.* (2017) and the link and node data are presented in Tables 1 and 2, respectively. The pipe diameters are chosen from the commercial sizes, costs and carbon emissions that are available in Marques *et al.* (2015b).

A planning horizon of 20 years was evaluated by dividing it into 5-year periods and allowing interventions in the network by reinforcing and replacing old pipes. There are thus four phases, $t = 1$ from year 0 to year 4, $t = 2$ from year 5 to year 9, $t = 3$ from year 10 to year 14 and $t = 4$ from year 15 to year 19. The interventions in the network are implemented at the beginning of each phase for $y_1 = 0$, $y_2 = 5$, $y_3 = 10$ and $y_4 = 15$ years. In the first phase ($t = 1$), the network interventions have to be done now ($y_1 = 0$). In the next phases ($t = 2$, 3 and 4) it will be possible to modify the upgrade plan according to the availability of new information ($y_2 = 5$, $y_3 = 10$ and $y_4 = 15$ years). A decrease of the Hazen–Williams (H–W) coefficient at a fixed rate of 2.5 per decade as was assumed in DWSD (2004).

Table 1 | Characteristics of the pipes

Pipe	L (m)	D (mm)	H–W coef.	Pipe	L (m)	D (mm)	H–W coef.
1	606	457	110	20	2,334	229	100
2	454	457	110	21	1,996	229	95
3	2,782	229	105	22	777	229	90
4	304	381	135	23	542	229	90
5	3,382	305	100	24	1,600	457	110
6	1,767	475	110	25	249	305	105
7	1,014	381	135	26	443	229	90
8	**1,097**	**381**	**6**	27	743	381	110
9	1,930	457	110	28	931	229	125
10	**5,150**	**305**	**10**	29	2,689	152	100
11	762	457	110	30	326	152	100
12	914	229	125	31	844	229	110
13	822	305	140	32	1,274	152	100
14	411	152	100	33	1,115	229	90
15	701	229	110	34	615	381	110
16	1,072	229	135	35	1,408	152	100
17	864	152	90	36	500	381	110
18	711	152	90	37	300	229	90
19	832	152	90				

Values in bold indicate pipes that are very old and have low H–W coefficients.

Table 2 | Characteristics of the nodes

Node	Elev (m)	Q (L/s)	Node	Elev (m)	Demand (L/s)
1	18	10	14	20	10
2	18	15	15	8	25
3	14	5	16	10	5
4	12	10	17	7	5
5	14	35	18	8	10
6	15	15	19	10	10
7	14.5	5	20	7	5
8	14	25	21	10	5
9	14	5	22	15	25
10	15	10	23	0	5
11	12	15	24	0	5
12	15	5	25	0	5
13	23	5	26	2	Reservoir

Scenarios

A set of demand scenarios was randomly generated for the four design phases, using a uniform distribution considering some bounds for the demand variation. The same reference demand value (Table 2) was used for $y_1 = 0$. For $y_2 = 5$ demand variations could be between threshold limits of −5% and +20%, relative to the reference demand of $y_1 = 0$. As this is a hypothetical WDN, the limits are fixed as plausible values. In real networks, they can be determined by statistical analyses of data or proposed by stakeholders. For $y_3 = 10$ and $y_4 = 15$, the demand scenarios were generated between the same threshold limits but with the reference demand values obtained in years $y_2 = 5$ and $y_3 = 10$, respectively. The demand variation is considered to be the same (as a percentage) for all network nodes. A set of 200 demand scenarios is generated and presented in Figure 1. A single scenario is also highlighted in this figure by a thick line that assumes a demand increase of 7.5% in $y_2 = 5$, 15% in $y_3 = 10$ and 22.5% in $y_4 = 3$. This is the reference scenario used to design the alternatives.

