Article

Improving Water Distribution Systems Robustness through Optimal Valve Installation

Young Hwan Choi [1], Donghwi Jung [2], Hwandon Jun [3] and Joong Hoon Kim [4,*

[1] Research Center for Disaster Prevention Science and Technology, Korea University, Anamdong, Seongbukgu, Seoul 136713, Korea; younghwan87@korea.ac.kr

[2] Department of Civil Engineering, Keimyung University, 1095 Dalgubeoldae-ro, Dalseogu, Daegu 42601, Korea; donghwiku@gmail.com

[3] School of Civil Engineering, Seoul National University of Science and Technology, 232 Gongneung-ro Nowongu, Seoul 01811, Korea; hwjun@seoultech.ac.kr

[4] School of Civil, Environmental and Architectural Engineering, Korea University, Anamdong, Seongbukgu, Seoul 136713, Korea

* Correspondence: jaykim@korea.ac.kr; Tel.: +82-2-3290-4722

Abstract: This study proposes a framework for improving the robustness of water distribution systems using the optimal valve installation approach with regard to system reinforcement. To improve the robustness in valve design, this study introduces critical segment selection technique and optimal valve location determination within the concept of segment. Using the segment finding algorithm, the segment and the unintentional isolation can be identified. To select the critical segment, a multicriteria decision technique is applied by considering the hydraulic, social and economic effect. Finally, the optimal valve locations and the number of additional valves is determined by pipe failure analysis through the trade-off relationship with the number of additional valves and the maximum damage under pipe failure situations. To verify the proposed technique, the real-world water distribution systems are applied and compared with the original design.

1. Introduction

In the past, the methods for improving water distribution systems (WDSs) have focused on providing more consumers with a stable water supply. However, the importance of resilience, namely the ability to maintain a stable water supply capacity, has recently emerged, even under abnormal conditions (i.e., system failure due to the deterioration of the water supply network and rapid climate change). Bruneau et al. [1] introduced four elements associated with system resilience—robustness, redundancy, resourcefulness and rapidity (Table 1). Among these factors, robustness is the ability to maintain the required pressure during sudden changes in demand. Hashimoto et al. [2] presented indicators (i.e., reliability, resiliency and vulnerability) for evaluating the conditions of a water resource system. They anticipated that the indicators presented in their study would be useful in future water resource planning or management policies. They emphasized resilience as the degree to which the system can return to its previous normal conditions after its original function has been damaged by internal or external disturbance factors.

Lansey [3] proposed strategies to improve the four elements of resilience in a water distribution network. To improve robustness, the diameter of the pipe should be increased and an additional valve should be installed. To improve redundancy, double pipe and looped systems could be constructed. Rapidity can be improved by using algorithms to detect abnormal conditions and constructing

an alternative water source and securing a recovery workforce could improve resourcefulness. Jung et al. [4] introduced a robustness-based WDSs design approach and confirmed that considering robustness improves system performance under uncertain failure conditions.

Table 1. Four elements of resilience.

Resilience Factors	Description
Robustness	Ability to maintain system functionality under failure event
Redundancy	The degree to which spare the alternative resources are secured to prevent the system from damage due to interference factors
Resourcefulness	The ability to detect abnormal conditions of the system by disturbance factors and to allocate resources appropriately
Rapidity	The ability to respond quickly to abnormal conditions

Increasing the pipe diameter or constructing additional valves can improve the robustness of WDSs. If an additional valve is installed at a suitable location, the customer can receive a more stable supply as the area where water would be shut off during the event of repairing a broken pipe or maintenance would be minimized. In this case, an area containing pipes and nodes that are isolated by closing valves is defined as a segment and the size of the segment is directly related to the range of damage that occurs during water blockages [5].

A segment can consist of only one pipe or node when there are two valves at the ends of the pipe or node. Otherwise, more neighboring valves would have to be closed to isolate a section containing broken components. In this case, the whole isolated section can be considered as a single segment. Considering the segment concept, the impact of component failure in a WDS can be estimated efficiently.

