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EFFICACY OF SURROGATE MEASURES IN PERFORMANCE-BASED DESIGN OF WATER DISTRIBUTION NETWORKS

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Abstract: *Reliability-based design of water distribution networks (WDN) has been of significant interest to researchers and practitioners in the recent past. The evaluation of network reliability under various possible uncertainties is highly computationally-intensive, and hence some surrogate performance measures are often used in the design optimization process with a view to reduce the computational burden, but at the same time providing a common base for comparative evaluation of various design alternatives. The resilience index of Todini (2000) is one of the popular surrogate performance measures, and is indicative of the surplus internal power in the network. Jayaram and Srinivasan (2008) recently showed that the resilience index, however, does not accurately reflect the ability of the network to handle uncertainties in case of networks with multiple sources, and they proposed a modification to the same and termed it "Modified Resilience Index", which can be used in networks with single or multiple sources. The current research work uses an illustrative multi-source WDN to investigate the efficacy of these two surrogate performance measures in the design of water distribution networks along with two other surrogate measures termed network resilience and modified network resilience. This is done by designing the multi-source WDN with the objectives of minimizing cost and maximizing performance, and comparing the efficacy of the pareto-optimal network designs with the reliability obtained by actually investigating the performance of the network designs under demand, hydraulic and mechanical uncertainties using Monte-Carlo simulation.*

Keywords: *WDN; resilience index; modified resilience index; network resilience; modified network resilience; surrogate measures; Monte-Carlo simulation.*

INTRODUCTION

The traditional least cost design of the water distribution network (Alperovits and Shamir, 1977; Savic and Walters, 1997) is known to produce netwoks that work well in normal conditions but are highly susceptible to failure during abnormal conditions that could result from several types of uncertainties such as hydraulic (pipe roughness conditions), demand (nodal demands) and mechanical (pipe breaks) uncertainties (Goulter et al., 1999, Bhave, 2003). A more realistic goal is to design a WDN with the least possible cost, while ensuring a desirable level of performance of the network. Reliability is the indicator most often used to describe the performance of any engineered system. Reliability is typically construed as the ability of the network to provide adequate supply to the customers under both normal and abnormal conditions (Xu and Goulter, 1999).

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Ideally, the reliability of a WDN is computed using Monte-Carlo simulation (MCS) where in the network performance is evaluated under a large number of simulated scenarios resulting from hydraulic, demand and mechanical uncertainties. This approach, however, is computationally intensive, particularly while designing or rehabilitating large WDN's. Therefore, a commonly-used approach is to employ approximate measures of network reliability that are reflective of the ideal MCS-based reliability. These approximate measures are known as surrogate reliability measures. Typical examples are the minimum surplus nodal head in the network, the surplus power in the network and the resilience index (Todini, 2000). The resilience index proposed by Todini (2000) is one of the popular surrogate performance measures, and is defined as the ratio of the surplus internal power in the network to the maximum power that could be dissipated internally, while still satisfying the constraints on nodal demands and nodal heads. Todini (2000) stated that providing higher surplus heads and power at the nodes may help the network sustain its performance even under abnormal conditions on account of the additional energy that is available for dissipation in such cases. Jayaram and Srinivasan (2008) have recently shown that the resilience index sometimes does not accurately reflect the ability of a WDN to handle uncertainties in case of networks with multiple sources. They have also modified the resilience index to obtain a surrogate performance measure termed 'modified resilience index', which can be used in networks with single or multiple sources. The modified resilience index is directly proportional to the surplus power at the demand nodes and is normalized by the minimum required output power.

Another reliability based surrogate measure is the network resilience, proposed by Prasad and Park (2004), which adds an additional dimension to the resilience index of Todini (2000) by way of reliable loops to reflect the effects of redundancy of the network. This improved surrogate performance measure is expected to provide more robust designs than Todini's resilience index especially in terms of handling critical conditions arising out of pipe failures. This measure also uses the maximum surplus power in the denominator (just as the Todini's measure), and hence suffers from the same drawback as that of Todini's in not being able to accurately reflect the ability of the WDN to handle uncertainties when multiple sources are present. Recently, Raad et al. (2010) have comparatively evaluated the performance of three of the reliability surrogate measures used in water distribution systems design, namely, flow entropy, resilience index, and network resilience, and a mixed surrogate measure introduced by them, under stochastic demand variations and pipe failure conditions. They have found the network resilience and their mixed surrogate measure to be more competent than the other two measures based on a few benchmark networks.