Network alternatives

In its present form, the network cannot satisfy minimum pressure requirements. Figure 2 shows the possible changes that can be implemented to build ten possible alternatives to reinforce the WDN with parallel pipes, new pumps and/or replacing old pipes, to be evaluated through the MCDA. There are ten old pipes (indicated in Figure 2 by brown lines) with high roughness and high break rates that need to be replaced using the commercially available diameters. Pipes 8 and 10, in particular, are very old with low H–W coefficients (highlighted in bold in Table 1) and have to be changed now (year 0) for all ten alternatives. The other old pipes represent H–W coefficients of 90 (Table 1) and can be replaced now or in future phases. The network design alternatives (NDA) are proposed by considering the possibility of reinforcing the WDN by replacing old pipes, by installing parallel pipes (PP) in the network links without pipe replacements and the possibility of including new pumps (NP) in parallel to the existing ones. The decision about installing or not installing new pumps (that have the same characteristics as the existing ones) are implemented in year 0 ($y_1 = 0$) but old pipe replacements (PR) and new PP can be made in different time phases (Figure 2). This means that the alternatives are proposed according to intervention strategies in different moments in time. For example, in NDA1 (Figure 2), all old pipes are replaced now ($y_1 = 0$), and in NDA2 (Figure 2) they are replaced in two time phases ($y_1 = 0$ and $y_2 = 5$) because pipes 8 and 10 have to be replaced now and the other eight old pipes are replaced in year 5. As the old pipe replacements are not enough to satisfy all pressure requirements, the alternatives also include reinforcements with new PP as in alternatives NDA1, NDA2, NDA3, NDA4 and NDA9 or with NP in alternatives NDA5, NDA6, NDA7, NDA8 and NDA10. The aim is to understand what are the best options between

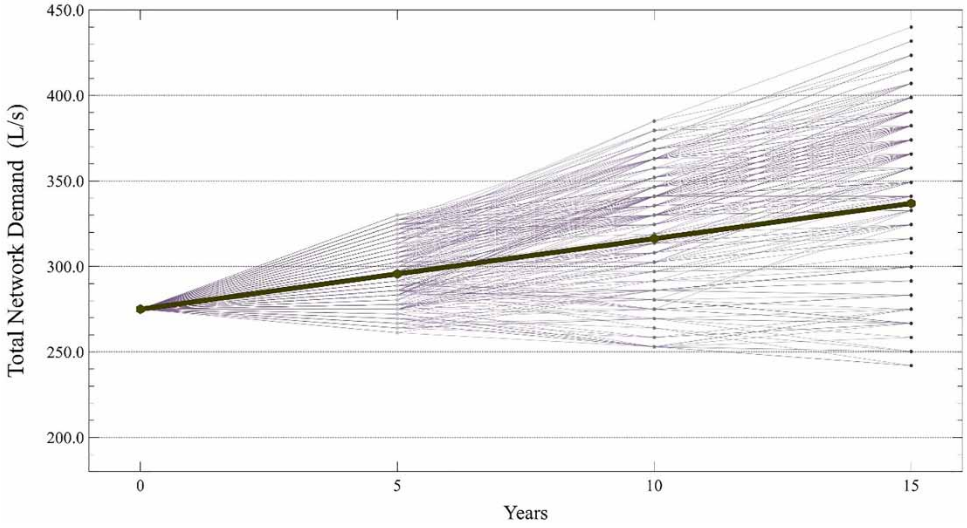
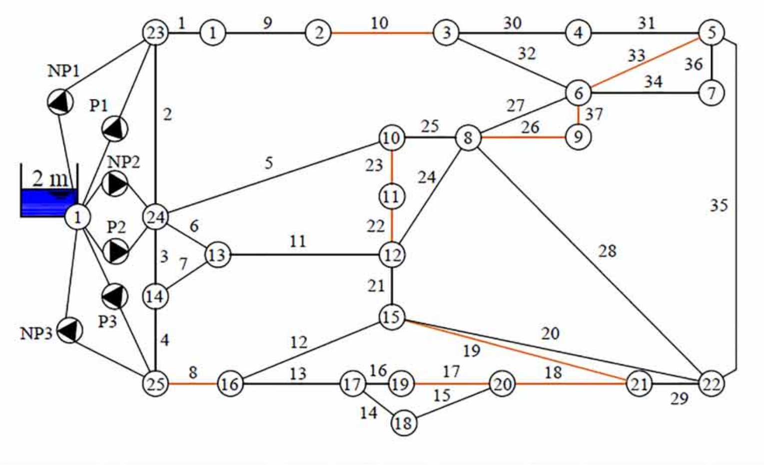


Figure 1 | Demand variations for the network with a total base demand of 275 (l/s).



