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Ranking alternatives for the flexible phased design of water distribution networks

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Abstract

A multi-criteria decision analysis (MCDA) approach is proposed as a useful tool to support decision making in the phased design of water distribution networks over a long planning horizon. The criteria are evaluated for various design phases of the planning horizon and organised in four groups: investment costs, carbon emissions, pressure deficits and undelivered demand. Furthermore, a number of alternative designs, obtained by using optimisation techniques, are analysed for a number of different demand scenarios. The values of the criteria are computed and the alternatives are ranked by an MCDA method (PROMETHEE) to identify the best design solutions to implement according to different weights attributed to the criteria. The designs that best satisfy the most criteria are identified to be considered by the decision maker for the implementation in the first design stage.

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Keywords: Water distribution networks; decision making; multi-criteria analysis; phased design

1. Introduction

Efficient design solutions for water distribution networks that take economic, environmental and quality of service dimensions into account and assume an uncertain future can be identified with the help of appropriate tools. Multi-criteria decision analysis (MCDA) is a transparent, structured approach that can be used in coherent decision

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making [1]. There are a few examples in the specialist literature of applying MCDA to water distribution network problems. Most of the literature in this area focuses on the analysis of alternative pipe replacement strategies for existing networks, as studied in [2] and [3]. The authors of this paper have also presented an MCDA for the reinforcement of existing water distribution networks with lack of hydraulic capacity [4]. Here, we introduce an MCDA to identify the best ranked alternatives for designing new water distribution networks, considering criteria evaluated for different phases. The alternatives and criteria are proposed according to a phased design scheme that enables the designer to adapt water networks if required. There is a gap in literature regarding the use of MCDA in the phased design of new water distribution networks. Therefore, the main purpose of this work is to show how the MCDA can help to identify the best ranked network design solutions from a number of alternatives and understand how preferences given to criteria at specific design phases influence the best alternatives to adopt.

The method proposed for solving the multi-criteria analysis is the preference ranking and organisation method for enrichment evaluation (PROMETHEE) developed by Brans and Vicke [5]. The use of this method in different areas is reviewed in [6]. It uses an outranking principle based on pairwise comparisons and requires the identification of different alternatives, criteria and weights to solve the problem. The results obtained with this method indicate the rank of the alternatives by computing a ranking index (*Phi*) to show decision makers a relationship between different options and help them to select the best. The rest of this work is organised as follows: section 2 sets out the methodology, section 3 describes the case study and presents the results and section 4 contains the conclusions and suggestions for future work.

2. Methodology

2.1. Scenarios building and criteria definition

Water distribution networks are planned to operate over long time horizons. Pipes installed are often in service for decades and many can function for more than a century. We propose making the decision-making process flexible by implementing phased design schemes that divide the planning horizon into phases and make it possible to intervene in the network at different times. The goal is to identify the network design for the first phase, keeping the whole planning horizon in mind and proposing reinforcing the network, if required, in future phases. As long-term predictions are highly uncertain, this work makes use of a set of synthetic demand scenarios generated randomly and with the same probability of occurrence for each time phase and between predefined minimum and maximum threshold limits. Furthermore, criteria are defined according to the planning phases. The idea is to evaluate the investment costs (this study considers only the capital expenditure costs CAPEX), carbon emissions, pressure deficits and undelivered demand independently for each phase. A cost criterion aggregating all investment costs in the planning horizon is also proposed to compare the overall cost of different alternatives. The present value of the total investment costs for all time phases is given by the criterion of Eq. 1 and the group of criteria of the investment costs for each time phase is given by Eq. 2.

$$CI_{tot} = \sum_{t=1}^{NPH} CI_t \tag{1}$$

$$CI_t = \sum_{i=1}^{NPI} \left(Cpipe_i(Dc_{i,t}) \times L_i \right) \frac{1}{(1+IR)^{y_t}} \quad t \in NPH \tag{2}$$