In this paper, a modified form of network resilience is proposed and is referred to as "modified network resilience" (MNR). This measure incorporates the same modification as done by Jayaram and Srinivasan (2008) to the network resilience of Prasad and Park (2004) in order to make it usable for WDN's with multiple sources. The current research work also presents a comparative evaluation of the efficacy of the four surrogate performance measures, resilience index (RI), modified resilience index (MRI), network resilience (NR) and modified network resilience (MNR) in the context of performance (reliability) based design of WDN's, using an illustrative two-source network. The Monte-Carlo simulation based reliability is employed as the benchmark for the evaluation.

SURROGATE MEASURES OF PERFORMANCE

The resilience index (RI) introduced by Todini (2000) is the ratio of the surplus internal power in the network to the maximum power that can be dissipated internally, after satisfying the constraints on nodal demands and nodal heads, and is given as:

$$RI = 1 - \frac{P_{\text{int}}}{P_{\text{int,max}}} \tag{1}$$

where P_{int} is the amount of power dissipated internally in the network in order to satisfy the nodal demands and $P_{\text{int,max}}$ is the maximum power that could be dissipated internally in order to satisfy the constraints in terms of the nodal demands and the nodal heads. Using appropriate expressions for P_{int} and $P_{\text{int,max}}$, it can be shown that, for networks without pumps, *RI* takes the following form:

$$RI = \frac{\sum_{j=1}^{nn} Q_j^{req}(H_j - H_{min,j})}{\sum_{r=1}^{nr} Q_r H_r - \sum_{j=1}^{nn} Q_j^{req} H_{min,j}} \tag{2}$$

where Q_j^{req} is the demand at node *j*; H_j is the head at node *j*; $H_{min,j}$ is the minimum required head at node *j* at which the nodal demands are to be supplied, *nn* is the number of nodes, Q_r is the discharge delivered by the reservoir *r* and H_r is the head at the reservoir *r* and *nr* is the number of reservoirs (sources) feeding the network.

Jayaram and Srinivasan (2008) argued that the resilience index may not be directly proportional to the total surplus power in the demand nodes (which is $\sum_{j=1}^{nn} Q_j^{req}(H_j - H_{\min,j})$), in the case of networks with multiple sources although such an assumption is valid for networks with a single reservoir ($r = 1$). This is because, in case of single source networks, the flow output from the source (Q_r) and hence, the term $\sum_{r=1}^{nr} Q_r H_r$, are independent of the pipe diameters and pipe roughness values, which is not true in the case of networks with multiple sources. For instance, in a network with multiple sources, when the diameter of a pipe connected to a reservoir that operates at a higher hydraulic grade line value (as compared to the other reservoirs) is increased, it is likely that a larger portion of the total demand would be served by this reservoir than before. This would result in an increase in the $\sum_{r=1}^{nr} Q_r H_r$ value in addition to the possible increase in the value of $\sum_{j=1}^{nn} Q_j^{req}(H_j - H_{\min,j})$. This may result in a low value of resilience index despite a high value of surplus power at the demand nodes. A more detailed discussion on this can be found in Jayaram and Srinivasan (2008).

The modified resilience index (MRI) proposed by Jayaram and Srinivasan (2008), on the other hand, is based on the premise that the intent of a designer is to provide additional power at the demand nodes than what is normally required in order to handle uncertainties. Therefore, the measure is directly defined as the amount of surplus power available at the demand nodes as a percentage of the sum of the minimum required power at the demand nodes.

$$MRI = \frac{\sum_{j=1}^{nn} Q_j^{req} (H_j - H_{\min, j})}{\sum_{j=1}^{nn} Q_j^{req} H_{\min, j}} \times 100 \tag{3}$$

It can be seen from the above equation that the value of the modified resilience index is directly proportional to the total surplus power at the demand nodes. The term $\sum_{j=1}^{nn} Q_j^{req} H_{\min,j}$ is used in the denominator to non-dimensionalize the value of the surplus power at the demand nodes. (The above definition can be extended for use in networks with pumps and tanks as well.)