NDA1: PR (8, 10, 17, 18, 19, 22, 23, 26, 33, 37) in year 0 + reinforcement with PP
NDA2: PR (8, 10) in year 0 and PR (17, 18, 19, 22, 23, 26, 33, 37) in year 5 + reinforcement with PP
NDA3: PR (8, 10) in year 0 and PR (17, 18, 19, 22, 23, 26, 33, 37) in year 10 + reinforcement with PP
NDA4: PR (8, 10) in year 0 and PR (17, 18, 19, 22, 23, 26, 33, 37) in year 15 + reinforcement with PP
NDA5: PR (8, 10, 17, 18, 19, 22, 23, 26, 33, 37) in year 0 + reinforcement with NP1,NP2 and NP3
NDA6: PR (8, 10) in year 0 and PR (17, 18, 19, 22, 23, 26, 33, 37) in year 5 + reinforcement with NP1,NP2 and NP3
NDA7: PR (8, 10) in year 0 and PR (17, 18, 19, 22, 23, 26, 33, 37) in year 10 + reinforcement with NP1,NP2 and NP3
NDA8:PR (8, 10) in year 0 and PR (17, 18, 19, 22, 23, 26, 33, 37) in year 15 + reinforcement with NP1,NP2 and NP3
NDA9: PR (8, 10) in year 0 + reinforcement with PP
NDA10: PR (8, 10) in year 0 + reinforcement with NP1,NP2 and NP3

Figure 2 | Network design alternatives.

reinforcing with new PP or with new NP, as these interventions have different outcomes in terms of investments, energy use during network operation, carbon emissions and pipe breaks.

The alternatives, described in Figure 2, are sized by considering minimum nodal pressures of 30 m and assuming the demand scenario represented by the thick line in Figure 1. Designs are obtained using an optimization tool proposed by Marques *et al.* (2015c), with the purpose of minimizing the investment and operating costs subject to a set of constraints. The hydraulic behaviour is verified with EPANET (Rossman 2000).

Criteria

The alternatives obtained in the previous section will be evaluated using 200 equally probable demand scenarios (Figure 1). For this, three groups of criteria are analyzed: cost with five criteria (total cost and cost for each phase: C_{tot}, Cph_1, Cph_2, Cph_3 and Cph_4) computed by Equations (1) and (2); carbon emissions with four criteria (carbon emissions for each phase: EC_1, EC_2, EC_3 and EC_4) determined by Equation (5); and pipe breaks with four criteria (sum of the pipe breaks for all pipes and for phases NB_1, NB_2, NB_3 and NB_4), calculated by Equation (6). These criteria are computed for each NDA using the 200 generated demand scenarios mentioned, and the results are provided in Table 3.

The high partial costs and carbon emissions criteria values occur in the phase in which most of the old pipes are replaced. The NDA1 and NDA5 alternatives assume all the ten old pipes are changed in the first phase and these alternatives thus include values for Cph_1 and EC_1 that are much higher than the costs and carbon emissions in the subsequent phases. But NDA1 and NDA5 are also the alternatives with the lowest number of pipe breaks, due to all the old pipes being substituted in the first phase. By contrast, in NDA9 and NDA10, only two of the ten old pipes are replaced and these are the alternatives with the highest number of pipe breaks. From the energy-consumption operating cost perspective, the alternatives that do not consider NP have lower operating costs, as expected. For instance, NDA2 has a $Cph_4 = 0.62 \times 10^6$ USD and NDA6 a $Cph_4 = 0.74 \times 10^6$ USD. These alternatives are compared because they are obtained from the same replacement scheme of the old pipes (replacement of pipes 8 and 10 in year 0 and replacement of pipes 17, 18, 19, 22, 23, 26, 33 and 37 in year 5), but NDA2 use pp to reinforce the WDN and NDA6 use NP. As NDA6 uses more energy than NDA2, the carbon emissions of NDA6 ($EC_4 = 1.59 \times 10^3$ tonnesCO_2) are also higher then NDA2 ($EC_4 = 1.34 \times 10^3$ tonnesCO_2). The comparison of the alternative designs also makes it possible to conclude that a phased intervention allows a more efficient adaptation of the networks to current conditions.