Goulter et al. [6] provided a detailed review of methods of analyzing the reliability of WDSs, including valve location analysis. Bouchart and Goulter [7] directly addressed the role of valves and provided relevant critical discussions. They observed that the demand nodes are not present in real WDSs and that the demand is continuously distributed along pipes. They presented a model for selecting a set of valve locations to minimize the demand volume deficit. They assumed that the volume deficit is only caused by a failed pipe and the impact on the rest of the network can be ignored. Therefore, to minimize the impact of the failure, valves should be placed with the shortest possible distance between them. Regarding the role of valves in WDSs, Hoff [8] addressed practical considerations related to valve maintenance, selection, storage and installation. Whittaker and Arscott [9] described the potential problems in valve identification, selection, operation, monitoring and record keeping. Skousen [10] provided a comprehensive reference for valve selection, type and sizing, and addressed the various problems associated with valves and costing. Jung et al. [11] investigated the correlation between a system availability measure quantified based on segment isolation and unmet segment demand identified considering adjacent valves and other reliability surrogate measures. Another method of using valves to improve the reliability of the WDSs is to minimize water loss by optimizing valve locations for controlling pressure [12,13].

Along these lines, Jun et al. [14] proposed an algorithm for searching the segment by considering the value of the whole system. Their segment search algorithm used three matrices for searching all segments by closing the valves. The first matrix is the node-arc matrix, which shows the relationship between the nodes and the pipe. The valve location matrix is defined using the location of the pipe. The final matrix computes the difference between two matrices and is defined as a valve deficiency matrix.

These previous studies were carried out to quantify these damages when component failures of the WDSs caused problems in normal system operation. In other words, these studies have focused on minimizing hydraulic damage by including optimal valve locations in the WDSs design process. However, the failure of WDSs causes not only hydraulic damages but also social and economic

problems. Therefore, to effectively manage future water supply systems, the focus must be changed from considering only the hydraulic factor as in the past to including social and economic factors.

Therefore, this study proposes a framework for effective segment division by installing additional valves at appropriate positions for ensuring system reinforcement. To find all the segments, valve location information is used and the importance of segments is calculated considering the hydraulic, social and economic factors that can directly or indirectly indicate the degree of damage based on the segment. To calculate the segment priority, the weighted utopian approach is applied to consider multiple criteria. Finally, the optimal valve locations and the number of additional valves are determined. To determine valve locations, the candidate group is set based on the experience of the engineer, from among all the valve installable locations. In the installable location candidates, additional valves are installed and the performance is evaluated. The number of additional valves is determined simultaneously with the selection of the valve locations. To determine the number of valves, the trade-off relationship with the number of additional valves and the maximum damage under pipe failure situations is checked and the number of appropriate valves is determined by the number of marginal valves.

2. Development of Robustness-Based Optimal Valve Installation Model

Three methodologies were considered to improve WDSs robustness through optimal valve installation: (1) the segment finding algorithm, (2) the critical segment selection technique and (3) the determination of valve locations.

The segment finding algorithm can identify the segment as well as unintentional isolation. To replace the previous technique used for selecting the segments to be divided, a multicriteria decision technique that considers hydraulic, social and socio-economic criteria is used to evaluate the critical segment selection technique. In this chapter, a new valve location determination technique to ensure reinforcement, that could replace an engineer's experience when deciding an additional valve installation location to improve the segment's robustness, is proposed. This technique analyzes pipe and valve failures to determine the optimal valve location.

2.1. Valve Location Determination to Improve System Robustness

Regionalizing the WDSs while considering the segment concept is a core approach for constructing robust WDSs and efficient management. Therefore, more efficient and robust construction techniques are needed than the approach that uses engineers' experience to optimize the segmentation of the WDSs.

This study proposes a framework of the optimal valve installation approach for robust water distribution network segmentation. This technique uses basic valve location information to identify all segments of the WDSs and organize pipe and node lists included within them. The importance of each segment is then quantified considering hydraulic, social and socio-economic factors and the weight of each factor is then calculated. The priority of the segment is determined by the weighted utopian approach, applying various system factors with different weights. Finally, the optimal valve position is determined considering the probability pipe and valve failure. The procedure can be detailed as follows.

Step 1: Data collection

Data that can quantify the segment's importance (EPANET input file, location of the valve, demand data, location of important facilities, the number of water users, the type of residence) are collected.

Step 2: Segment identification

The segments in the whole WDSs are identified using the segment identification algorithm and the nodes, pipes and valves in each segment are listed.