CI_{tot} – total investment cost *(USD)*
NPH – number of phases into which the planning horizon is divided
t – time phase (phase $t=1$ starts in year zero)
CI_t – present cost of investment for time phase t *(USD)*
NPI – number of pipes in the network
$Cpipe_i(Dc_{i,t})$ – unit cost of pipe i as function of the commercial diameter $Dc_{i,t}$ adopted *(USD/m)*
$Dc_{i,t}$ – commercial diameter of pipe i installed in time phase t *(mm)*
Li – length of pipe i *(m)*
IR – annual interest rate for updating costs

y_t – starting point of the time phase t (for $t=1$ the starting point is year zero $y_1=0$) *(years)*

The total cost criterion of Eq. 1 calculates the investment costs of all time phases of the planning horizon and Eq. 2 computes the present value for the year zero of the investment costs of pipes to be installed in each time phase and is given by the unit commercial diameter cost multiplied by the length of the pipe. The criteria of Eq. 3 include the carbon emissions arising from pipe construction. These carbon emissions are given by the total emissions for all the installed pipes in each phase of the planning horizon. The process described in [7] is used to compute the carbon emissions produced by making pipes in the traditional way, for each of the commercial pipe diameters. The emissions are calculated for the whole life cycle, including the extraction of raw materials, transport, manufacture, assembly, installation, disassembly, demolition and/or disposal.

$$CE_t = \sum_{i=1}^{NPI} \left(CEpipe_i(Dc_{i,t}) \times L_i \right) \qquad t \in NPH \tag{3}$$

CE_t – carbon emissions for time phase t *($TonCO_2$)*
$CEpipe_i(Dc_{i,t})$ – unit carbon emission of pipe i as a function of the commercial diameter $Dc_{i,t}$ installed *($TonCO_2/m$)*

Criteria relating to quality of service measures are included in this work by measuring insufficient pressures by the criteria in Eq. 4 and undelivered nodal demands by the criteria in Eq. 5.

$$PD_t = \sum_{s=1}^{NS} \sum_{n=1}^{NN} max\left\{0; \left(Pdes_{\min,n} - P_{n,s,t}\right)\right\} \qquad t \in NPH \;\wedge\; t \neq 1 \tag{4}$$

$$UD_t = \sum_{s=1}^{NS} \sum_{n=1}^{NN} \left(ND_{n,s,t} - C_{n,s,t}\right) \qquad t \in NPH \;\wedge\; t \neq 1 \tag{5}$$

PD_t – pressure deficits for time phase t *(m)*
NS – number of scenarios
NN – number of nodes
$Pdes_{min,n,}$ – minimum desirable pressure at node n *(m)*
$P_{n,s,t}$ – pressure at node n for scenario s in time phase t *(m)*
UD_t – undelivered demand for time phase t *(m^3/h)*
$ND_{n,s,t}$ – nodal demand at node n for scenario s in time phase t *(m^3/h)*
$C_{n,s,t}$ – supply at node n for scenario s in time phase t *(m^3/h)*

In the first phase of the planning horizon, we assume that a desired level of minimum pressure ($Pdes_{min}$) has to be achieved, therefore, the pressure deficit criteria for t=1 should be zero. However, pressures can be lower than $Pdes_{min}$ in future phases. These deficits are computed for all network nodes and for all demand scenarios by Eq. 4. The values of the undelivered demand criteria are computed by Eq. 5 by summing the differences between the required demand and the simulated delivered water for all network nodes and for all scenarios. A pressure driven hydraulic simulator is used to compute the values of these criteria.

