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ScienceDirect

Procedia Engineering 119 (2015) 1202 – 1211

Procedia Engineering

www.elsevier.com/locate/procedia

13th Computer Control for Water Industry Conference, CCWI 2015

Flexibility ranking of water distribution system designs under future mechanical and hydraulic uncertainty

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Abstract

Annually a large amount of money should be spent by water authorities to adapt and update water distribution systems (WDSs) to the latest client's needs and variations known as adaptation cost. To prevent or lessen WDSs' adaptation cost it is essential to insert a level of flexibility into WDS layouts from the very beginning in planning or designing stages [1]. This study proposed a simple technique based on multi-criteria decision analysis to rank a set of WDS layouts based on their level of flexibility under future mechanical and hydraulic uncertainty.

Keywords: Water distribution system; felexibility; uncertainity; reliability.

1. Introduction

Engineered service systems such as water distribution systems (WDSs) are mainly built to provide services for a range of clients. However, the nature of client's needs is dynamic and may vary over time (e.g. demand variation over time). Moreover, designed systems gradually get old and older, deteriorate and run into several random component failures. However, without considering these variations, WDSs are traditionally designed for a deterministic and accurately known future water demand and pipe friction [2, 3, 4]. Consequently, annually a large amount of money should be spent by water authorities to adapt and update WDSs to the latest client's needs and variations (adaptation cost). To prevent or lessen the system adaptation costs it is essential to insert a level of flexibility into WDS layouts from the very beginning in all decisions at planning or designing stages [1].

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doi:10.1016/j.proeng.2015.08.975

Now the question is that how to determine which WDS layout is more flexible than the other layouts to handle future uncertainties more easily. To solve this problem, this study introduced a novel technique to rank a set of WDS layouts base on their level of flexibility. Given the future uncertainties, the ultimate objective of this study is to introduce a technique to find the most flexible and broadly reliable layout for a WDS among a set of designs. A flexible design is a long-lasting and reliable layout, which can meet functionality under wide range of future uncertainties and unplanned events. The goal is to expand the novel concept of most mechanical failure-based reliable layout which was initially proposed by Gheisi and Naser [5] to the most flexible design. The chosen system layouts using Gheisi and Naser [5] technique is merely able to handle different states of possible component failure combinations in future (mechanical uncertainty). However, the major source of future uncertainty for a WDS is broader (hydraulic and mechanical uncertainty) and may include demand variations at nodes, variations in pipe roughness and failure of different system components [2, 4, 6, 7, 8, 9, 10].

Surrogate reliability measure of resilience index was chiefly cited in literature as a proper index to handle future hydraulic uncertainty [11, 12, 13, 14, 15, 16, 17]. However, few cases were also reported in literature regarding mechanical uncertainty [12, 14]. Raad et al. [14] and Baños et al. [16] argued about this contradiction and concluded that that the surrogate reliability measure of resilience index cannot be an appropriate index to show how properly a WDS may operate in future under possible mechanical failures. In another study Atkinson et al. [17] found it difficult to optimize the cost of Anytown WDS considering both resilience index and surrogate reliability measure of flow entropy together (increasing one results in decreasing the other). Systems which were optimized solely based on flow entropy were found to be more reliable in mechanical aspects. However optimized systems based on flow entropy were more expensive and also showed a poorer performance in case of any hydraulic or water quality failures.

This research provides water authorities with a useful tool to rank a set of WDS layouts based on their level of flexibility under future mechanical and hydraulic uncertainty. There is always an inverse relationship between level of flexibility and adaptation cost. As the level of flexibility for a WDS increase, the upcoming expenditure to adapt that WDS to future needs and variations decrease. In fact flexibility is an investment for the uncertain future [1, 18]. When the level of flexibility among a set of WDS layouts is determined and systems are ranked based on flexibility the next step is to choose the best WDS with the optimum degree of flexibility. A WDS with optimum flexibility is the layout with the least amount of total cost. Total cost is the summation of changeability and adaptation expenditures. Changeability cost is the amount of money which should be spent by the water authorities to give a specific level of flexibility to a WDS. However, the adaptation cost is the amount of money which should be spent by water authorities in future to adapt the system to the unforeseen needs and variations [1].