Step 3: Weight calculation

The weights of each factor are calculated using the data collected in step 1 (data that quantify the attributes for multicriteria decision-making) and the expected damage of each segment during system failure is quantified.

Step 4: Prioritization of each segment

The weighted utopian approach is applied to determine segment priority and the highest priority segment to be divided is selected. In this case, each factor's weight, which was calculated in step 3, is applied to each segment.

Figure 1 shows a model for determining segment priority for division. The model regards factors related to segment importance as (1) hydraulic, (2) social and (3) socio-economic importance. Before determining the weights of each factor in the model, a questionnaire survey analysis is conducted to evaluate the relative importance and the targets are experts in the WDSs field.

(1) Hydraulic importance: The WDSs are complex and interacts with various hydraulic components, such as pipes, nodes, valves and sources. It can determine priority according to the properties of the hydraulic components within the segment. In this model, three criteria are considered: undelivered demand (the number of water users), increasing head loss to isolate the segment and the number of valves required to isolate the segment.

(2) Social importance: The WDSs are inseparable from social activities and social importance factors, such as important facilities including government offices and medical facilities, composition of ages, restoration infrastructure (equipment, workforce, system) and secondary damage caused by restoration (traffic congestion, blackout, communication damage) can be criteria for judging importance.

(3) Socio-economic importance: Economic activity is closely related to water supply. In this model, we consider two factors, the average income level and the characteristics of the water user (residential, commercial and industrial districts as criteria for determining the economic importance of the segment).
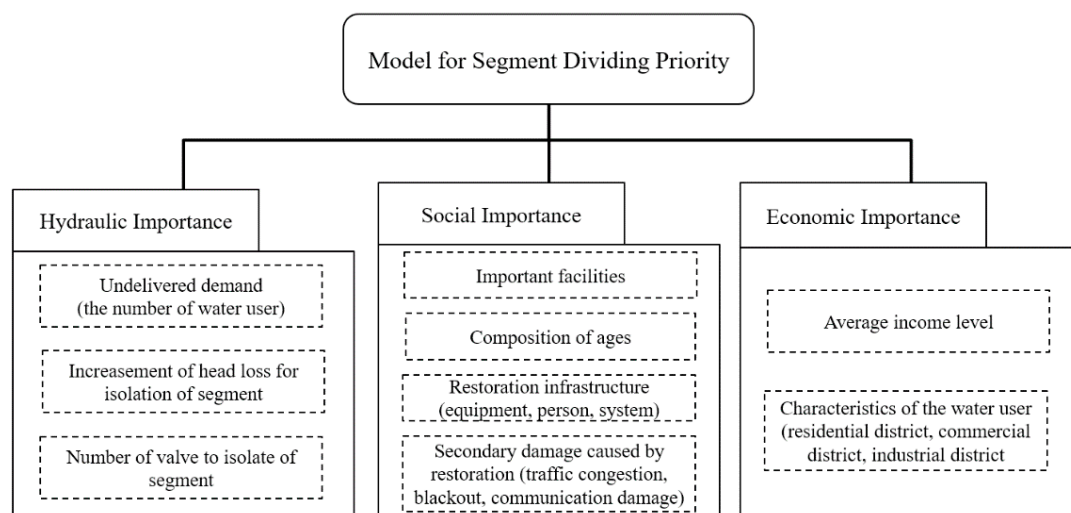

Figure 1. Model for segment division priority.

Step 5: Search for optimal valve location

Finally, the optimal valve locations and the number of additional valves are determined. This process starts with the highest priority segment identified in Step 4. The candidate valve locations are set based on engineering knowledge from among all potential locations. In the installable location candidates, the additional valve is installed and the performance of the segmented segments (i.e., the number of water user, undelivered demand) is evaluated. The number of additional valves is determined simultaneously with the selection of the valve locations. First, the relationship between the number of additional valves and the maximum damage under pipe failure situations is