2.2. Alternatives

This work uses a set of synthetic demand scenarios that are generated randomly for future time phases. The alternative designs are obtained by sizing the network for each of these scenarios. Therefore, the number of alternative network designs is the same as the number of demand scenarios. An optimization model [8] is used to size the networks with the objective of minimising the investment costs and most of the constraints of the model are those generally used in the optimisation of water networks [8]. However, here we adopt an additional constraint that limits the amount of undelivered demand (Eq. 6) above which the network has to be reinforced. Eq. 6 is used to define previously undelivered demand thresholds as a function of the total network demand for a given scenario and time y_t. For a later time y_t, a larger maximum undelivered demand volume is allowed because of the increased uncertainty associated with long-term predictions relative to predictions for the short term. For the first phase, network pipes have to be installed "now", which means that they should work properly for the first phase conditions. However, previous predictions can be reassessed in future phases, and therefore the option to reinforce the system can also be re-examined. These maximum undelivered demand values are included in the optimisation model to limit the volumes of undelivered demand of the alternative designs.

$$UD\max_{s,t} = \sum_{n=1}^{NN} ND_{n,s,t} \times 0.01 y_t \qquad s \in NS \quad t \in NPH \ \wedge \ t \neq 1 \tag{6}$$

$UDmax_{s,t}$ – maximum undelivered demand for scenario s in time phase t (m^3/h)

2.3. Ranking alternatives

This work uses Visual PROMETHEE [9] to compare and rank the alternatives and arrive at the best alternative design for the network. This program is based on the PROMETHEE method [5] and has been successfully employed to solve real problems in water resources, environmental management and water infrastructure. The outputs of the program are provided as a ranking index (*Phi*). *Phi* is a number between -1 and 1 that is given by the difference between two preference indexes *Phi*+ and *Phi-*. *Phi*+ is the positive preference index that measures how much an alternative (*a*) is preferred over the other *N-1* alternatives of the problem (*N* is the number of alternatives). It is an overall measure of the strengths of an alternative (*a*) and the larger *Phi*+ is, the better the alternative. The negative index (*Phi-*) measures by how much the *N-1* alternatives are preferred over alternative (*a*). It is an overall measure of the weakness of an alternative (*a*) and the smaller *Phi-* is, the better the alternative. The *Phi* index aggregates both the strengths and weaknesses of the alternative into a single score and the larger *Phi* is, the better the alternative.

3. Application and results

3.1. Case study

This study makes use of a real network (Hanoi) [10] to design a set of new pipes and meet minimum pressure requirements. This network has a single reservoir whose level is constant, 34 pipes, 3 loops and 31 supply nodes. The layout of the network and the length of the pipes can be seen in [10], and the Hazen Williams coefficient of 130 is used for all commercial pipe diameters. The same minimum pressure of 30m is required for all nodes. Six commercial diameters are available for the network design (Table 1). The original design assumes a single demand condition for which minimum pressures have to be verified. However, in our study, a set of demand scenarios in a phased scheme is analysed.

Table 1. Commercially available diameters

Diameter (mm)	Unit pipe cost (*USD*/m)	Carbon emissions (tonnes CO_2/m)	Diameter (mm)	Unit pipe cost (*USD*/m)	Carbon emissions (tonnes CO_2/m)
304.8	45.73	0.81	609.6	129.33	1.32
406.4	70.40	0.96	762.0	180.75	1.59
508.0	98.39	1.14	1016.0	278.28	2.04

Pipes can remain in service for long periods and it is very difficult to choose the right size of water pipes for water distribution systems that can be operated for more than a century. This work takes a planning horizon of 100 years, which is divided into 25-year periods, for the design of the water network pipe system. There are thus, four phases, t=1 from year 0 to year 25, t=2 from year 25 to year 50, t=3 from year 50 to year 75 and t=4 from year 75 to year 100. The decisions of interventions for each phase are implemented at the beginning of the phase, taking into account the demand scenarios generated for y_1=0, y_2=25, y_3=50 and y_4=75 years (see next section). Pipe diameters must be chosen in each phase from the set of commercial sizes (Table 1). The carbon emissions indicated in Table 1 are computed according to the methodology described in [7], which is used for traditional pipe construction. As the long planning horizon is evaluated in this study, the characteristics of the pipes will change during this time and so the Hazen-Williams coefficient is considered to decrease at a fixed rate of 2.5 per decade [11]. In the first phase (t=1), 34 pipes are sized and have to be installed then (y_1=0). For future phases (t=2, 3 and 4) there is the possibility of reinforcing the network by installing parallel pipes (y_2=25, y_3=50 and y_4=75 years). However, in this case study each network link can be only reinforced once, over the whole period.