2. Methodology

In this study, technique of multi-criteria decision analysis (MCDA) was employed to rank a set of WDS layouts (alternatives) based on their level of flexibility under future mechanical and hydraulic uncertainty. Weighted sum model (WSM) [19], weighted product model (WPM) [20, 21] and technique for order of preference by similarity to ideal solution (TOPSIS) [22] were applied. Resilience index and network resilience index were chosen as the criteria to measure hydraulic flexibility. Zeroth and first state of reliability measures lower state of mechanical flexibility and flow entropy was applied as a representative of higher state of mechanical flexibility. Hence, a comprehensive flexibility ranking technique considering both mechanical and hydraulic aspects was formed and weights were also assigned to each criterion.

MCDA takes the advantage of assigning weight to each criterion to compute an overall score for each alternative (WDS layout). Weights represent the importance and percentage contribution of each criterion in final score. Sorting the alternatives (WDS layouts) based on their final score can easily result in flexibility ranking. Combinative weighting approach proposed by Jahan et al. [23] was employed in this study. It combines the subjective, objective and independency weights to estimate an overall weight using normalized geometric mean of weights.

Subjective weights can easily be determined based on the engineering judgment or expertise of the decision maker using the available history about any type of hydraulic or mechanical failures in a WDS. In hydraulic aspect any information about domain of demand variation or pipe roughness changes in future could be useful.

However, objective weights depend on the variation of flexibility results for WDS layouts. Objective weights show which criterion to measure flexibility should have more contribution in final decision based on the variation of flexibility results. The criterion under which flexibility results vary more over changing the layouts should receive more objective weight and contribute more in final decision. This research applied the concept of information entropy of Shannon [24] to find the amount of scattering and variation in flexibility results under a specific criterion. Accordingly the objective weights were estimated as the ratio of scattering in flexibility results for each criterion to the total scattering under all applied criteria in MCDA [22].

Independency weight is the third applied weight in the combinative weighting approach proposed by Jahan et al. [23]. The independency weight can be applied to lessen the correlation among applied criteria in MCDA [23]. The criterion which has the largest correlation and is highly correlated with the other criteria in MCDA receive less independency weight.

2.1. Resilience Index

The total input power into a WDS should be enough to overcome system's major and minor energy losses and provide consumers with adequate amount of water with sufficient pressure. Any sudden hydraulic changes in a WDS such as fire flow may result in a dramatic increase of energy losses in vicinity of the affected region. A WDS which has some surplus power at demand nodes in addition to the minimum required power is hydraulically more flexible and can handle the unexpected hydraulic variations more easily [11]. With the aim of quantifying the available surplus power in a WDS, Todini [11] presented the novel concept of resilience index. The ratio of the surplus hydraulic power at demand nodes to the hydraulic power required to meet the consumers' demands is defined as the resilience index [11, 12, 13, 25, 26]. Resilience index is mainly cited in literature to be correlated with the hydraulic flexibility and functionality of a WDS under hydraulic uncertainties [11, 12, 13, 14, 15, 16, 17].

Resilience index (RI) can be estimated as follows [11]:

$$RI = \frac{\sum_{i=1}^{n_n} Q_i^{req}(H_i - H_i^{req})}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} \frac{P_j}{\gamma} - \sum_{i=1}^{n_n} Q_i^{req} H_i^{req}} \tag{1}$$

where RI is resilience index (unitless); P_j is the power of the pump j ($N.m/s$); Q_i^{req} is the required water or demand at node i (m^3/s); Q_k is the discharge of water provided by reservoir k (m^3/s); H^i_{req} is the minimum required water pressure head at node i to satisfy consumers' demand (m); H_i is water pressure head at node i (m); H_k is pressure head of water at reservoir k (m); γ is the specific weight of water (N/m^3); n_r, n_p and n_n are the number of reservoirs, pumps and demand nodes, respectively.