determined as shown in Figure 2. Then, the proper number of additional valves is determined from a marginal effect analysis using Figure 2 that yield optimal efficiency with additional valve installation. The determined number of valves can increase or decrease depending on the additional requirements of the decision maker.
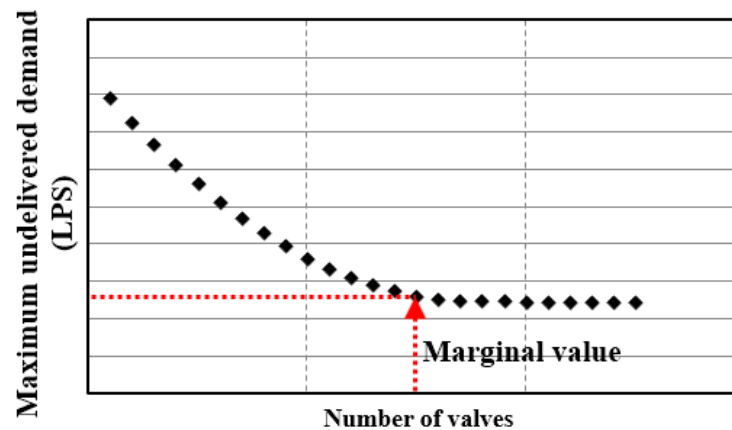

Figure 2. Relationship between the number of additional valves and the maximum damage.

To evaluate the efficiency of the additional valve, Monte Carlo simulation is conducted considering the valve operation success ratio and pipe failure analysis. The valve operation ratio indicates the probability that a valve operates successfully when the valve is closed due to pipe failure. At that time, if a valve fails and cannot be closed, the segment will be expanded up to the neighboring valves successfully closed. For example, if pipe 6 fails, valves 1 and 2 are closed to isolate pipe 3, pipe 6 and node 6. However, if valve 2 malfunctions as indicated in Figure 3, the segment is expanded to cover pipe 3, pipe 6, pipe 8, node 4, node 5 and node 6, increasing the undelivered demand. Therefore, the valve operating rate is considered in this chapter because this factor can be used to evaluate reasonably the damage in the present WDSs.
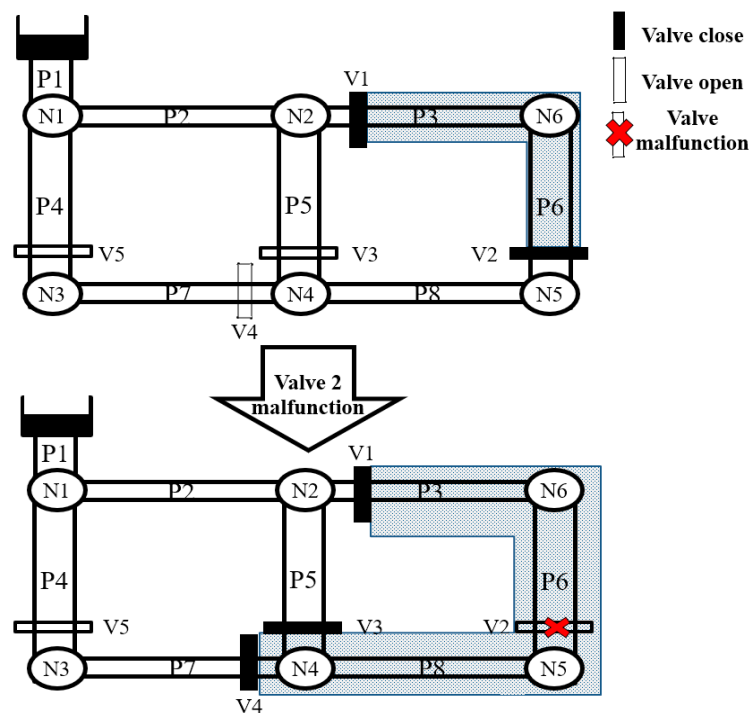

Figure 3. Concept of valve failure impact.