3.2. Scenarios

This work takes a set of demand scenarios generated according to the four design phases. All demand scenarios have the same initial value, which is the same as in the original case study. Therefore, this is the reference demand for y_1=0, while for y_2=25 demand varies between (-5% and +25%), for y_3=50 it varies between (-10% and +50%) and for y_4=75 it varies between (-15% and +75%). A set of 28 demand scenarios are detailed in Fig. 1. The demand variation is considered to be the same (as a percentage) for all network nodes and the alternatives are designed with these nodal demands to function during 25 years after year (y_t). In these 28 demand scenarios, 25 are randomly generated and three are specific scenarios (indicated in Fig. 1 by blue diamond icons). Scenario 26 with a constant demand increase of 25% per phase is represented by the top icons. Scenario 27 with zero demand variation is represented by the horizontally aligned icons. Finally, scenario 28 with constant demand decrease of 5% per phase is represented by the bottom icons. Fig. 1 also highlights with diamond icons scenario 8 (violet) and scenario 21(orange), which are discussed below in the results section. In Fig. 1, lines connecting the icons are used to facilitate the visualization of scenarios and do not correspond to linear variations of demand between the time phases.

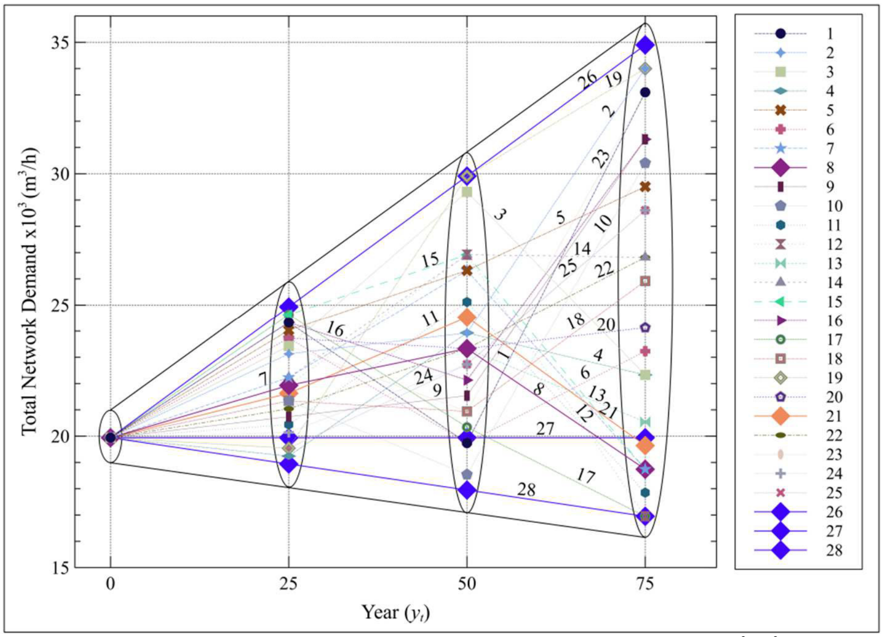

Fig. 1. Demand variations for the network with a total base demand of 19.94×10^3 (m^3/h)

3.3. Network alternatives

Minimum cost solutions are identified for each of the demand scenarios in Fig. 1, considering the possibility of reinforcement with parallel pipes and respecting the constraints described in section 2.2. The hydraulic constraints are verified with EPANET for pressure-driven analysis [12]. In the first time phase (t=1), a minimum pressure of 30m has to be achieved, and for future phases (t=2, 3 and 4) the minimum pressure is allowed to fall down to 10m but, for pressures between 30m and 10m, the demand is not totally satisfied. Therefore, there will be pressure deficits and undelivered demands in the network, which can be computed using Eqs 4 and 5 (considering $Pdes_{min}$=30m for all supply nodes).