Network Resilience (*NR*) proposed by Prasad and Park (2004) incorporates the effects of surplus power and reliable loops simultaneously. A loop is considered reliable if the pipes incident at a node have nearly the same diameter. If 'n_j' denotes the number of pipes incident at node 'j' and the diameters of these pipes are $D_1, D_2, \ldots, Dn_j$, then, the uniformity of that node 'j' is given by

$$U_j = \frac{\sum_{k=1}^{n_j} D_k}{\left(n_j \times Max\{D_1, D_2, \ldots, D_n\}\right)} \tag{4}$$

In Equation 4 the value of U_j equals one, if all the pipes incident at node 'j' have the same diameter. The surplus power given by the numerator in Equation 2 is weighted by the uniformity U_j and normalized with respect to the maximum surplus power (denominator in Equation 2) to obtain the network resilience of Prasad and Park (2004). In other words,

$$NR = \frac{\sum_{j=1}^{nn} U_j . Q_j^{req} \left(H_j - H_{\min, j}\right)}{\sum_{r=1}^{nr} Q_r H_r - \sum_{j=1}^{nn} Q_j^{req} H_{\min, j}} \tag{5}$$

The surrogate measure proposed in this paper a modification to the network resilience to make it appropriate for networks with multiple sources. This modification is on the same lines as done to the resilience index by Jayaram and Srinivasan (2008). The modified network resilience (*MNR*) is expressed as follows:

$$MNR = \frac{\sum_{j=1}^{nn} U_j . Q_j^{req} (H_j - H_{\min,j})}{\sum_{j=1}^{nn} Q_j^{req} H_{\min,j}} \tag{6}$$

EVALUATION OF THE EFFICACY OF THE SURROGATE PERFORMANE MEASURES

As discussed earlier, surrogate reliability measures are often used in place of the MCS-based reliability measure for performance-based design of WDN's in order to achieve substantial savings in computational burden. While it is generally assumed that the network designs so obtained will perform well under demand, hydraulic and mechanical uncertainties, this assumption has not been subjected to much of detailed testing. This section discusses the design of an illustrative multi-source WDN with the objectives of minimizing cost and maximizing performance, where the performance is computed using the four surrogate measures discussed. The actual performances of the chosen designs are then evaluated under possible uncertain conditions, using a MCS designed for the same. The results of the comparative evaluation with the MCS are used to understand the relative efficacy of the four surrogate reliability measures considered.

Design problem formulation

The objective of the design problem is to determine the optimal pipe diameters required for the WDN shown in Figure 1. This is done using a performance-based design framework, where the diameters are estimated by solving the following optimization problem:

Determine D_j for $j \in \{1, np]$ with the two objectives being

$$\text{Minimize } C = \sum_{j=1}^{np} UC(D_j) L_j \tag{7a}$$

Maximize surrogate reliability measure: RI or MRI or NR or MNR (7b)

where D_j refers to the diameter of pipe j, np denotes the total number of pipes, C denotes the design cost, L_j is the length of pipe j, $UC(D_j)$ is the unit cost of a pipe with diameter D_j. The set of available pipe diameters and the corresponding unit costs are presented in Table 3. This is a dual-objective optimization problem that aims to determine pipe diameters so as to minimize the design cost while maximizing a chosen surrogate reliability measure. This problem has multiple feasible pareto-optimal solutions (designs) in the design cost – surrogate reliability measure plane.