2.2. Segment Identification Algorithm

The segment finding algorithm was developed by Jun et al. [14] and introduced three matrices (i.e., the node-arc, valve location and valve deficiency matrices) to identify a segment based on valve location in WDSs. These three matrices have the same configuration, in which a row represents a node and a column represents a pipe. Figure 4 presents an example of segment identification.
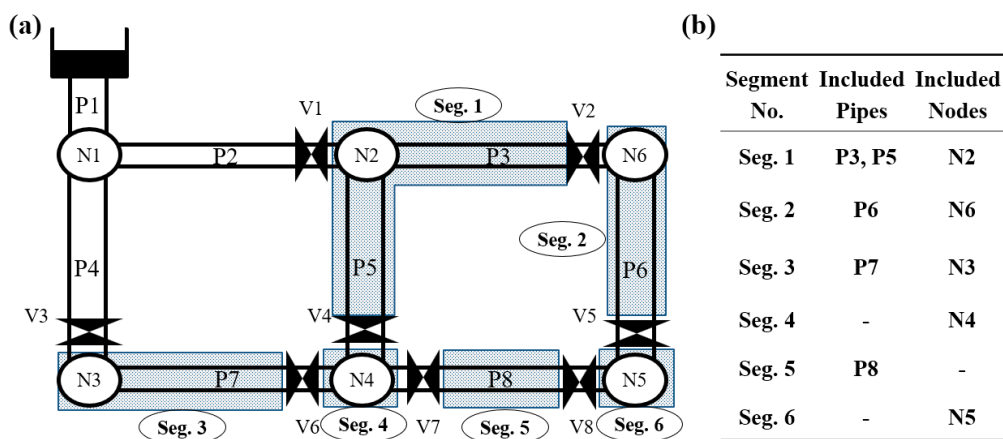

Figure 4. Example of segment identification: (**a**) Example network; (**b**) Results of segment identification.

Node-Arc matrix

The node-arc matrix shows the relationship between the nodes and pipes that constitute the WDSs. If there are nodes corresponding to both ends of the pipe, the value is 1; if not, the value is 0. Table 2(a) is an example of a node-arc matrix.

Valve Location Matrix

The valve location matrix indicates the position of the drain valve. If the valve is located at one end nodes of the pipe, the value is 1; if not, the value is 0. Table 2(b) is an example of a valve location matrix.

Valve Deficiency Matrix

The valve deficiency matrix is composed of the difference between the node-arc and valve location matrices and indicates points with and without installed valves. A matrix value of "1" indicates that no valve is installed at that point, while "0" indicates that there is a valve. An example of a valve deficiency matrix is presented in Table 2(c). The segment finding algorithm is based on the valve deficiency matrix and repeats row and column searches to identify all the segments of the WDSs. To understand the segment search process, the following is an explanation of the identification process of Seg. 1. First, a column search is performed on P3 in the matrix to find "1." At this time, a value of "1" is found at point (N2, P3). A row search is then performed on N2 to find "1." As a result of the row search, "1" is found at P5. As P5 is found on the N2 row, rather than P3, a column search is performed for P5. After the column search, "1" is not found in row P5; therefore, the search process is finished. The segment identification then shows that N2 is within Seg. 1 after the column search and P3 and P5 are included in Seg. 1 as a result of the row search. Therefore, Seg. 1 is composed of P3, P5 and N2. The segment can be found based on the pipe in a similar manner. If all columns and rows in the valve deficiency matrix are "0", the pipe or node can be identified as an independent segment.

As a follow-up to the segment search algorithm, Jun et al. [14] proposed an optimal segment design technique for WDSs. This technique automated segment and unintentional isolation identification; it can be applied to large-scale WDSs and suggests an efficient method of segmenting one that is over-designed. However, when selecting segments to be divided, only the population is

considered and the optimal valve location is selected based on the experience of the engineer, not by a mathematical algorithm.

Table 2. Three segment-identifying matrices: (**a**) Node-Arc Matrix; (**b**) Valve Location Matrix; (**c**) Valve Deficiency Matrix.

Node \ Pipe	1	2	3	4	5	6	7	8
(a)								
Source	1	0	0	0	0	0	0	0
1	0	1	0	1	0	0	0	0
2	0	1	1	0	1	0	0	0
3	0	0	0	1	0	0	1	0
4	0	0	0	0	1	0	1	1
5	0	0	0	0	0	1	0	1
6	0	0	1	0	0	1	0	0
(b)								
Source	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0
3	0	0	0	1	0	0	0	0
4	0	0	0	0	1	0	1	1
5	0	0	0	0	0	1	0	1
6	0	0	1	0	0	0	0	0
(c)								
Source	1	0	0	0	0	0	0	0
1	0	1	0	1	0	0	0	0
2	0	0	1	0	1	0	0	0
3	0	0	0	0	0	0	1	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	1	0	0

Therefore, this study proposes a new criterion for evaluating segment importance, as well as the number of water users and a multicriteria decision technique is used to prioritize segments that should be divided.