3.4. Criteria

Four groups of criteria are analysed: investment costs with 5 criteria (total investment cost: CI_{tot}, investment costs for each phase: CI_1, CI_2, CI_3 and CI_4); carbon emissions with 4 criteria (carbon emissions for each phase: CE_1, CE_2, CE_3 and

CE_4); pressure deficits with 3 criteria (pressure deficits for phases PD_2, PD_3 and PD_4), and undelivered demand, also with 3 criteria (undelivered demand for phases UD_2, UD_3 and UD_4). To compute the values of these criteria, each network design alternative (NDA) is simulated using all the 28 demand scenarios and the results are shown in Table 2.

Table 2: Evaluation criteria for the 28 network design alternatives (NDAs)

NDA	Investment costs $x10^6$ (USD)					Carbon emissions $x10^4$ (Tonnes CO_2)				Pressure deficits $x10^3$ (m)			Undelivered demand $x10^4$ (m^3/h)		
	CI_{tot}	CI_1	CI_2	CI_3	CI_4	CE_1	CE_2	CE_3	CE_4	PD_2	PD_3	PD_4	UD_2	UD_3	UD_4
1	7.35	6.97	0.14	-	0.24	6.02	0.28	-	4.02	-	0.87	0.06	-	1.11	0.09
2	7.61	7.12	0.15	0.09	0.24	6.12	0.30	0.45	3.83	-	0.36	0.01	-	0.49	0.02
3	7.50	7.14	0.14	0.21	0.00	6.11	0.28	1.69	0.04	-	0.02	0.93	-	0.02	1.48
4	6.69	6.63	-	0.05	-	5.87	-	0.29	-	3.31	0.67	2.67	3.73	0.92	4.08
5	7.34	6.92	0.14	0.17	0.11	6.01	0.28	1.25	1.90	-	0.20	0.50	-	0.27	0.76
6	7.05	6.90	0.14	-	0.01	6.01	0.28	-	0.20	-	0.89	2.65	-	1.22	4.43
7	6.86	6.60	0.14	0.12	-	5.85	0.28	0.95	-	-	0.27	2.08	-	0.37	3.32
8	**6.81**	**6.67**	**0.14**	**-**	**-**	**5.90**	**0.28**	**-**	**-**	**-**	**0.91**	**3.14**	**-**	**1.21**	**4.84**
9	7.09	6.72	0.14	-	0.22	5.91	0.28	-	3.85	-	0.85	0.25	-	1.15	0.41
10	7.00	6.67	0.14	0.01	0.18	5.89	0.28	0.06	3.30	-	0.81	0.41	-	1.09	0.64
11	7.42	7.26	0.11	0.05	-	6.17	0.41	0.28	-	1.73	0.13	1.51	1.96	0.17	2.44
12	7.24	6.97	0.14	0.12	-	6.03	0.28	1.19	-	-	0.14	1.57	-	0.19	2.50
13	6.88	6.73	0.14	-	-	5.92	0.28	-	-	-	0.98	3.31	-	1.26	5.20
14	7.35	7.05	0.14	0.12	0.03	6.06	0.28	1.04	0.74	-	0.12	1.11	-	0.17	1.84
15	7.34	7.11	0.14	0.09	-	6.11	0.28	0.74	-	-	0.13	1.58	-	0.18	2.56
16	7.09	6.72	0.14	-	0.22	5.91	0.28	-	3.85	-	0.85	0.25	-	1.15	0.41
17	6.83	6.68	0.14	-	0.00	5.89	0.28	-	0.01	-	1.02	3.35	-	1.30	5.25
18	7.92	7.30	0.56	0.05	-	6.19	1.73	0.28	-	1.16	0.01	0.92	1.35	0.01	1.49
19	8.30	7.80	0.15	0.20	0.15	6.41	0.30	1.27	2.42	-	-	0.01	-	-	0.02
20	7.03	6.87	0.14	-	0.03	5.99	0.28	-	0.67	-	0.89	2.32	-	1.27	4.07
21	**6.94**	**6.79**	**0.14**	**0.02**	**-**	**5.96**	**0.28**	**0.17**	**-**	**-**	**0.42**	**2.04**	**-**	**0.55**	**3.06**
22	7.71	7.37	0.29	0.05	-	6.22	0.96	0.28	-	1.36	0.04	1.14	1.57	0.05	1.83
23	7.35	6.97	0.14	-	0.24	6.02	0.28	-	4.02	-	0.87	0.06	-	1.11	0.09
24	6.89	6.61	0.14	-	0.14	5.85	0.28	-	2.78	-	0.79	0.80	-	1.07	1.24
25	6.90	6.61	0.14	0.01	0.14	5.86	0.28	0.06	2.52	-	0.88	0.76	-	1.15	1.21
26	8.38	7.70	0.38	0.12	0.18	6.36	0.74	0.96	2.69	-	-	-	-	-	-
27	6.69	6.68	-	-	0.01	5.90	-	-	0.21	3.95	6.25	4.15	4.37	8.42	6.74
28	6.62	6.62	-	-	-	5.87	-	-	-	3.76	5.95	4.73	4.16	7.83	8.06

