Technical Note

Water Distribution System Design to Minimize Costs and Maximize Topological and Hydraulic Reliability

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Abstract: Many surrogate measures for water distribution system (WDS) reliability have been introduced in the last three decades. This study investigated the differences between designs based on topological and hydraulic reliabilities. The former considers network structural redundancy and connectivity, whereas the latter considers system performance under uncertain future conditions. Two topological reliabilities are proposed based on the network theory: the average node degree ratio (AND_r) and meshedness coefficient ratio (MC_r). The capacity reliability and robustness are classified as hydraulic reliability. The Pareto optimal pipe sizes and configuration were found for a real medium-size grid-type network to minimize the total cost and maximize AND_r, MC_r, capacity reliability, and robustness individually. The nondominated sorting genetic algorithm II was used for the optimization, and the uncertainty of the nodal pressures was quantified using the first-order second-moment approximation method. The results were compared in terms of the configuration, pipe sizes, and four reliability values to develop guidelines on selecting a reliability metric for WDS design. **DOI: 10.1061/(ASCE)WR.1943-5452.0000975.**

Author keywords: Reliability; Robustness; Average node degree; Meshedness coefficient; Multiobjective optimization; Pipe sizing and layout optimization.

Introduction

Water distribution system (WDS) design generally involves determining the size and capacity of components such as pipes, pumps, and tanks. The least-cost design was used first, but this is vulnerable to uncertain future conditions (Kapelan et al. 2005; Giustolisi et al. 2009; Jung et al. 2016). Since then, various performance metrics have been considered to incorporate the WDS performance when subjected to uncertainties (Lansey et al. 1989; Xu and Goulter 1999; Todini 2000). One of the most widely used performance metrics is system reliability, which is a system's ability to supply an adequate quantity of water to customers, with acceptable pressure and water quality (Goulter 1995). Reliability metrics can be classified into two groups: hydraulic and topological. Hydraulic reliability can be further divided into capacity and mechanical reliability. The former considers a system's performance under varying system hydraulic conditions (e.g., demand variation), whereas the latter is concerned with component failures (e.g., pipe breakage). Note that the present study focused on the capacity hydraulic reliability; in this paper, the term "reliability" is often used as a surrogate term for any system performance measure (e.g., system robustness can be considered as a reliability) (Jung et al. 2016). The topological reliability considers the graphical linkage among nodes in a WDS (i.e., network). Flow-entropy-based reliability measures fall in the topological reliability group, where the flow path redundancy of a WDS is quantified based on Shannon's entropy (Tanyimboh and Templeman 1993; Ostfeld 2004; Liu et al. 2014, 2017).

Lansey et al. (1989) were the first to suggest a hydraulic reliability measure: the service success probability. This is quantified as the probability that the stochastic nodal pressure is greater than or equal to the minimum pressure requirement. They introduced a chance-constraint model that sets the level of the reliability measure under the constraint of the least-cost design model. Since their introduction of a reliability measure, various capacity reliability metrics have been proposed (Xu and Goulter 1999; Babayan et al. 2005; Kapelan et al. 2005; Giustolisi et al. 2009).

Yazdani and Jeffrey (2012) introduced structural redundancy and robustness measures (i.e., topological reliability) for a WDS based on network theory. If a WDS is considered as a graph, the topological redundancy measure quantifies the degree of connectivity and looping. This serves as an indicator for the availability of alternative paths to supply demand in the case of component failure. For example, the average node degree (AND) is the expected number of pipes connected to a node; a higher number is better. Network robustness metrics include the spectral gap and algebraic connectivity, which are calculated from eigenvalues of the graph's adjacency matrix and normalized Laplacian matrix, respectively. The topological redundancy and robustness measures proposed by Yazdani and Jeffrey were calculated for four benchmark WDSs, including the Anytown and Colorado Springs networks.

In contrast to the topological redundancy and robustness metrics introduced by Yazdani and Jeffrey (2012), and Jung et al. (2014) proposed a hydraulic robustness index that quantifies the persistence of WDS performance. The proposed robustness index is calculated as one minus the coefficient of variation of stochastic nodal pressures at a critical point and was incorporated into a multiobjective optimal design model for a WDS that minimized the total cost and maximized the robustness. The robustness-based design model was applied to optimizing the design of the Anytown network, and the result was compared to the traditional reliability-based design. The robustness-based design was confirmed to

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Note. This manuscript was submitted on May 31, 2017; approved on March 15, 2018; published online on June 19, 2018. Discussion period open until November 19, 2018; separate discussions must be submitted for individual papers. This technical note is part of the ***Journal of Water Resources Planning and Management***, © ASCE, ISSN 0733-9496.

perform better than the reliability-based design in the cases of fire flow and pipe breakage, which were not considered in the design phase.

The WDS layout design determines not only the pipe sizes but also whether or not a pipe is installed to a link. These have been considered since the early history of WDS design. Lansey et al. (1989) confirmed that considering different levels of capacity reliability results in different network configurations with a similar network density for the Anytown network design. Afshar and Jabbari (2008) optimized the layout and pipe sizes simultaneously by using a genetic algorithm for a simple network and Morgan and Goulter's (1982) network. Recently, Gheisi and Naser (2015) proposed a multi-criteria decision-making (MCDA) approach for determining the layout of a simple 12-nodes network published by Tanyimboh and Templeman (2000) for different failure states (i.e., no failure, single failure, and multiple failure). They calculated the statistical flow entropy and various resilience indices and ranked 22 potential layout alternatives of the study network with respect to their final scores calculated from the weights determined by Jahan et al.'s (2012) approach and the reliability values (i.e., scores). Because large realistic pipe networks are considered common, most recent design studies have focused on pipe sizing under the assumption that the layout is determined.