2.2. Network Resilience Index

Considering mechanical uncertainty, Todini's resilience index suffer from lack of a term to incorporate the degree of redundancy. A branched WDS with high surplus power at demand nodes (high resilience index) cannot properly handle mechanical uncertainty. Although the excess powers in demand nodes are high but in case of pipe failure many consumers particularly those located at the end of branches may not receive water due to lack of redundancy in the system [25]. To address this problem and find the reliable loops, Prasad and Park [25] added a term of "pipe diameter uniformity" to Todini's resilience index. The aforementioned uniformity coefficient measures the degree of diameter consistency among a set of pipes ending at one node. Ratio of the average pipes diameter connected to one node to the maximum diameter reaching that node defines pipe diameter uniformity. Higher pipe uniformity and less variation in diameter of pipes can increase the chance of higher redundancy and existence of more reliable loops in a WDS [25].

The network resilience can be estimated using the following equation [25]:

$$NR = \frac{\sum_{i=1}^{n_n} U_i Q_i^{req}(H_i - H_i^{req})}{\sum_{k=1}^{n_r} Q_k H_k + \sum_{j=1}^{n_p} \frac{P_j}{\gamma} - \sum_{i=1}^{n_n} Q_i^{req} H_i^{req}} \quad (2)$$

where NR stands for network resilience (unitless) and U_i stands for the uniformity index for node i.

2.3. Zeroth and higher states of reliability

This study applied the technique proposed by Gheisi and Naser [5, 27, 28, 29, 30] to determine the reliability of a WDS under different state of pipe failures. It measures reliability as a probability-weighted average of performance indices of the WDS. Assigned weight to each performance index was defined as the probability of occurrence of a specific combination of pipe failure. Probability of occurrence was obtained using the concept of components availability.

This technique has several advantages and was employed several times in the literature to estimate lower state of reliability [31, 32, 33, 34, 35]. Zeroth state reliability, R^0, of a WDS can be obtained as follows [27, 5]:

$$R^0 = PI(0)\cdot P(0) + \sum_{a=1}^{N} PI(a_1)\cdot P(a_1) + \frac{1}{2}\left(1 - P(0) + \sum_{a=1}^{N} P(a_1)\right) \quad (3)$$

Where, N represents the total number of pipes in the WDS. $PI(0)$, $PI(a_1)$ are the performance indices of the WDS when zero and one pipe was failed in the WDS. In this study performance of the WDS was evaluated using water utility index of supply ratio or the supplied fraction of required water. It can be obtained by dividing the amount of water delivered to consumers during an operational or failure condition to the minimum quantity that consumers require.

Weighting coefficients of $P(0)$, and $P(a_1)$ are the probability of failure in the WDS with zero, and one pipe failure, respectively. In this study the concept of availability (A) and unavailability (U) of the pipe i (A_i and $U_i = 1 - A_i$) was employed to determine the probability of failure for different pipe combinations [36, 37]:

$$P(0) = \prod_{i=1}^{N} A_i \quad , \quad P(a_1) = P(0)\cdot\frac{U_{a_1}}{A_{a_1}} \quad (4)$$

where A_{a_1}, A_{a_2},… and U_{a_1}, U_{a_2} represents the availability and unavailability of the pipes a_1, a_2, and "Π" is the product operator and "i" is the pipe number. Following Cullinane et al. [38] this study employed equation 5 to estimate the availability of pipe i with the diameter D_i (in meter):

$$A_i = \frac{45.60858\, D_i^{1.462131}}{0.00211\, D_i^{0.285} + 45.60858\, D_i^{1.462131}} \qquad i = 1, 2, \ldots, N \quad (5)$$

Cullinane et al. [38] indicated that a pipe can be in operation or failure condition. In another word a pipe can be in a time between two sequential failures or in the time required to repair or pipe replacement. Pipe availability was defined as the ratio of the time when the pipe is in operation or it is between two sequential failures to the pipe lifetime. Pipe lifetime comprises the time between two sequential failures and the time required to repair or replacement.