The criteria values are organised in Table 2 for each NDA according to the groups of criteria. In this table, NDA 8 and NDA 21 are also highlighted (numbers in bold) as in Fig. 1. From the results, it is possible to conclude that NDAs with high investment cost and carbon emission values (NDAs 2, 18, 19, and 26) have low pressure deficit and low values of undelivered demand. These alternatives were obtained for scenarios with high demand growth (Fig. 1), and therefore, have high hydraulic capacity due to the use of large pipe diameters in the initial phase (t=1) and also by reinforcing the network in future phases to satisfy the constraints. These findings can be observed in NDA 2, for example, which includes initial investment cost of (*USD*) CI_1=7.12x10^6 and future investment costs for parallel pipe reinforcements amounting to (*USD*) CI_2=0.15x10^6, CI_3=0.09x10^6 and CI_4=0.24x10^6. It should be noted that the future investment costs are calculated as the present value computed for the year zero and should not be directly compared with the first phase investment costs. However, the carbon emissions criteria, which are also computed according to the pipe diameters used, make a direct comparison with the planned pipe reinforcements for each alternative possible. For NDA 2, carbon emissions due to pipe construction are CE_1=6.12x10^4, CE_2=0.3x10^4, CE_3=0.45 x10^4 and CE_4=3.83x10^4 (tonnes of CO_2). These values allow us to conclude that in last phase (t=4) the network will require considerable reinforcement. This is because the NDA 2 obtained for scenario 2 envisages a very high increase in demand in the last phase (see Fig. 1). In terms of pressure deficits and undelivered demand criteria, these have low values for NDA 2 thanks to the high hydraulic capacity of this design that can perform well for almost all the scenarios. Table 2 also shows that, as expected, NDAs with low investment costs and low carbon emissions have high pressure deficits and undelivered demand (NDAs 4, 7, 8, 13, 17, 21, 24, 25, 27 and 28). These alternatives were achieved for low or negative demand growth scenarios (Fig. 1).

3.5. Weight sets

For an MCDA analysis, a set of weights has to be established to rank alternatives against criteria. As we are dealing with a phased design, the criteria adopted will have different weights for each time phase. In fact, it is very important for decision makers to know the consequences of their choices regarding the investment schedule and it is important to assess the effect of being focused on short term strategies and paying less attention to future needs. Therefore, we propose the use of three different weight sets (WS) as shown in Table 3. In terms of the groups of criteria, all these WS give preference to investment cost although the analysis can also be applied to the other criteria. In WS1, more preference is given to criteria of the first phases and less preference to the last phase criteria. In WS2, the same importance is given to all time phases' criteria and in WS3 preference is given to the criteria of the last phases.