Comparing the design results obtained with different reliability metrics helps identify the characteristics of the reliability metric being used. Atkinson et al. (2014) compared the design results for the Anytown network when minimizing the total cost and maximizing different reliability indicators such as the resilience index, entropy, and minimum surplus head. They used the nondominated sorting genetic algorithm-II (NSGA-II) (Deb et al. 2002) to find the optimal rehabilitation and expansion strategy for the study network. The no-pipe option was not considered in the optimization because the configuration was assumed fixed. To the best knowledge of the authors, no study has investigated the impact of considering the hydraulic reliability and nonhydraulic (topological) reliability for the optimal WDS design of a real-sized network. Comparing the configurations and pipe sizes optimized with different secondary objectives would provide insights into WDS design and planning and reliability improvement.

In this paper, two new topological reliabilities based on network theory are proposed: the AND ratio ($\mathrm{AND_r}$) and meshedness coefficient ratio ($\mathrm{MC_r}$). These are the ratios of AND and MC, respectively, to their maximum values given the nodes and links available in a system. A Pareto optimal set of the pipe sizes and configuration was found for a real medium-size grid-type network to minimize the total cost and individually maximize (1) $\mathrm{AND_r}$, (2) $\mathrm{MC_r}$, (3) Lansey et al.'s reliability, and (4) Jung et al.'s robustness. The present study is the first (1) to compare the differences between design approaches based on topological and hydraulic reliabilities and (2) to investigate the Pareto optimal configuration changes of a robustness (Rob)-based design approach with increasing total system cost (TC). NSGA-II was used for the optimization and the first-order second-moment (FOSM) approximation method was used to quantify the uncertainty of the reliability and robustness calculation. The results were compared with respect to their configurations, pipe sizes, and reliability values to develop guidelines on selecting a reliability metric for WDS design.

Methodology

This section describes the details of the proposed new topological reliability indices and multiobjective optimal WDS design model.

Topological Reliability Indices

A dense WDS with high connectivity may have alternative routes to supply demand in the case of system component failure such as pipe breakage. In a sparse network or branch-dominated system, an upstream pipe breakage generally results in water supply failure in the downstream nodes (i.e., service interruption). A grid network with a decent degree of looping can mitigate the impact of such failures. Vulnerability/failure analyses have been conducted for calculating the mechanical reliability to design a cost-effective redundant WDS (Su et al. 1987; Cullinane et al. 1992; Shinstine et al. 2002; Jun et al. 2007; Laucelli and Giustolisi 2014; Jung et al. 2016). These designs considered the nodal pressures and demand supplied under various failure conditions (e.g., fire flow, pipe breakage, and earthquakes).

Topological reliability measures are generally quantified according to the level of graphical connectivity among components (i.e., nodes and links); they do not require hydraulic simulation. Yazdani and Jeffrey (2012) introduced several topological reliability measures—including AND, the clustering coefficient, MC, the spectral gap, and the algebraic connectivity—for quantifying the WDS structural redundancy and robustness. Diao et al. (2012) used a modularity index for community detection in a WDS with which intra-cluster connections are maximized while inter-cluster links are minimized. For example, a high modularity index value indicates many connections inside a cluster (a group of nodes). Yoo et al. (2016) confirmed that a network with high AND has high water supply capacity in the case of seismic events characterized by multiple component failures.

In this paper, two topological reliability indices are proposed for WDS design in the normalized form of Yazdani and Jeffrey (2012)'s redundancy measures: $\mathrm{AND_r}$ and $\mathrm{MC_r}$. First, $\mathrm{AND_r}$ is defined as the ratio of AND to the maximum AND given the nodes and links available in a WDS. Here, a link is a potential location for a pipe being installed. Therefore, $\mathrm{AND_r}$ is calculated as

$$\mathrm{AND_r} = \frac{\sum_i^{nn} npipe_i}{\sum_i^{nn} nlink_i} \tag{1}$$

where $npipe_i$ = number of pipes installed and connected to node i ($i = 1, 2, \ldots, nn$); nn = number of nodes; and $nlink_i$ = number of potential pipe links connected to node i. Thus, $npipe_i \leq nlink_i$ because no pipe option is considered in WDS layout optimization. Please note that the AND value of most WDSs is between 2 and 3.5, which indicates that two to three pipes are connected to a node on average (Yazdani and Jeffrey 2012).

MC is defined as the proportion of the total number of independent loops in a planar graph to its maximum number in the given fixed node configuration. It indicates the degree of looping (Buhl et al. 2006) and system topological redundancy (Yazdani and Jeffrey 2012; Jung et al. 2016). The number of actually present independent loops is $np - nn + 1$, where np is the number of pipes installed. The maximum potential loops is $nl - nn + 1 = 3nn - 6 - nn + 1 = 2nn - 5$, where nl is the number of potential pipe links (Yazdani and Jeffrey 2012). Therefore, MC is calculated as

$$\mathrm{MC} = \frac{np - nn + 1}{2nn - 5} \tag{2}$$

$\mathrm{MC_r}$ is defined as the ratio of MC to the maximum MC given the nodes and links available in a WDS and is calculated as

$$\mathrm{MC_r} = \frac{np - nn + 1}{nl - nn + 1} \tag{3}$$

Note that np is less than or equal to nl in the WDS layout optimization for the same reason why $npipe_i \leq nlink_i$. MC of a benchmark WDS (e.g., Anytown, Colorado Springs, and Richmond) is less than or equal to 0.5 because nodes in proximity are generally connected in a WDS. For example, nodes near and downstream a reservoir are not connected to those at the periphery of the system because of the hydraulic and economic inefficiency.