Table 3 | Evaluation criteria for the ten network design alternatives

	Costs × 10^6 (USD)					Carbon emissions × 10^3 (tonnesCO_2)				Number of pipe breaks			
NDA	C_{tot}	Cph_1	Cph_2	Cph_3	Cph_4	EC_1	EC_2	EC_3	EC_4	NB_1	NB_2	NB_3	NB_4
1	4.39	2.01	0.85	0.92	0.61	7.08	1.23	2.80	1.31	10	12	14	16
2	4.96	1.59	1.99	0.76	0.62	4.58	7.27	1.34	1.34	16	12	14	16
3	5.05	1.88	0.89	1.65	0.62	6.53	1.30	7.24	1.34	16	18	14	16
4	4.52	1.79	0.84	0.75	1.15	6.37	1.22	1.32	5.36	16	18	21	16
5	4.72	2.19	0.91	0.88	0.74	7.49	1.32	1.55	1.59	10	12	14	16
6	4.86	1.60	1.64	0.88	0.74	4.48	5.20	1.55	1.59	16	12	14	16
7	4.73	1.60	0.91	1.48	0.74	4.48	1.32	5.42	1.59	16	18	14	16
8	4.62	1.60	0.91	0.88	1.23	4.48	1.32	1.55	5.46	16	18	21	16
9	4.24	2.02	0.84	0.76	0.62	6.57	1.21	1.34	1.34	16	18	21	24
10	4.78	2.07	0.96	0.94	0.82	6.73	1.39	1.67	1.76	16	18	21	24

Weight sets

The criteria and weights of the MCDA are organized according to the phased network interventions to allow giving high weight to criteria in the early phase and less to those in the later phases (because the solutions for the next phases can be reassessed if new information becomes available). An additional situation giving the same weight to all phases and to all criteria is also considered. In this case study, four weight sets (WS) are used (Table 4). In WS1, high weights are given to costs, in WS2 more importance is given to carbon emissions and in WS3 more importance is given to the number of pipe breaks criteria. The WS1 can reflect the lack of capital availability of water utilities, the WS2 can represent the high importance given to environmental concerns and the WS3 is more oriented to improving the reliability of the water distribution network. Finally, in WS4 all criteria have the same weight, equal to $(1/13 \approx 0.08)$.

Ranking alternatives

The intervention options were evaluated with Visual PROMETHEE Mareschal & De Smet (2009) using the index (ϕ) which is used to rank the alternatives. The results are shown in Table 5 for the four WSs.

From the results provided in Table 5, NDA1 is the best ranked for WS1, WS3 and WS4, and NDA8 for WS2. In terms of the best ranked solutions, if a high weight is given to the investment cost (WS1), the best positioned alternative is NDA1, which includes low values for almost all the criteria, including low values for the cost criteria set. If high weights are given to carbon emission criteria (WS2), the best ranked alternative is NDA8. This alternative includes low carbon emissions for the first three phases and a high value for the last phase, related to replacing eight old pipes in this phase. As the weights attributed to criteria of the last phases are low, due to the uncertainty of the future, NDA8 is the best positioned alternative, even with

Table 4 | Weight sets of criteria

	Costs					Carbon emissions				Number of pipe breaks			
Weight sets	C_{tot}	Cph_1	Cph_2	Cph_3	Cph_4	EC_1	EC_2	EC_3	EC_4	NB_1	NB_2	NB_3	NB_4
WS1	0.1	0.20	0.15	0.1	0.05	0.09	0.06	0.03	0.02	0.09	0.06	0.03	0.02
WS2	0.04	0.12	0.08	0.04	0.02	0.20	0.15	0.1	0.05	0.09	0.06	0.03	0.02
WS3	0.04	0.12	0.08	0.04	0.02	0.09	0.06	0.03	0.02	0.20	0.15	0.1	0.05
WS4	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08

Table 5 | Alternative design rankings for four weights sets identified by visual PROMETHEE

	WS1		WS2		WS3		WS4	
Rank	**NDA**	**Φ**	**NDA**	**Φ**	**NDA**	**Φ**	**NDA**	**Φ**
1	1	0.15	8	0.14	1	0.31	1	0.23
2	8	0.11	7	0.10	5	0.25	5	0.17
3	7	0.06	1	0.08	6	0.12	6	0.09
4	6	0.04	6	0.07	2	0.10	2	0.06
5	5	0.03	2	0.03	7	0.03	7	0.02
6	2	0.00	5	0.03	8	−0.03	9	−0.06
7	4	−0.01	4	−0.06	4	−0.14	8	−0.06
8	9	−0.02	9	−0.07	3	−0.15	4	−0.13
9	10	−0.16	10	−0.14	9	−0.21	3	−0.15
10	3	−0.20	3	−0.19	10	−0.27	10	−0.17