Table 3: Weight sets of criteria

	Investment costs					Carbon emissions				Pressure deficits			Undelivered demand		
	CI_{tot}	CI_1	CI_2	CI_3	CI_4	CE_1	CE_2	CE_3	CE_4	PD_2	PD_3	PD_4	UD_2	UD_3	UD_4
WS1	0.12	0.20	0.14	0.12	0.06	0.06	0.03	0.02	0.01	0.06	0.04	0.02	0.06	0.04	0.02
WS2	0.12	0.13	0.13	0.13	0.13	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04
WS3	0.12	0.06	0.12	0.14	0.20	0.01	0.02	0.03	0.06	0.02	0.04	0.06	0.02	0.04	0.06

3.6. Ranking alternatives

Visual PROMETHEE [9] is used to rank the alternatives by computing the index (*Phi*), considering the alternatives and criteria values. The results for the three weight sets are shown in Table 4. Considering the rankings provided in Table 4, we can see that alternatives NDAs 4, 8, 17, 21 and 24 are well placed for all the three WSs. It is also possible to verify that alternatives NDAs 2, 18, 19 and 26 are the least preferred alternatives for all the WSs. Some conclusions can be drawn from these results. NDAs 4, 8, 17, 21 and 24 are well placed because they have low values for investment cost criteria and preference is given to the investment costs group. In terms of design, the best positioned NDAs use small diameter pipes installed in the first phase (t=1) and plan for low reinforcements in future phases (this can be seen from the low carbon emission values for these NDAs in Table 2). This is also because these NDAs are obtained for scenarios in which demand is relatively low growth or decreases (Fig. 1). In the opposite situation, the alternatives (NDAs 2, 18, 19 and 26) are in the last rank positions as they use large pipe diameters and plan for strong future reinforcements, thereby increasing the values of the investment cost criteria (Table 2).

Table 4: Alternative design rankings for three weight identified by Visual PROMETHEE [9]

	WS1		WS2		WS3			WS1		WS2		WS3	
Rank	NDA	Phi	NDA	Phi	NDA	Phi	Rank	NDA	Phi	NDA	Phi	NDA	Phi
1	**8**	**0.170**	**21**	**0.155**	**21**	**0.163**	*15*	23	0.051	12	0.014	14	0.015
2	24	0.165	**8**	**0.153**	**8**	**0.139**	*16*	12	0.006	28	0.009	27	0.012
3	17	0.164	17	0.145	4	0.134	*17*	28	0.005	1	0.000	10	-0.011
4	25	0.163	13	0.136	17	0.129	*18*	15	0.001	23	0.000	22	-0.015
5	13	0.151	20	0.128	20	0.128	*19*	27	-0.013	27	-0.001	9	-0.032
6	**21**	**0.147**	6	0.123	6	0.124	*20*	14	-0.026	11	-0.009	16	-0.032
7	20	0.129	25	0.115	13	0.123	*21*	5	-0.030	14	-0.009	3	-0.048
8	10	0.124	24	0.114	11	0.077	*22*	2	-0.092	5	-0.050	1	-0.060
9	6	0.122	4	0.108	15	0.076	*23*	11	-0.098	3	-0.089	23	-0.060
10	9	0.110	7	0.073	25	0.064	*24*	3	-0.121	22	-0.118	5	-0.064
11	16	0.110	10	0.060	7	0.060	*25*	22	-0.217	2	-0.124	18	-0.109
12	7	0.096	9	0.043	24	0.058	*26*	18	-0.298	18	-0.207	2	-0.167
13	4	0.084	16	0.043	12	0.031	*27*	19	-0.428	19	-0.371	19	-0.320
14	1	0.051	15	0.037	28	0.016	*28*	26	-0.527	26	-0.477	26	-0.431