Gheisi and Naser [28] derived the governing equations for higher states of reliability analysis. Following Tanyimboh et al. [33], Kalungi and Tanyimboh [34] and Gheisi and Naser [28] equation (6) and (7) can be used to determine the first (R^1) and k^{th} state of reliability (R^k), respectively. First and k^{th} state of reliability represents the reliability of the WDS when there is at least one and k (≥ 2) number of simultaneous pipe failures in the whole WDS.

$$R^1 = \frac{R^0 - P(0) \cdot PI(0)}{1 - P(0)} \tag{6}$$

$$R^k = \frac{\sum_{j=k}^{F} \left[\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} PI(a_1,\ldots,a_j) \cdot P(a_1,\ldots,a_j) \right]}{1 - P(0) - \sum_{j=1}^{k-1} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} P(a_1,\ldots,a_j) \right)} + \frac{1}{2} - \left[\frac{\sum_{j=k}^{F} \left[\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} PI(a_1,\ldots,a_j) \right]}{2 \left(1 - P(0) - \sum_{j=1}^{k-1} \left(\sum_{a_1=1}^{N-j+1} \sum_{a_2=a_1+1}^{N-j+2} \cdots \sum_{a_j=a_{j-1}+1}^{N} P(a_1,\ldots,a_j) \right) \right)} \right] \tag{7}$$

where F ($\geq k$) is the number of pipe failure combinations incorporated in higher states of reliability analysis. $PI(a_1,\ldots, a_j)$ is the performance index of WDS when j number of pipes are unavailable at the same time in the system.

2.4. Flow entropy

Gheisi and Naser [5] showed that the statistical flow entropy is a proper surrogate measure for higher states of reliability analysis. Therefore this study employed flow entropy as the representative of higher states of reliability in MCDA. Using the discharge and direction of flow in pipes, the amount of flow entropy (S) for a single-source WDS can be obtained as follows [39]:

$$\frac{S}{K} = -\sum_{j \in I} \left(\frac{Q_j}{T}\right) \ln \left(\frac{Q_j}{T}\right) - \frac{1}{T} \sum_{j=1}^{J} T_j \left[\left(\frac{Q_j}{T_j}\right) \ln \left(\frac{Q_j}{T_j}\right) + \sum_{i \in N_j} \left(\frac{q_{ij}}{T_j}\right) \ln \left(\frac{q_{ij}}{T_j}\right) \right] \tag{8}$$

where K is a constant number generally chosen to be 1 [40]; T is the supplied water by source (m^3/s); T_j represents total inflow and incoming discharge to node j (m^3/s); Q_j represents the amount of demanded or supplied water at node j (m^3/s); q_{ij} is the discharge (m^3/s) in pipe ij; I is for the source nodes; J is for the demand nodes and their number; and N_j refers to upstream nodes immediately linked to node j.

3. Test Case

Following the literature [40, 41, 42, 5] this research tested the hypothetical WDS in Fig. 1 with a set of 22 different layouts (alternatives) of in Fig. 2. Elevation of all the demand nodes is 0 m. The pipes are 1 km long with a Hazen-Williams coefficient of 130. Table 1 shows the diameter of the pipes for each layout. The pressure head at source node 1 is 100 m. Minimum required residual head at each node is 30 m. Failure of a pipe may cause a sudden pressure drop in the WDS. The original version of EPANET2 [43] is unable to study with the pressure deficient condition when the residual pressure head at nodes is not enough to fully satisfy the demands. Therefore, this study applied the modified version of EPANET2 known as EPANET-Emitter [44] to perform the hydraulic simulations in pressure-deficient conditions.

Table 1. Diameter of pipes for the case study (data derived from Tanyimboh and Templeman [40]).