Capacity Reliability and Robustness

Statistical approaches are starting to be used to consider the stochastic nature of nodal pressure. Lansey et al. (1989) proposed using the capacity reliability (CRel), which indicates the service success probability. Sets of stochastic random demands and pipe roughness are generated from a probability density function (PDF) and entered into a network solver [EPANET (Rossman 2000)] to obtain sets of nodal pressures. Lansey et al.'s CRel is calculated as the probability that the stochastic nodal pressures at a critical node are greater than or equal to the minimum pressure requirement (P_m). On the other hand, the robustness (Rob) is defined as a system's ability to maintain its function under disturbances (e.g., varying demands and pipe breakages) and is calculated as 1 minus the coefficient of variation (CV) of stochastic pressures.

In order to calculate both CRel and Rob, uncertainty analysis should be conducted to obtain the standard deviation of the nodal pressures (i.e., system output) given stochastic random demands and pipe roughness (i.e., system input). Various uncertainty quantification methods have been proposed and used for uncertainty quantification, such as Monte Carlo simulation (MCS), a Latin hypercube sampling (LHS)-based method, and first-order second-moment (FOSM) (Giustolisi et al. 2009; Kang et al. 2009; Pasha and Lansey 2010; Jung et al. 2014, 2016; Jung and Lansey 2015; Surendran and Tota-Maharaj 2015). In this study, FOSM is used to quantify the uncertainty of the reliability and robustness calculation. Please refer to Kang et al. (2009) and Jung et al. (2016) for more details on the FOSM used in this study.

Multiobjective Optimal WDS Design Model

For a multi objective optimal WDS design, two competing objectives are optimized simultaneously. A system's performance stability when subjected to disturbances can be improved by cost investment, such as installing larger pipes and pumps or constructing additional tanks. One the other hand, a least-cost design sacrifices the system's ability to function under uncertain future conditions. The Pareto relationship between these two objectives is identified and used for marginal cost analysis, final design selection, and investment decision. A decision maker likes to select a design alternative at the point where the marginal cost is maximized. Generally, the marginal cost increases nonlinearly as the total cost increases (e.g., more cost is required to increase CRel by 1% for designs with a high total cost). While the total cost is usually the first objective considered, various system performance measures can be considered for the second objective. Identifying and comparing Pareto relationships between different sets of two objectives provide insight into the WDS performance characteristics and system improvement.

For a multi objective optimal design model, the first objective function (F1) is to minimize TC. The second objective function (F2) is to maximize $\mathrm{AND_r}$, $\mathrm{MC_r}$, CRel, or Rob, which can be expressed as

$$\text{Minimize F1} = \text{TC} \tag{4}$$

$$\text{Maximize F2} = \mathrm{AND_r}, \mathrm{MC_r}, \text{CRel, or Rob} \tag{5}$$

where TC = total system cost and $\sum_{j=1}^{nl}(y_j \times L_j)$. y_j and L_j = unit pipe cost and length of pipe j, respectively. Note that y is calculated by using the pipe construction cost function in Clark et al. (2002) and is zero when no pipe is installed. Pressure constraints are included in the four design problems. The nodal pressure should be equal to or greater than P_m for the peak demand condition.

Jung et al. (2014) compared design approaches based on reliability (i.e., the second objective is to maximize CRel) and robustness (i.e., it is to maximize Rob) to size new pipes for the Anytown network, where pipe sizes are determined according to the two objectives under the assumption that the layout is fixed. While optimal layout determination has been considered with CRel-type reliability measures (e.g., service success probability) (Lansey et al. 1989; Tanyimboh and Templeman 2000; Afshar and Jabbari 2008; Gheisi and Naser 2015), the current study was the first to investigate the impact of optimizing Rob on the optimal configuration and pipe sizes of WDS. This study was also the first to compare hydraulic and topological, reliability-based design approaches.

NSGA-II was used to seek the Pareto optimal solutions for each of the four design problems given in Eqs. (4) and (5). Initial solutions for NSGA-II are randomly generated from available pipe size candidates in order to guarantee search diversification in the early optimization phase (Cuevas et al. 2014; Wang et al. 2014). A sensitivity analysis is conducted to identify the number of generations for the Pareto front to converge. Each NSGA-II run is stopped at the predefined number of generations identified in the sensitivity analysis. A penalty cost is added to the total pipe construction cost [Eq. (4)] to handle constraints so that infeasible solutions are naturally excluded from the population.

Study Network

A 2×2 km grid network (Jung et al. 2016) was used to compare the four different design approaches. This network was a representative demand metering area in B-city, Korea. Two versions of the grid networks are presented here: one supplied by a gravity flow and the other by a pump flow. Grid-1 consisted of 61 pipes, 36 nodes, and a single reservoir with a total head of 80 m. Grid-2 replaced the source pipe in Grid-1 with a pump for which the head gain was calculated as $68 - 1.471 \times 10^{-6} \times Q^2$, where Q is the elevated flow in liters per second (Fig. 1). The total head of the reservoir was set to 0 m in Grid-2, so the two systems had a similar surplus pressure head at critical nodes when all pipes were 1,000 mm in diameter.

Each node in the grid network had a demand of 94.7 L/s, which was calculated by multiplying the peak factor of 1.6 with 59.2 L/s. The latter value was obtained by multiplying B-city's liter per capita per day (lpcd) (278 L/person), population density (0.0046 persons/m^2), and the section area assigned to a node. The total system demand was 3,409 L/s.