Alternatives 8 and 21 are the best ranked according to Table 4. The designs of these alternatives are given in detail in Fig. 2(a) and Fig 2(b), respectively, in terms of pipe diameter (mm) used in each network link. These figures show that the designs of these alternatives are similar. This is because they are sized for similar demand scenarios (scenarios 8 and 21 of Fig. 1). Moreover, NDA 8 includes a single pipe reinforcement of 1016 mm between nodes 2 and 3 in time phase t=2 (R1016 t=2) and NDA 21 includes one parallel pipe of 1016 mm between nodes 2 and 3 to reinforce the network in t=2 (R1016 t=2) and three more parallel pipes, (between nodes 1 and 2, 8 and 9, and 25 and 32) to reinforce the network in t=3. These reinforcements of NDA 21, associated with the use of higher diameter pipes near the reservoir than are used in NDA 8, gives NDA 21 additional hydraulic capacity to cope with all demand scenarios and thus it has lower values for the pressure deficits and undelivered demand criteria than NDA 8. These differences in design also explain why NDA 8 is preferred for WS1, which has low criteria values in the first phase (t=1) relative to NDA 21. However, if future phase criteria have the same preference or have high preference, as in WS2 and WS3, then NDA 21 is the best ranked alternative. The use of criteria and criteria weights for each phase enables conclusions to be drawn about the rank of the alternatives for the different weight sets. For example, NDA 24 is in the 2nd position for WS1, in the 8th position for WS2 and in the 12th position for WS3. This is because NDA 24 is obtained for a demand scenario that has a relatively low demand growth in all phases except the last one (see Fig. 1). This is expressed in very low investment costs in the first phases and very high investments in the final one (Table 2). This explains why NDA 24 has a low ranking if preference is given to future phases and the investment costs group.

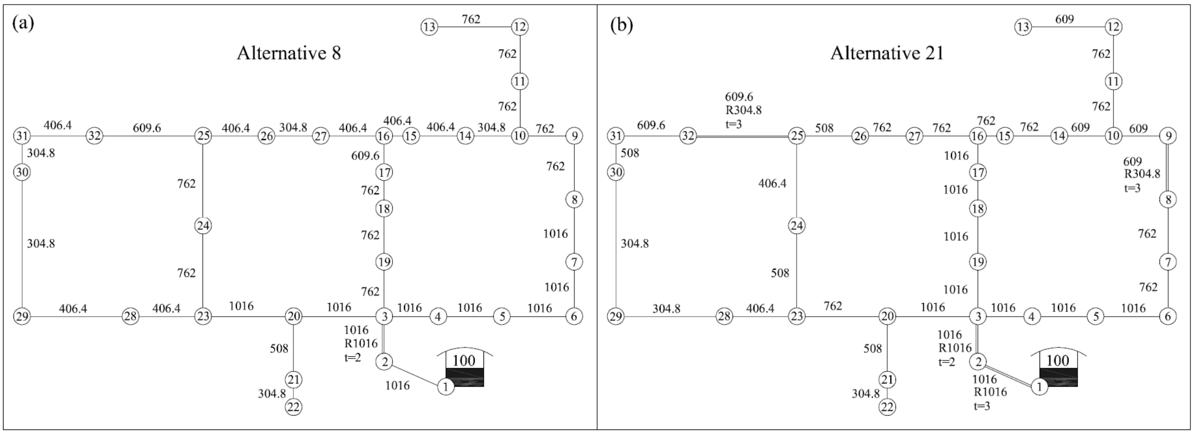

Fig. 2. Network designs of alternative 8(a) and alternative 21(b)

4. Conclusions

This work made use of multi-criteria decision analysis to identify the best ranked alternative network designs of new water distribution networks. These network designs are obtained for different demand scenarios and considering a phased and flexible design scheme that allows reinforcement of the network in future phases if necessary. In this work, the design of a new network for a planning horizon of 100 years was studied and the analysis proposed 28 alternative network designs considering 15 criteria. These alternatives were ranked using the PROMETHEE method for three different weight sets. The best alternatives to implement are identified according to the preferences given to the criteria. The results presented are for those to be implemented at the beginning of the planning horizon (i.e., year zero). After 25 years, the alternatives should be revaluated as new information becomes available. Future work will focus on analysing the results for other weights, giving preference to the groups of criteria that have not been analysed here.

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