high last phase carbon emissions. NDA4 also considers the same replacement scheme with eight old pipes to be replaced in the last phase, as for the NDA8 case. However, in NDA4, the network reinforcement is proposed using parallel pipes and in NDA8 the reinforcement is achieved by installing pp. NDA4 contains a high value for the carbon emissions criterion ($EC_4 = 5.36 \times 10^3$ tonnesCO_2) of the last phase, as does NDA8. But NDA4 also includes high carbon emissions in the first phase ($EC_1 = 6.37 \times 10^3$ tonnesCO_2), related to the installation of pp to reinforce the network. This increases carbon emissions and thus contributes to reduce the ranking of this alternative to the 7th position in WS2.

For WS3, more importance is given to pipe break criteria and the best ranked alternatives are NDA1 and NDA5, which consider replacing all old pipes in the first phase and have the lowest number of pipe breaks. For WS4, the same importance is attributed to all criteria in all phases, and the same position of WS3 is obtained for the 5 best ranked alternatives (NDA1, NDA5, NDA6, NDA2 and NDA7) and for the worst ranked solution (NDA10). But there are also some differences. NDA9 comes in the penultimate position in WS3 and is in 6th position in WS4. NDA9 is one of the alternatives with the highest number of pipe breaks, which contributes to it achieving the penultimate ranking position in WS3. If the same weight is considered for all criteria (WS4) the ranking of NDA9 is higher in comparison to WS3. In WS4, a lower weight is given to the number of pipe breaks criteria and higher weight is given to the cost and carbon emissions criteria. As NDA9 includes very low cost and carbon emissions criteria, this tends to improve its ranking in WS4. NDA1 and NDA5 are the best positioned alternatives for both weights because they have the best number of pipes breaks for all phases and also relatively low total investment costs and total carbon emissions for almost all phases. In fact, NDA1 only has high weaknesses in the criteria values Cph_1 and EC_1, related to replacing all the ten pipes in the first design phase (just two in 13 criteria). In the case of NDA5, this also includes high weaknesses in the criteria values Cph_1 and EC_1 related to replacing all ten pipes in the first phase and it also includes some higher weaknesses in the criteria values C_{tot}, Cph_4 and EC_4 relative to the NDA1 case. But the overall cost and carbon emissions for all phases are not very high and, therefore, this alternative reaches the 2nd ranking position. These are the alternatives that replace all the old pipes in the first phase. NDA6 and NDA2 consider the replacement of two pipes in the first phase and eight more pipes in the second phase (year 5), and NDA7 considers the replacement of two pipes in the first phase and eight pipes in the second phase (year 10). In fact, the best ranked alternatives are those that consider pipe replacements as soon as possible. This reduces the number of breaks and is thus the best option for the number of pipe breaks criteria. The same ranking ensues for all these alternatives in WS3 and WS4 because in WS3 the high weights given to the number of breaks criteria places, as best ranked alternatives, those with the lowest values for these criteria and the worst ranked alternatives are those with the highest values for the number of breaks. In WS4 the same weight is given to all phases and to all criteria. This reduces the strengths of these alternatives in the number of pipe breaks criteria (relative to WS3), but it also reduces the weaknesses by giving lower weight to the criteria of the first phases, such as Cph_1 and EC_1, i.e. those for which these alternatives have worst values, associated with the pipe replacements in these phases.

From the rankings of alternatives for these weight sets it can also be concluded that the four worst ranked alternatives in almost all the cases are NDA3, NDA4, NDA9 and NDA10. There is just one exception: NDA9 in WS4 is in 6th position. The NDA3 and NDA4 alternatives replace all old pipes, but eight of them are only in the last phases ($y = 10$ and $y = 15$). NDA9 and NDA10 only replace the two oldest pipes. This means that the replacement of the old pipes should be a priority for water utilities.

Alternatives NDA1 and NDA8 are shown in detail in Figures 3 and 4. These figures show different intervention strategies to reinforce the WDN.