In this study, the Pareto optimal designs and configurations were found by using each of the four different design approaches independently based on the fixed locations of the demand nodes and reservoir. For each potential pipe link (Fig. 1), either a pipe was installed from 16 commercial pipe sizes available (50, 100, 200, 300, 400, 500, 600, 700, 800, 900, 100, 1,200, 1,400, 1,600, 1,800, or 2,000 mm), or no pipe is determined. Note that a pump downstream of the source should not be designed with the fixed

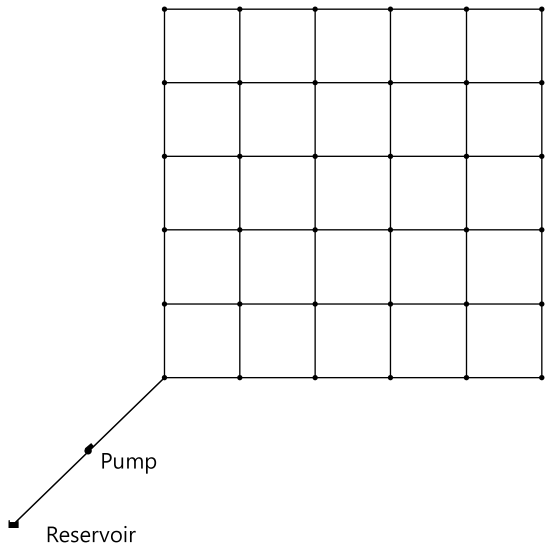

Fig. 1. Configuration of the grid network supplied by a pump flow (i.e., Grid-2). The Grid-1 network has a source pipe downstream of the reservoir instead of a pump (not presented here).

pump characteristic curve. Thus, the sizes of 60 pipes were determined for Grid-2 despite there being 61 links (one pump link). The parameter values used by Jung et al. (2014) were used to calculate the pipe construction cost based on Clark et al.'s (2002) approach [Eq. (4)]. The Hazen–Williams roughness coefficient was 120 for all pipes. The minimum pressure requirement was 28 m (40 psi) for the peak demand condition. The preceding assumptions and values were consistently applied in the four different designs (i.e., minimize TC and maximize AND_r, MC_r, CRel, or Rob) for a fair comparison. Note that the maximum AND value of Grid-1 was 3.361 and that of Grid-2 was 3.333. The maximum MC value of Grid-1 was 0.388, and that of Grid-2 was 0.373.

The same optimization parameters were used for the four design formulations given in Eqs. (4) and (5). The population of 100 evolved over 3,000 generations with crossover rate of 90% and mutation rate of 2%. Multi-point crossover and standard mutation were adopted here. Hydraulic simulations were performed with EPANET (Rossman 2000) to check the pressure constraints.

Application Results

Comparison of the Pareto Fronts for the Grid-1 Network

Fig. 2 shows the Pareto fronts identified in Grid-1 by using the design approaches based on (a) AND (i.e., minimizing TC and maximizing AND_r), (b) MC (i.e., minimizing TC and maximizing MC_r), (c) CRel, and (d) Rob. First, a distinct difference was observed between the Pareto curve shapes for the topological [Figs. 2(a and b)] and hydraulic reliabilities [Figs. 2(c and d)]. That is, AND_r and MC_r increased almost linearly as TC increased, whereas CRel and Rob increased nonlinearly. This indicates that the marginal cost required to increase a unit of CRel/Rob varied at different ranges. For example, TC = 0.521 million USD was required to increase CRel by 0.1 from 0.5 to 0.6, while twice that value (i.e., 1 million USD) was necessary to increase CRel by 0.1 from 0.8 to 0.9.

Another significant difference between the topological and hydraulic reliabilities was that the former's Pareto front was discrete with a stepwise increase, whereas the latter's front was almost continuous. This is because AND_r was determined based on the number of installed pipes and their locations, while MC_r was

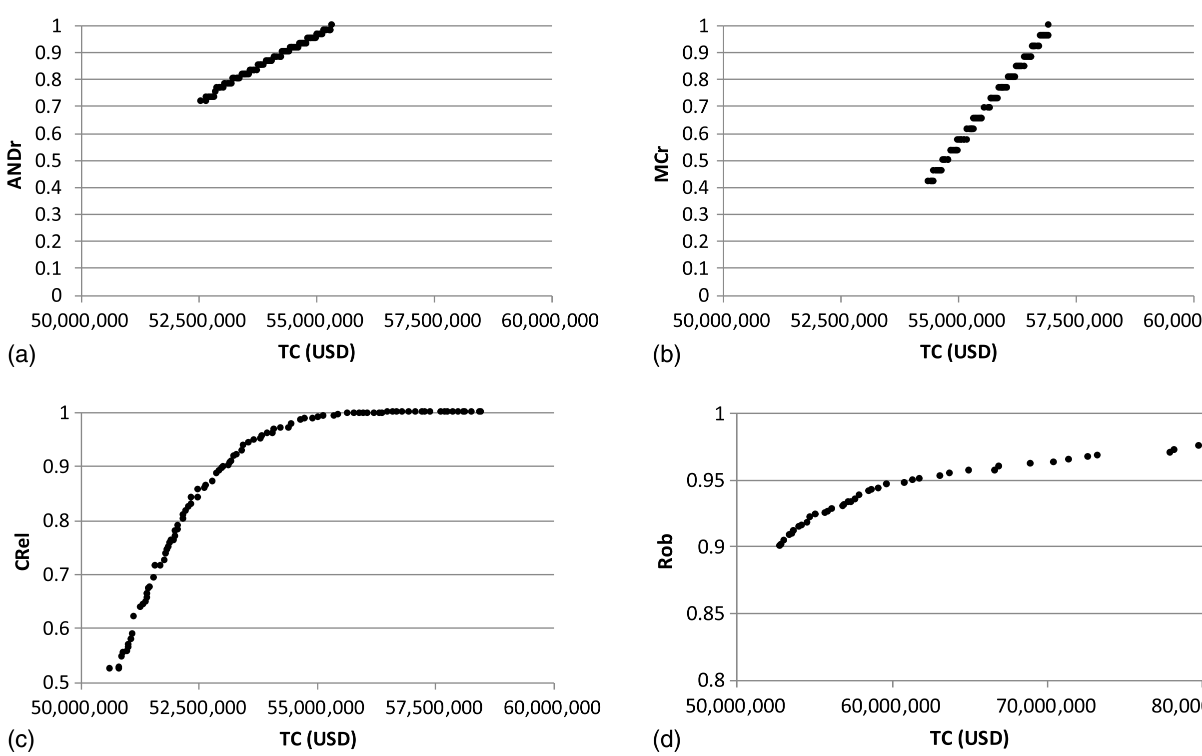

Fig. 2. Pareto fronts obtained with the four different design approaches: (a) AND-based; (b) MC-based; (c) CRel-based (i.e., capacity-reliability-based); and (d) Rob-based (i.e., robustness-based) approaches.