WDN considered in this study

In this study, it is intended to optimally design an illustrative network whose topology is provided by Larock et al. (1999) (Figure 1). The network consists of 11 nodes, where the nodes 10 and 11 refer to the source nodes with fixed hydraulic grade line (HGL) elevations of 792.48 m and 762 m respectively, while the remaining nodes (nodes 1 to 9) are demand nodes. The minimum HGL elevation requirement at each demand node is assumed to be 15 m more than the nodal elevation. The values of the mean daily demands at the nodes along with the nodal elevations are given in Table 1. There are 14 links in the network, the lengths and the mean pipe roughness (measured in terms of the Hazen-Williams coefficient) of which are given in Table 2.

Solution technique – NSGA II

A popular solution technique used for solving such multi-objective problems is the genetic algorithm. In this study, we use the multi-objective evolutionary algorithm "Fast Elitist Non-Dominated Sorting Genetic Algorithm-II (NSGA-II)" of Deb et al. (2002) to generate the trade-off curve between the two objectives listed in Equations 7a and 7b. The algorithm proceeds by starting out with randomly chosen network designs (i.e., randomly chosen pipe diameters from the available set of pipe diameters), and generates improved designs from these starting designs using operations such as selection, cross-over and mutation. The quality of each design is measured using 'fitness functions', which are based on the values taken by each objective function. Evaluating the objective functions requires the use of a hydraulic network solver, and

EPANET2 (Rossman, 2000) is used in this study. The final output from the NSGA-II is a set of non-dominated design alternatives, which consists of designs that correspond to the best achievable tradeoff between cost and surrogate reliability. The complete description of this algorithm can be found in Deb et al. (2002).

Optimal WDN designs and evaluation

The performance-based optimal design problem described in Section 3.2 issolved using NSGA-II, for each of the four surrogate reliability measures, namely, resilience index (RI), modified resilience index (MRI), network resilience (NR) and resilience index (RI). In order to assess whether these designs actually perform well under uncertain conditions, the performance of each design alternative is explicitly evaluated under demand, hydraulic and mechanical uncertainties using a Monte Carlo-simulation (MCS). This evaluation procedure is described in the following paragraph.

Several hydraulic, demand and mechanical scenarios are simulated using pre-defined hypothetical probability density functions for these uncertain variables, and the network performance is evaluated under each uncertainty scenario. Demand uncertainty refers to the uncertainty in the nodal demands. It is assumed that the nodal demands at each node in the network follows a univariate normal distribution with the mean specified in Table 1 with a coefficient of variation of 0.2. The demands at any two different nodes are assumed to be statistically independent. Hydraulic uncertainty refers to the uncertainty in the pipe roughness coefficient (measured in terms of the Hazen-Williams coefficient), which determines the head drop associated with the flow in the pipe.The roughness coefficients of the pipes are assumed to be statistically independent of each other, and individually follow a univariate normal distribution with the mean specified in Table 2 and a coefficient of variation of 0.2. These assumptions are in line with those made in past research works such as that of Kapelan et al. (2005). Mechanical uncertainty refers to the possibility of pipe breaks. We model the occurrence of pipe break as a Poisson random variable based on Bouchart et al. (1989). Based on this assumption, the probability of a pipe break is expressed as follows.

$$P_j = 1 - \exp\left(-r(D_j)L_j\right) \tag{8}$$

where P_j denotes the probability of pipe break and $r(D_j)$ is the expected number of pipe breaks per year per unit pipe length for a pipe of diameter D_j (Table 3) and L_j is the length of pipe j. The probability density functions described above are used to simulate sufficient demand, hydraulic and mechanical scenarios. The performance of each design alternative obtained using NSGA-II is evaluated under the 500 uncertainty scenarios and summarized using the probability that all the nodal heads exceed the minimum required heads under these simulated scenarios. This probability is referred to as MCS-based reliability or network capacity reliability (NCR) using the terminology of Tolson et al. (2004).

The value of NCR is computed as follows:

$$NCR = \frac{1}{n}\sum_{i=1}^{n} X(Q_i, C_i, P_i) \tag{9}$$

where n (=500) is the number of simulated scenarios, Q_i denotes the set of nodal demands simulated in scenario i, C_i denotes the set of pipe roughness coefficients simulated in scenario i, P denotes the set of pipe availabilities (available/ broken) simulated in scenario i, $X(Q_i, C_i, P_i)$ is an indicator variable which equals 1 if all the nodal heads exceeded the minimum required head in scenario *i* and 0 otherwise.