The NDA1 design (Figure 3) assumes the reinforcement with a new pp and the substitution of all old pipes in year 0. NDA8 (Figure 4) involves three NP (NP1, NP2 and NP3) in parallel to the existing ones, the substitution of pipes 8 and 10 in year 0 and the substitution of pipes 17, 18, 19, 22, 23, 26, 33 and 37 in year 15. In terms of criteria values of costs and carbon emissions (Table 3), the replacement of two pipes and three new pumps plus the operating energy expenditure of NDA8 ($Cph_1 = 1.60 \times 10^6$ USD and $EC_1 = 4.48 \times 10^3$ tonnesCO_2) amounts to less than replacing all old pipes plus the operating energy expenditure of NDA1 ($Cph_1 = 2.01 \times 10^6$ USD and $EC_1 = 7.08 \times 10^3$ tonnesCO_2). NDA1 includes a new pp in year 10 (Figure 3). This increases costs and carbon emissions ($Cph_3 = 0.92 \times 10^6$ USD and $EC_3 = 2.80 \times 10^3$ tonnesCO_2) in year 10 compared to NDA8 ($Cph_3 = 0.88 \times 10^6$ USD and $EC_3 = 1.55 \times 10^3$ tonnesCO_2) with no infrastructure investments in this

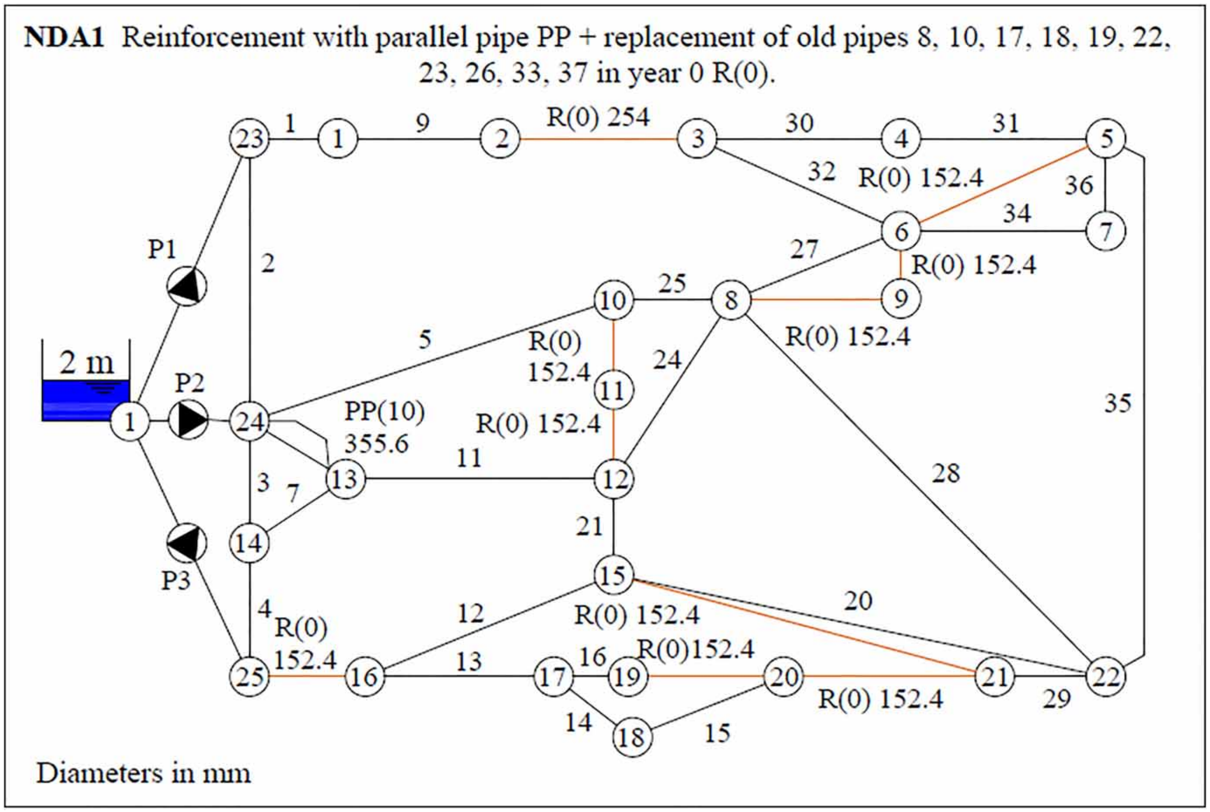


Figure 3 | Network design alternative NDA1.