determined based on the former (the number of nodes was fixed). This is shown in Eqs. (1) and (3), respectively. For example, MC was 0.388 $(= (61 - 36 + 1)/(2 \times 36 - 5))$ when a pipe was installed at all potential links, which resulted in MC_r of 1.0. If a pipe was not installed at a single link, MC became 0.373, which resulted in MC_r of 0.962 (Fig. 1). There was no reliability value available between 0.962 and 1.0. On the other hand, CRel and Rob were affected by the system hydraulics depending on the configuration and pipe sizes. Thus, different values could be calculated, even for the same configuration and number of installed pipes.

The cost range of designs based on hydraulic reliability was wider than that of designs based on topological reliability (Fig. 2). Given the same number of pipes and their locations for ANDr-based design, high-cost solutions were not included in the Pareto optimal solutions because they were dominated by low-cost solutions in the topological-based design approaches. Note that topological reliability measures do not consider any hydraulics in their quantification [Eqs. (1) and (3)].

Comparison of Four Reliability Values for the Grid-1 Network

Table 1 presents the four reliability measure values of three selected Pareto optimal solutions (two from the AND_r-based approach) in the Grid-1 network. The solutions with the same identifier had similar costs, which provided a solid basis for consistent comparison. The cost difference among the selected solutions was from 0.07 to 0.29%. For example, the minimum cost of Solution 1 was 54.38 million USD (MC_r-based), and the maximum cost was 54.54 million USD (Rob-based) for a percentage difference of $(54.54–54.38)/54.38 \times 100 = 0.29\%$. The gray-filled reliability values are the optimized values. For example, AND_r of 0.917 was the AND value of a Pareto optimal solution with a TC of 54.45 million USD obtained by the AND_r-based design approach. The solution's other reliability values (i.e., MC_r, CRel, and Rob) were calculated from a post-optimization assessment.

The highest AND_r and MC_r were obtained with AND_r-based approach. Unexpectedly, the optimized MC_r value was lower than the MC_r of the solution obtained with the AND_r-based approach [e.g., the MC_r value of Solution 2 with the AND_r-based approach (0.923) was higher than that with the MC_r-based approach (0.577)] (Table 1). Considering MC_r as the second objective has a high risk of finding suboptimal solutions because there are very few potential MC_r values, and only the number of installed pipes np affects MC_r [Eq. (3)]. For the same MC_r (i.e., same np), many pipe size sets and configurations are possible; most are infeasible with a high penalty cost for their lack of hydraulic reasonability (e.g., pipe layout with disconnected nodes). These result in a fitness landscape with very few feasible spikes where a newly generated solution is subject to be infeasible or similar to an existing feasible solution far from even near optimum.

As expected, the design approaches based on hydraulic reliability produced solutions with high CRel and Rob compared to the approaches based on topological reliability. The CRel and Rob values of the solutions based on topological reliability were around 0.5 and 0.84, respectively, whereas those of the solutions based on hydraulic reliability were over 0.9. Note that CRel of 0.5 indicates that the probability that the pressure at critical node is less than or equal to the minimum pressure requirement of 28 m is 50%. That is, the pressure fails to satisfy the requirement for 50 out of 100 stochastic demand and roughness conditions in designs based on topological reliability that also have high pressure variation and unstable pressure behavior. The CRel- and Rob-based solutions had similar AND_r and MC_r values (0.736–0.769 and 0.385–0.462, respectively) compared to the solutions obtained with the MC_r-based approach.

The results in Table 1 confirm that Pareto optimal designs from topological-based approaches are very vulnerable to uncertain demand and roughness conditions and that considering the topological reliability does not guarantee high hydraulic reliability. Especially, MC_r is not a good system performance indicator to be used in a multi objective WDS design because of its simplicity and the risk of providing local optimal solutions. The hydraulics of a design should be checked with a network solver and incorporated into quantifying the system reliability for a reliable and safe WDS design.

Comparison of Pareto Optimal Configurations

Fig. 3 shows the (a–d) Pareto optimal pipe sizes and layouts determined in Solution 1 and pipe size differences (e) between Solutions 1 and 2 for the AND_r-based approach and (f–h) between Solutions 1 and 3 for the other approaches. While the overall pipe density was visually similar for Solution 1, the AND_r approach had 56 pipes (91.8% installation) [Fig. 3(a)], the MC_r approach had 46 pipes (75.4%) [Fig. 3(b)], and the CRel and Rob approaches had 47 pipes (77%) [Figs. 3(c and d), respectively]. No distinct design strategies could be identified for the AND_r-and MC_r-based designs. Large pipes and a high pipe density were observed near the reservoir and southwest corner of the study network, and the network became sparser farther from the source. On the other hand, the Rob-based approach seemed to have a unique strategy for minimizing the hydraulic failure depth and pressure variation. That is, Solution 1 with the Rob-based approach installed continuous pipes

Table 1. Reliability values of selected similar cost solutions in the Grid-1 network