RESULTS AND DISCUSSION

Figure 2 shows the plot of NCR of each design alternative obtained by solving the design formulation described in Section 3.2 using the surrogate reliability measures. Only non-dominated designs (i.e., solutions with the least cost for a given NCR value) are obtained and the designs with a NCR above 0.7 (for practical relevance) are shown in the plot. Also, for comparison, the tradeoff curve between cost and NCR obtained by solving the optimization formulation in Section 3.2 by minimizing cost and by directly maximizing NCR (instead of one of the surrogate reliability measures specified in Equation 7b is shown in Figure 2. This particular tradeoff curve obtained directly using NCR is the benchmark tradeoff curve, but is highly computationally-intensive to estimate. The effectiveness of the surrogate measure in representing the NCR is assessed by comparing the tradeoff curve obtained for the surrogate measure with that obtained using NCR.

The following observations can be made from Figure 2. There is a significant difference between the NCR-Cost tradeoffs obtained using NCR directly and any of the four Surrogate measures. The non-dominated solutions obtained by optimizing using MNR results in designs with larger NCR values than those obtained by optimizing using NR or MRI or RI. From Figure 2, it is evident that the reliability based performance is the best when the proposed measure MNR is used as surrogate, followed by NR, MRI and RI. The performance obtained by using MRI is better than that when RI is used as found by Jayaram and Srinivisan (2008). Similarly, MNR yields better results when compared to NR, which is expected for the multiple source network. The improvement in the reliability based performance obtained in case of NR is observed to be quiet significant when compared with that of RI, due to the introduction of the reliable loops. The same is true, when the performance of MNR is compared with that of MRI. The difference between the tradeoff curves obtained using NCR and the various surrogate reliability measures warrants further investigation to confirm the generality of this trend. Future work by the authors will focus on testing the effectiveness of the surrogate measures in larger and more complex networks, with components such as pumps and with a larger number of source nodes. It is also necessary to look at other MCS based reliability measures that consider the nodal demand satisfaction (rather than just head satisfaction) during normal and abnormal conditions.

SUMMARY AND CONCLUSIONS

The efficacy of four surrogate measures of reliability in performance based design of WDN's is investigated. This is done by determining the optimal set of diameters of an illustrative WDN considering the dual objectives of minimizing cost and maximizing the respective surrogate measure of reliability. The Monte-Carlo Simulation (MCS) based reliability of these optimal designs is evaluated by studying the network performance under several simulated demand (nodal demands), hydraulic (pipe roughness coefficients) and mechanical (pipe breaks) failure scenarios. The MCS-based reliability measure adopted for the study is network capacity reliability (Tolson et al., 2004), which is the probability that the nodal heads in the WDN remain above the minimum required heads during the simulated scenarios.

The designs obtained using any of the four surrogate reliability measures, are found to be inferior to those obtained by directly using network capacity reliability as the reliability measure in the optimization formulation. The designs produced by using modified network resilience index as the surrogate reliability measure yields better network capacity reliability than those produced by using the other three surrogate reliability measures, for the illustrative example network with two reservoirs. The limited performance investigation done in this study for a two source WDN indicates that the network resilience performs better when compared with the resilience index on account of better redundancy; likewise the modified network resilience is found to be better than the modified resilience index due to the same reason. Future work is required in investigating the effectiveness of the surrogate measures in larger and more complex networks, with components such as pumps and with a larger number of source nodes and on considering other surrogate measures as well as other MCS-based reliability measures that consider demand satisfaction as well.