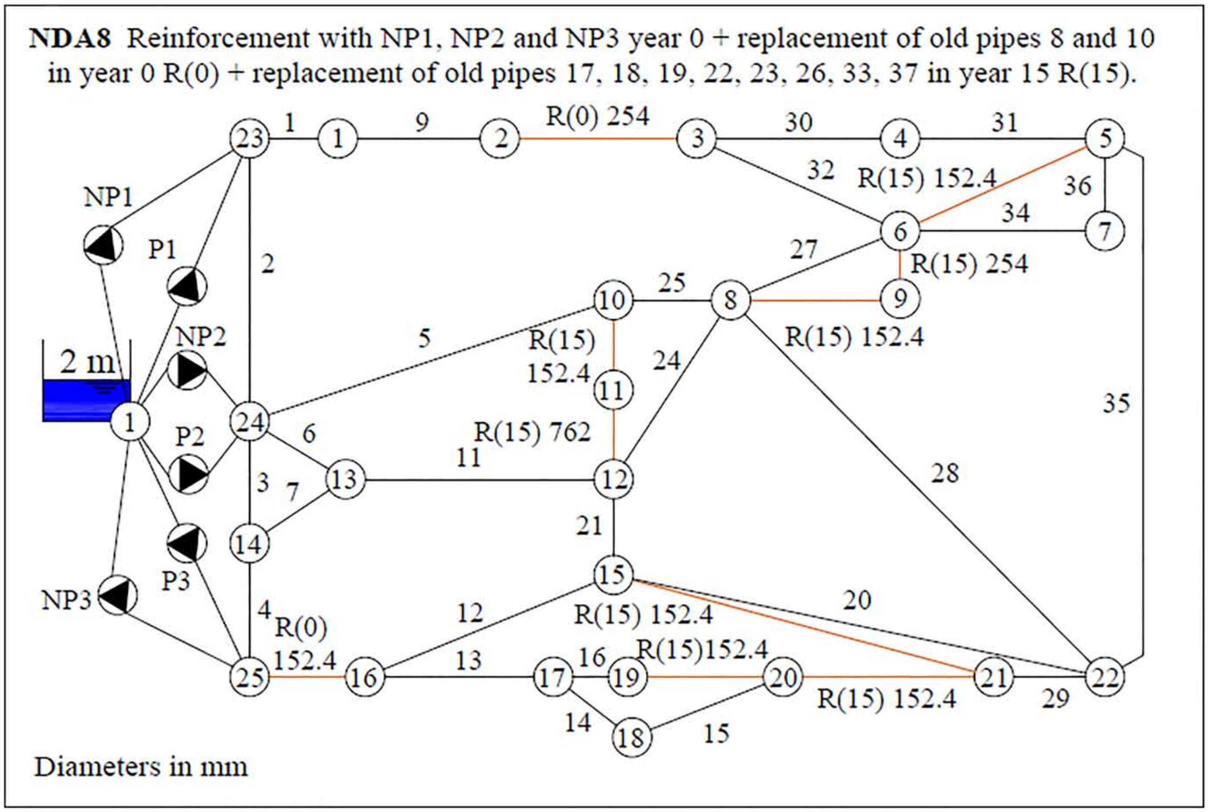


Figure 4 | Network design alternative NDA8.

phase. In the last planning phase, NDA8 plans to substitute eight old pipes (Figure 4), which increases the costs and carbon emissions ($Cph_4 = 1.23 \times 10^6$ USD and $EC_4 = 5.46 \times 10^3$ tonnesCO$_2$) compared to those of NDA1 ($Cph_4 = 0.61 \times 10^6$ USD and $EC_4 = 1.31 \times 10^3$ tonnesCO$_2$), which has no investment in this phase.

It should be noted that the investment costs of the future phases are calculated as the present value computed for year 0 and should not be directly compared to those of the first phase. However, the carbon emissions criteria, which are also computed according to the pipe diameters used, make a direct comparison possible with the first phase interventions and the planned pipe reinforcements for future phases. Regarding the number of breaks, the NDA1 design changes all old pipes by new ones in year 0 (Figure 3), which reduces the number of breaks in all phases of the planning horizon, e.g. $NB_1 = 10$ and $NB_4 = 16$ compared to NDA8, which does not replace the eight old pipes in the first phase and, therefore, the $NB_1 = 16$, but in the last phase when these eight pipes are replaced, the number of breaks decrease ($NB_4 = 16$).