Classification	Design approach	Solution identifier	TC (million USD)	Reliabilities			
				AND_r	MC_r	CRel	Rob
Topological reliability	AND_r-based	1	54.45	0.917	0.808	0.501	0.838
		2	55.01	0.967	0.923	0.518	0.838
	MC_r-based	1	54.38	0.752	0.423	0.511	0.840
		2	55.00	0.818	0.577	0.501	0.840
		3	56.94	1.0	1.0	0.501	0.843
Hydraulic reliability	CRel-based	1	54.41	0.769	0.462	0.972	0.904
		2	55.03	0.736	0.385	0.990	0.891
		3	56.95	0.752	0.423	0.99997	0.937
	Rob-based	1	54.54	0.769	0.462	0.940	0.919
		2	55.05	0.752	0.423	0.988	0.925
		3	56.91	0.769	0.462	0.999	0.932

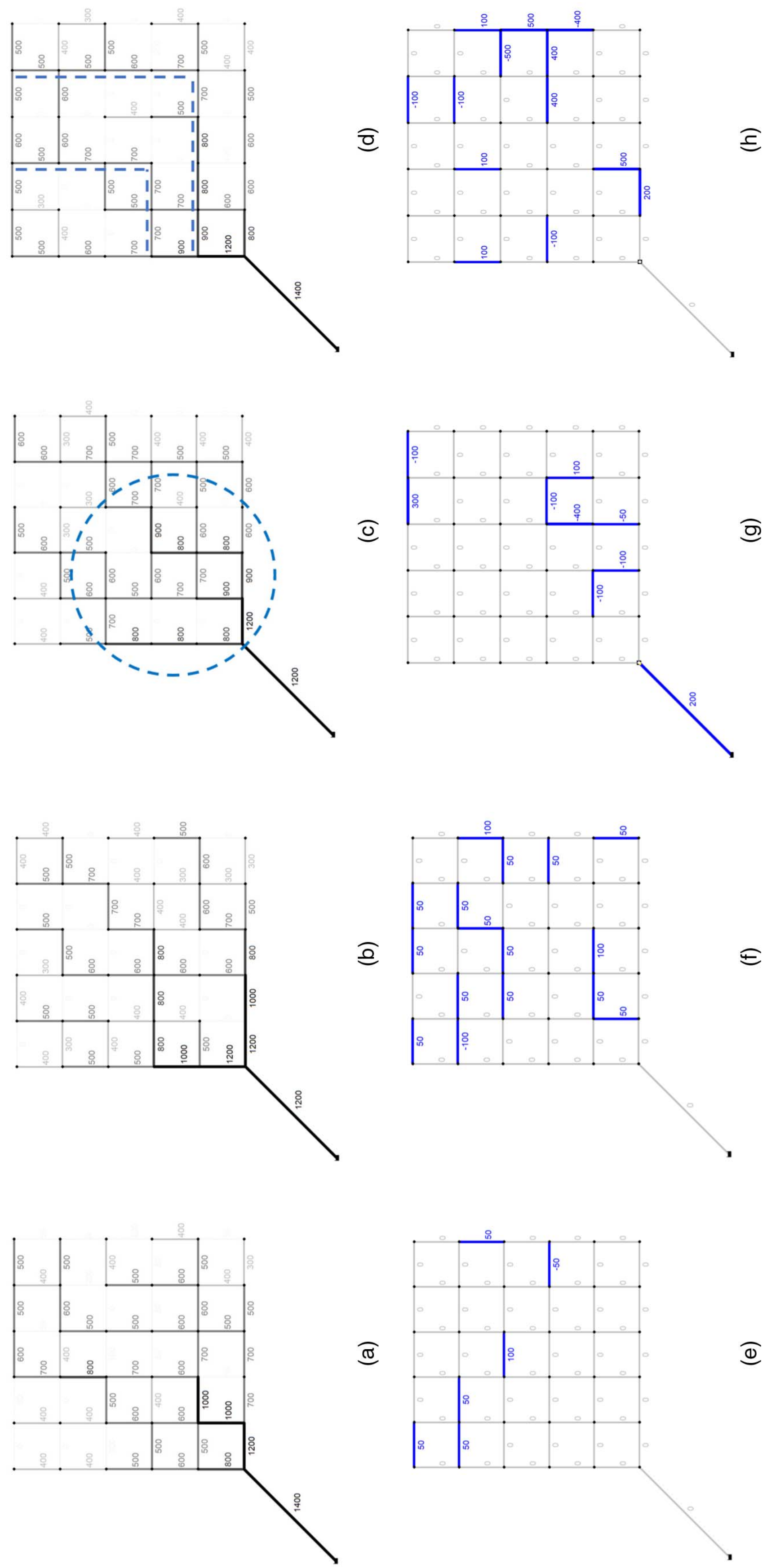

Fig. 3. Optimal layout and pipe sizes determined in Solution 1 of (a) AND$_r$-, (b) MC$_r$-, (c) CRel-, and (d) Rob-based design approaches and pipe size differences between (e) Solutions 1 and 2 for the AND$_r$-based design approach and between Solutions 1 and 3 for the (f) MC$_r$-, (g) CRel-, and (h) Rob-based design approaches. See Table 1 for the reliability values of the solutions. Pipe sizes are in millimeters, and the thickness of pipe is proportional to its size.