	Diameter for the pipes connecting the following nodes (mm)																
Design #	**1-2**	**1-4**	**2-3**	**2-5**	**4-5**	**4-7**	**3-6**	**5-6**	**5-8**	**7-8**	**7-10**	**6-9**	**8-9**	**8-11**	**10-11**	**9-12**	**11-12**
1	348	310	266	226		289	238		189	186	185	213		202	143	105	177
2	284	368	268		225	286	240		188	184	184	215		200	143	105	176
3	328	335	275	169	174	272	248		189	174	259	225			229	143	151
4	326	336	265	185	186	270	237		221	161	177	212		213	130	100	180
5	298	360	223	191	190	298	184		229	166	219	139	227		191	182	100
6	310	354	206	227	226	265	160	209	209	157	172	231		200	123	139	157
7	294	365	194	214	212	291	141	181	206	154	216	190	194		188	185	100
8	302	361	192	228	226	275	138	175	239	179	169	182	178	184	119	162	135
9	325	337	227	231	232	234	190		293		185	149	194	178	139	149	147
10	353	307	225	273		286	187	181	178	182	184	227		190	142	135	159
11	315	345	231	210	210	265	195		260		226	156	211		198	175	109
12	350	309	275	214		289	249		165	200	257	226			227	145	147
13	307	355	221	208	206	282	182		255	188	172	137	204	189	124	150	147
14	318	346	197	246	247	233	146	182	270		184	197	160	170	139	162	133
15	345	319	205	276		299	159	153	207	210	177	179	178	177	133	158	137
16	231	404	210		275	295	162	152	206	206	176	181	176	175	133	158	137
17	361	314	266	245	251	162	238		315	276	276	214			248	113	180
18	405	236	267	308		208	240		283	238	269	217			241	124	170
19	251	390	232		302	244	193	182	223		199	233		163	163	146	148
20	375	274	227	302		249	189	183	223		204	230		162	166	145	149
21	323	336	227	227		318	190	190		226	195	235		164	159	148	147
22	250	390	231		225	315	192	189		224	194	236		163	159	148	147

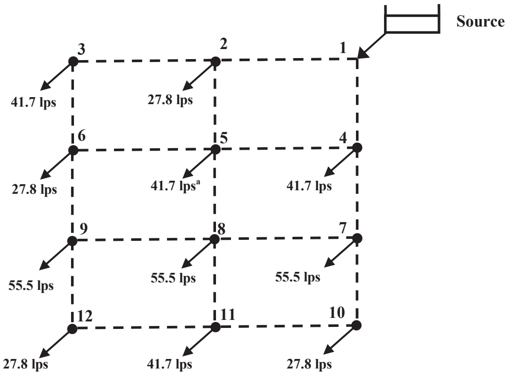

Fig. 1. A schematic view of the hypothetical WDS [40].

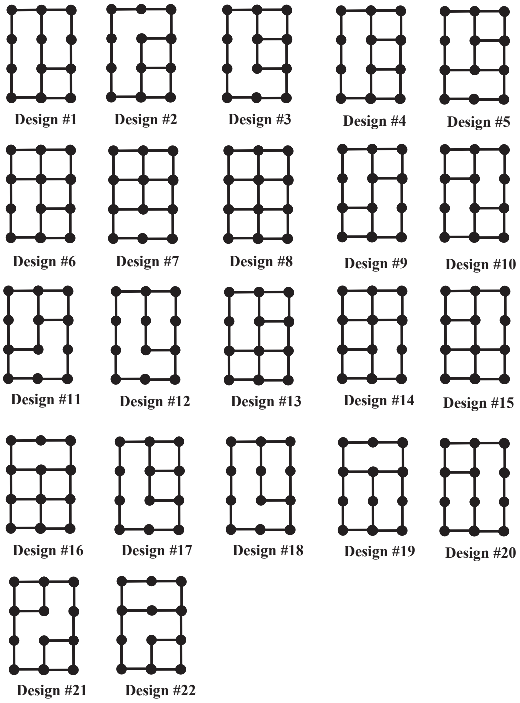

Fig. 2. Designs #1 to #22 for the hypothetical WDS [40].