CONCLUSIONS

This work includes a framework that makes use of MCDA to identify the best ranked alternative options for the reinforcement and renewal of a WDN that will work under uncertain future conditions. This framework was applied to a WDN from the literature using ten different alternative solutions, which are obtained considering a planning horizon of 20 years analyzed in 5-year intervals. The alternatives were then ranked using the PROMETHEE method, with four different weight sets to account for high weights given to specific criteria and to the initial phases of the planning horizon and an additional set that considers the same weight for all criteria. The results expose the different rankings of alternatives according to weights attributed to criteria. Furthermore, the high partial costs and carbon emissions criteria values occur in the planning phase, in that most of the old pipes are replaced and, as expected, the alternatives that include new pumps to reinforce the WDN are those with high operating costs. The replacement of old pipes should be a priority to water utilities because the worse ranked alternatives are those that do not replace, or replace just in the last phases, the old pipes of the network.

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REFERENCES

Basupi, I. & Kapelan, Z. 2015 Evaluating flexibility in water distribution system design under future demand uncertainty. *Journal of Infrastructure Systems* **21** (2), 04014034.

Behzadian, M., Kazemzadeh, R. B., Albadvi, A. & Aghdasi, M. 2010 PROMETHEE: a comprehensive literature review on methodologies and applications. *European Journal of Operational Research* **200** (1), 198–215.

Brans, J. & Vincke, P. 1985 A preference ranking organisation method (The PROMETHEE method for multiple criteria decision-making). *Management Science* **31** (6), 647–656.

Creaco, E., Franchini, M. & Walski, T. M. 2016 Comparison of various phased approaches for the constrained minimum-cost design of water distribution networks. *Urban Water Journal* **13** (3), 270–283.

de Neufville, R. & Scholtes, S. 2011 *Flexibility in Engineering Design*. Engineering Systems, MIT Press, Cambridge, MA, p. 293.

DWSD 2004 *Summary Report – Comprehensive Water Master Plan*. CH2M HILL, p. 113.

Gupta, A. D., Bokde, N., Marathe, D. & Kulat, K. 2017 Optimization techniques for leakage management in urban water distribution networks. *Water Science and Technology: Water Supply* **17** (6), 1638–1652.

Jowitt, P. W. & Xu, C. 1990 Optimal valve control in water-distribution networks. *Journal of Water Resources Planning and Management* **116** (4), 455–472.

Kirkpatrick, S., Gelatt, C. D. & Vecchi, M. P. 1983 Optimization by simulated annealing. *Science* **220** (4598), 671–680.

Mareschal, B. & De Smet, Y. 2009 Visual PROMETHEE: Developments of the PROMETHEE and GAIA multicriteria decision aid methods. In: *2009 IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 1646–1649.

Marques, J., Cunha, M. & Savić, D. 2015a A multicriteria approach for a phased design of water distribution networks. *Procedia Engineering* **119**, 1231–1240.

Marques, J., Cunha, M. & Savić, D. A. 2015b Using real options for an eco-friendly design of water distribution systems. *Journal of Hydroinformatics* **17** (1), 20–35.

Marques, J., Cunha, M. & Savić, D. 2015c Using real options in the optimal design of water distribution networks. *Journal of Water Resources Planning and Management* **141** (2), 04014052.

Marques, J., Cunha, M. & Savić, D. 2017 Ranking alternatives for the flexible phased design of water distribution networks. *Procedia Engineering* **186**, 567–575.

Pandey, P., Dongre, S. & Gupta, R. 2020 Probabilistic and fuzzy approaches for uncertainty consideration in water distribution networks – a review. *Water Supply* **20** (1), 13–27.

Rossman, L. A. 2000 *EPANET 2: Users Manual*. US Environmental Protection Agency National Risk Management Research Laboratory. US Environmental Protection Agency, Cincinnati, OH, p. 200.

Salehi, S., Jalili Ghazizadeh, M. & Tabesh, M. 2018 A comprehensive criteria-based multi-attribute decision-making model for rehabilitation of water distribution systems. *Structure and Infrastructure Engineering*. **14** (6), 743–765.

Xu, Q., Chen, Q., Li, W. & Ma, J. 2011 Pipe break prediction based on evolutionary data-driven methods with brief recorded data. *Reliability Engineering and System Safety* **96** (8), 942–948.

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