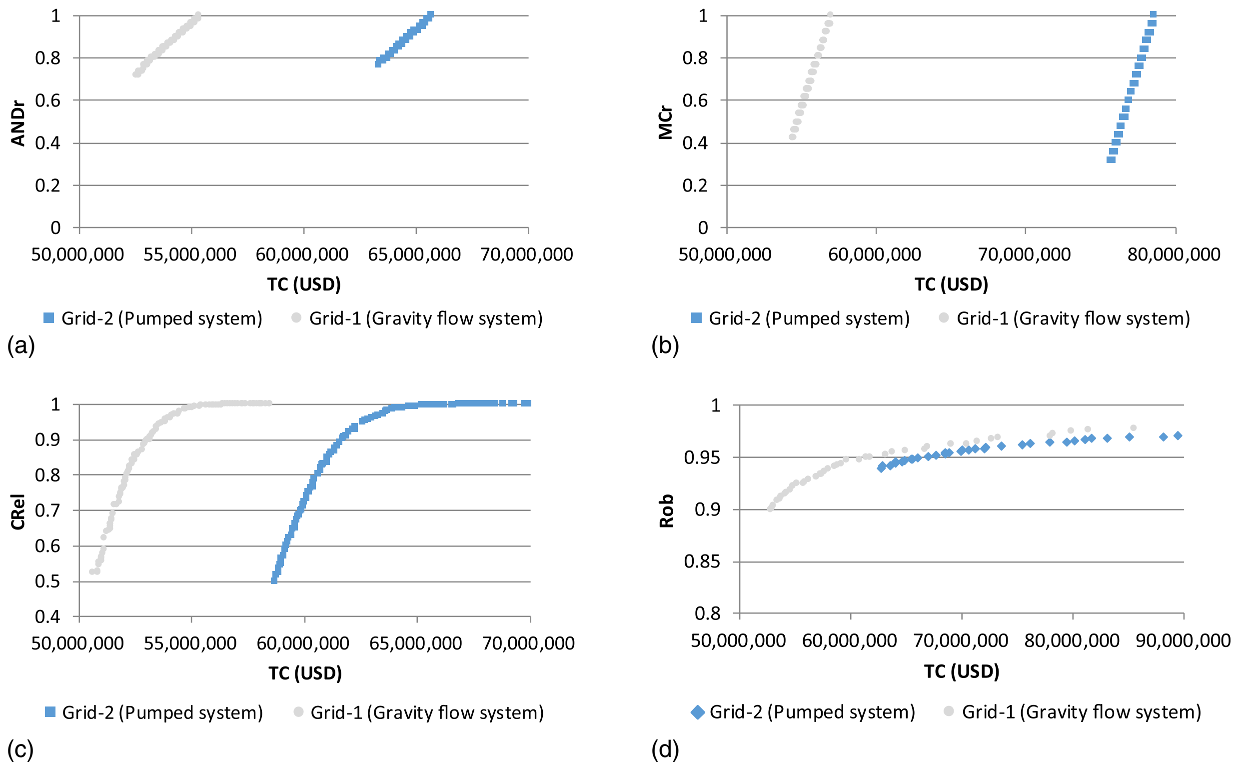

Fig. 4. Pareto fronts obtained using the four different design approaches for the Grid-2 network with those for the Grid-1 network as reference: (a) AND-based; (b) MC-based; (c) CRel-based; and (d) Rob-based.

with a size of 500–600 mm at the north end of the study network and two elbow-shaped transmission lines [indicated by dashed elbows in Fig. 3(d)] with a size of 500–900 mm around the center to link the outer lines at the west and north ends' outer lines. Small pipes with a size of 300–500 mm branched out from the main skeletons in the Rob-based Solution 1. The CRel-based Solution 1 showed a smooth pipe size decrease from the source to the system end compared to the AND_r- and MC_r-based Solution 1, with 1,000–1,200 mm pipe sizes at the southwest corner [dashed circle in Fig. 3(c)] linked to 500–600 mm pipe sizes downstream.

Among the three approaches [Figs. 3(f–h)], the MC_r-based approach added the greatest number of pipes (i.e., 15 pipes) for Solution 3, which resulted in a full network with pipes installed at all potential links [Fig. 3(f)]. Compared to Solution 1, the two topological-reliability-based approaches added small pipes of 50–100 mm for Solution 3, which increased the number of installed pipes but minimized the cost increase. The CRel-based approach was the only one that increased the size of the source pipe by 200 mm to increase the total head entering the study network [Fig. 3(g)]. This increased the average stochastic pressure, which eventually increased the service success probability (i.e., the PDF was shifting to the right to a high-pressure range). Compared to Solution 1, Solution 3 of the Rob-based approach modified the size of some branch pipes (some were increased while others were decreased) while mostly maintaining the main skeleton elbow lines [Figs. 3(d and f)].

Hydraulically reasonable pipe sizes and configurations were confirmed for the design approaches based on hydraulic reliability, and the Rob-based approach set up elbow-shaped main transmission lines in the middle of the network to which small branch pipes were appended with increasing TC. No sound strategy for improving the system reliability was observed with the designs based on topological reliability, except for adding pipes.

Comparison with the Grid-2 Network

Fig. 4 shows the Pareto fronts obtained for Grid-2 (pumped system) with the four design methods. Those for Grid-1 (gravity flow-fed system) are presented again as a reference. The linear [Figs. 4(a and b)] and nonlinear responses [Figs. 4(c and d)] of the topological and hydraulic reliabilities, respectively, were also observed in Grid-2 just like in Grid-1 (Fig. 2). This indicates that system hydraulic conditions (i.e., supply with a fixed head source or with a pump and dynamic total head entering the system) do not affect the relationship between the reliabilities and TC. In addition, the Pareto front of the design methods based on topological reliability was confirmed to be discrete for Grid-2 [Figs. 4(a and b)], just like for Grid-1 [Figs. 2(a and b)].

All Pareto fronts for Grid-2 were shifted to the right compared to those for Grid-1. Therefore, the former required more investment for a design of the same reliability level than the latter. This is because a smaller total head entered Grid-2 (51 m) under the peak demand condition than Grid-1 (80 m). Larger pipes should be constructed to compensate for the low total energy provided, which would result in more costs.