4. Results and Discussion

Table 2 demonstrates the independency, objective and overall weights computed and assigned to each criterion. Results of independency analysis revealed that applied criteria were not highly correlated with each other. However, the applied criterion of network resilience index was the most independent one and zeroth state of reliability showed relatively more dependency and correlation with the other applied criteria in this study. Objective weight analysis based on the concept of entropy revealed that the applied criteria of flow entropy and network resilience index showed the highest amount of variation and scattering in flexibility results and should receive higher objective weights. However, criteria of resilience index, first and zeroth state of reliability should receive lower objective weights due to their less dispersion in their flexibility results, respectively. Subjective weights were not assigned due to lack of information about type and number of possible hydraulic and mechanical failures which my happen in practice.

Combining all the assigned weights, Table 2 also demonstrates the overall estimated weights. It can be seen that higher overall weights were assigned to the criteria of flow entropy and network resilience index. This implies that the higher combination of pipe failures and also existence of more surplus power in a WDS along with the uniformity of pipes should receive more attention in decision making process regarding flexibility analysis of WDSs. This is an important finding since researchers often consider lower combination of pipe failures and they believe that the chance of failure of more than one pipe at a time in a WDS is very little [38, 45]. Finally using the overall weights and three MCDA methods of weighted sum model (WSM), weighted product model (WPM) and technique for order of preference by similarity to ideal solution (TOPSIS), the WDS layouts of the test case were all ranked based on their flexibility. Table 3 shows three flexibility ranking results under future hydraulic and mechanical uncertainty. The three flexibility ranking results are relatively similar and more comprehensive comparing to other techniques. The novel flexibility ranking technique introduced in this study considers five mechanical and hydraulic flexibility criteria of zeroth state of reliability, first state of reliability, flow entropy, resilience index and network resilience index at the same time.

Table. 2. Assigned weight to each criterion.

	0th Reliability	1st Reliability	Flow entropy	Resilience index	Network resilience index
Independency Weights	0.149597621	0.175186449	0.187489647	0.211799269	0.275927015
Objective Weights	2.56613E-07	0.072518602	0.513978067	0.102717748	0.310785327
Overall Weights	0.000226857	0.130504575	0.359427836	0.170779502	0.33906123

Table. 3. Reliability ranking of distribution systems' layouts based on three MCDA techniques.

Design Number	Rank # (WSM)	Rank # (WPM)	Rank # (TOPSIS)
1	17	17	18
2	22	22	22
3	8	8	10
4	19	19	15
5	15	15	14
6	4	3	2
7	10	10	8
8	1	1	1
9	11	11	11
10	13	12	13
11	14	14	16
12	3	7	9
13	9	9	6
14	5	4	3
15	2	2	4
16	6	5	7
17	7	6	5
18	12	13	12
19	18	18	19
20	21	21	21
21	16	16	17
22	20	20	20

5. Conclusions

In this study, the technique of multi-criteria decision analysis approach was employed to conduct a comprehensive flexibility ranking for a set of water distribution layouts (alternatives) considering five flexibility criteria. Accordingly, mechanical and hydraulic flexibility criteria of zeroth state of reliability, first state of reliability, flow entropy, resilience index and network resilience index were applied in decision making at the same time. Both independency and objective weights of attributes were applied reflecting the relative importance of each flexibility criterion in decision making process. Results of weighting assignment to attributes show that the higher overall weights were assigned to the criteria of flow entropy and network resilience index. This implies that the higher combination of pipe failures and also existence of more surplus power in a WDS along with the uniformity of pipes should receive more attention in decision making process regarding flexibility analysis of WDSs. Researchers have mainly considered one pipe failure at a time when assessing WDS reliability as they believe that the chance of failure of more than one pipe at a time in the system is very little. The methodology introduced in this study using MCDA approach and considering various flexibility criteria instead of just considering a single criterion can be applied as a more comprehensive approach for flexibility assessment of water distribution systems.

Acknowledgments

The authors wish to thank the Natural Sciences and Engineering Research Council (NSERC) of Canada, the Okanagan Basin Water Board (Kelowna, Canada) and the University of British Columbia (Canada) for their financial support. The authors would also appreciate Kerr Wood Leidal (Vernon, Canada) for their support.

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