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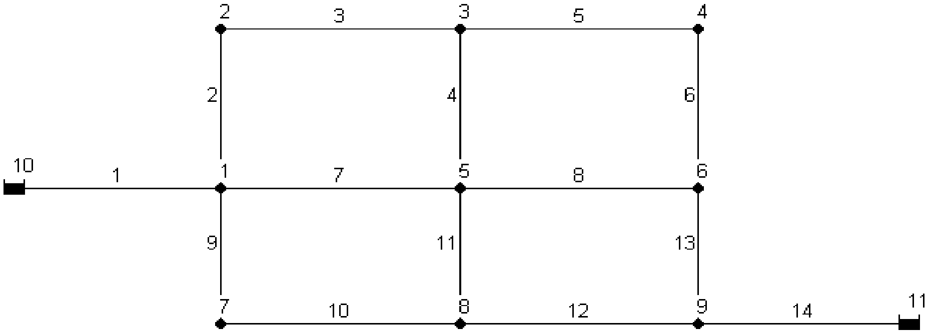

Fig. 1. Sample network – Source: Larock et al. (1999).

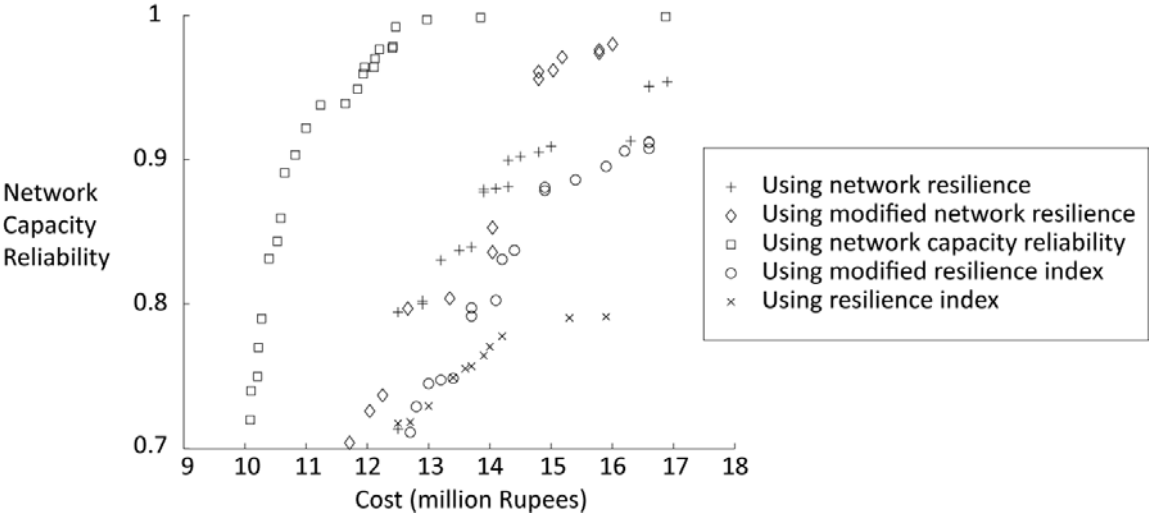

Fig. 2. Network capacity reliability of designs obtaining by solving the design formulation of minimizing cost and maximizing (a) Network Resilience (b) Modified Network Resilience (c) Network Capacity Reliability (d) Modified Resilience Index (e) Resilience Index.

Table 1. Demands and Elevations at nodes

Node	Mean Demand (l/min)	Elevation (m)
1 220	8.71	734.568
2 203	8.81	733.044
3 169	9.01	731.520

4 237	8.62	713.232
5 152	9.11	733.044
6 254	8.52	716.280
7 203	8.81	733.044
8 169	9.01	731.520
9 254	8.52	722.376

Table 2. Lengths and Roughness Coefficients for the links in the Network

Link	Length (m)	Mean Hazen-Williams Coefficient
1 457.20		100
2 304.80		100
3 609.60		100
4 304.80		100
5 609.60		100
6 304.80		100
7 609.60		100
8 609.60		100
9 365.76		100
10 609.60		100
11 609.60		100
12 365.76		100
13 365.76		100
14 457.20		100

Table 3. Costs and breakage rate data of commercially available pipes

Diameter (millimeter)	Unit cost of new pipe (Rupees/unit length)	Break rate of new pipe (breaks/yr/unit length)
100 6	15	1.36
150 9	00	1.04
200 12	90	0.71
250 17	40	0.39
300 22	50	0.07
350 27	90	0.05
400 34	20	0.05