Similar optimal configurations to those shown in Fig. 3 were obtained for Grid-2 with all reliability design methods. Interestingly, the minimum Rob value increased from 0.9 for Grid-1 to 0.94 when the source pipe was replaced with a pump in Grid-2 [Fig. 4(d)]. This contradicts the findings of Jung et al. (2014) for the pipe and pump design of the Anytown network; they showed that adding pumping units to a system decreases the overall system robustness level. Note that the range of CRel of 0.5–1.0 was the same for both networks following Jung et al., and the minimum value changes for the AND_r and MC_r-based approaches [Figs. 4(a and b)] were because of the change in the number of potential pipe lines nl ($nl = 61$ for Grid-1 and 60 for Grid-2).

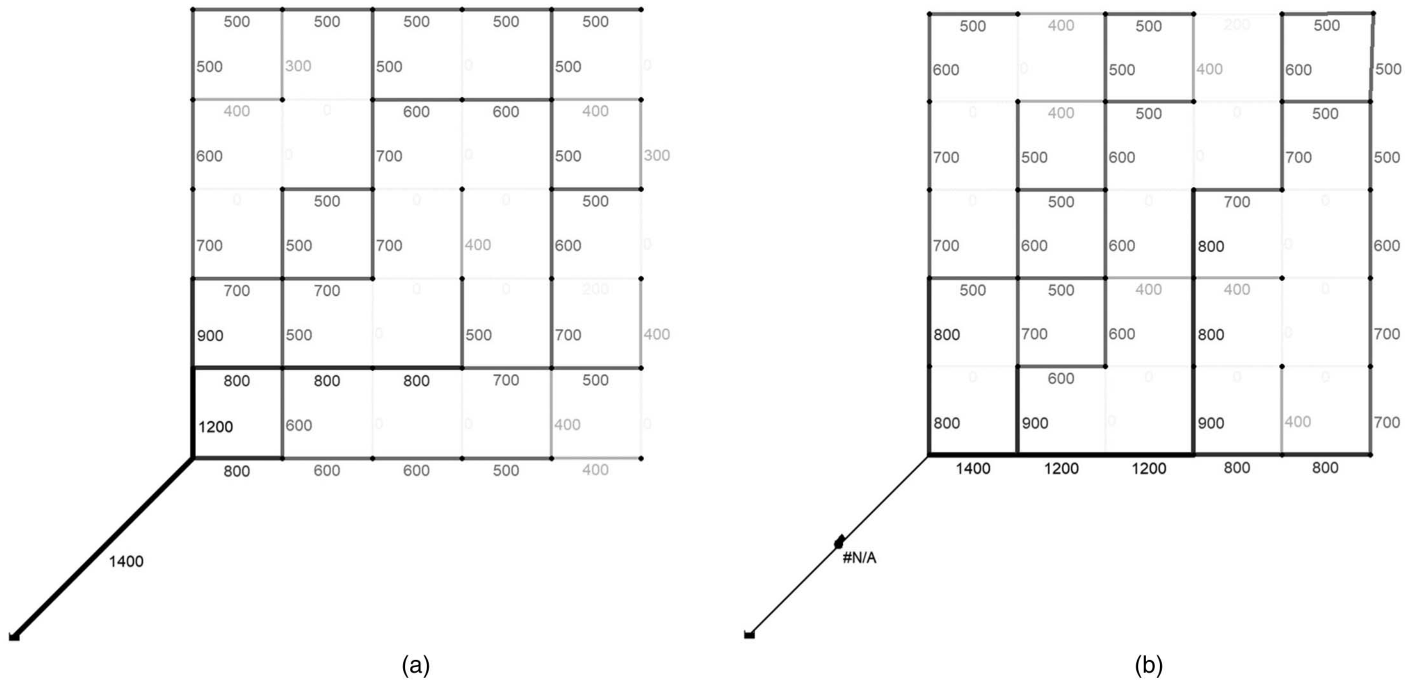

Fig. 5. Least Rob designs obtained for the (a) Grid-1; and (b) Grid-2 networks. The former had a TC of 52.74 million USD and Rob of 0.9, and the latter had a TC of 62.71 million USD and Rob of 0.94. Pipe sizes are in millimeters, and the thickness of pipe is proportional to its size.

The least-cost feasible design for Grid-2 obtained with the Rob-based design approach had much larger pipes near the source and pump (i.e., 1,200–1,400 mm at the southeast corner) than that for Grid-1 [Figs. 5(a and b)]. In addition, the east-end outer lines had pipe sizes of 500–700 mm [Fig. 5(b)] that were not present in Grid-1 [Fig. 5(a)]. All of these changes lowered the head loss in pipes and pressure variation at the nodes and offset the pressure variation of having a pump in the system. This would increase the minimum Rob value for Grid-2.

Summary and Conclusions

In this paper, two new topological reliability measures are proposed for a multi objective optimal WDS design model—AND_r and MC_r. These are the ratios of AND and MC, respectively, to their maximum values considering the nodes and links available in a system. A Pareto optimal configuration and pipe sizes were found for a Grid network by minimizing TC and maximizing AND_r, MC_r, Lansey et al.'s capacity reliability (CRel), or Jung et al.'s robustness (Rob), independently. The latter two are hydraulic reliability measures. Note that the present study is the first to (1) compare the differences between design approaches based on topological and hydraulic reliabilities and (2) investigate the Pareto optimal configuration changes of a Rob-based design approach with increasing TC. FOSM was used to quantify the uncertainty for the hydraulic reliability calculations, and NSGA-II with the same crossover and mutation rates was used for the optimization.

In conclusion, topological reliability measures should not be solely used because they do not account for system hydraulics or guarantee system performance under uncertain demand and roughness conditions. This can cause frequent hydraulic failures. The Rob-based design showed a distinct difference in the optimized configuration and pipe sizes and produce compared to other design approaches.

Acknowledgments

This work was supported by a grant from the National Research Foundation (NRF) of Korea funded by the Korean government (MSIP) (No. 2016R1A2A1A05005306).

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