Multicriteria decision techniques can determine the priorities of the segments that need to be divided and a new valve location determination technique is proposed that could replace the engineer's experience when the additional valve installation location for the highest priority segment is decided.

2.3. Critical Segment Selection Technique

In the existing optimal valve location determination technique, only the number of water users is considered when selecting the segment to be divided. This makes the selection process more efficient. Moreover, the selection of the valve location for optimal segmentation is based on the experience of the engineer, rather than a quantitative approach using a mathematical algorithm.

However, as WDSs performance and behavior is closely related to social and economic activities, the segments to be reinforced should be selected considering various criteria, including social and economic aspects as well as hydraulic.

Therefore, in this section, the segment to be divided by installing more valves is determined considering several criteria, including social, socio-economic and hydraulic factors, using multicriteria decision-making techniques. The multicriteria decision-making model applied in this study is the weighted utopian approach [15] that combines a weighting method and multi-criteria decision-making.

2.3.1. Weighted Utopian Approach

Decision problems are prioritized according to comparisons between alternatives (i.e., the diversity of alternatives, the evaluation criteria of the decision maker, or the objective of the decision) and the best alternative is then selected. When considering various decision factors, most cases have a trade-off relationship. Therefore, a compromise need to be presented that meets both conflicting standards.

When making decisions, the weight of each factor cannot be the same and the most important factor in decision-making is the method by which the weight that represents the relative importance among those factors is determined. However, the utopian approach proposed by Xanthopulos et al. [16] assumed that the weight of each factor is the same; therefore, it cannot reflect realistic decision-making and risks the production of results different from reality. To overcome the limitations of the existing utopian approach, Yoo et al. [15] proposed a weighted utopian approach that combines weight determination techniques with the utopian approach. As the weighted utopian approach can simultaneously consider various weighting methods, it can not only identify a reasonable alternative but also allow flexible coping by broadening the choice of alternatives according to the situation.

If there are two factors (F1 and F2) used for decision-making, the alternative factor can be expressed as Figure 5a by normalizing the two factors to values between 0 and 1. In this case, the weight of each factor has the same value and the coordinate of the utopian point is (1, 1). However, after calculating the weights of F1 and F2 following various weighting determination approaches, the weighted coordinate is that shown in Figure 5b. For example, when the weights of F1 and F2 are 0.6 and 0.4, respectively, the coordinates of the utopian point are (0.6, 0.4). The Euclidean distance is commonly used to determine the distance between a utopian point and an alternative and the formula to calculate it is shown in Figure 5b. The priority of the alternatives is determined in the order of the shortest Euclidean distance.
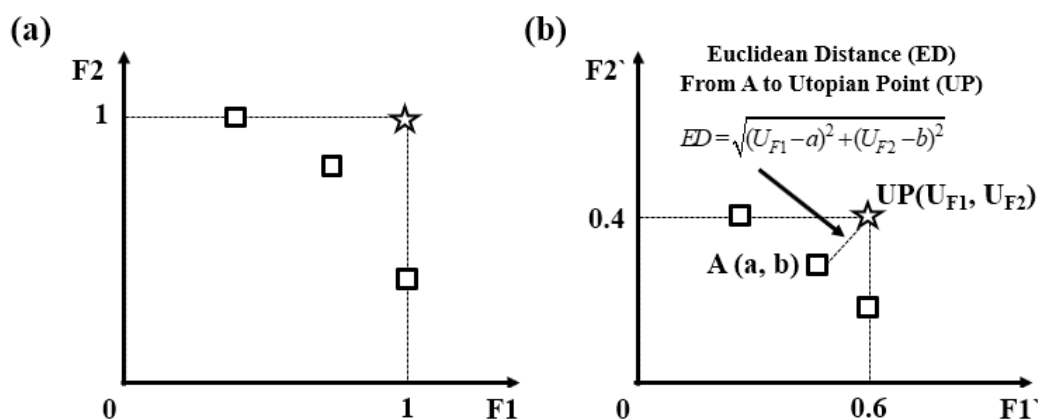

Figure 5. Concept of (**a**) utopian approach; (**b**) weighted utopian approach.

2.3.2. Determination Weight Factor Approaches

The most important task in decision-making and prioritization is the determination of each factor's weight, which represents the relative importance of different factors.

Many previous studies [17–19] have calculated the relative weights of each factor using the multicriteria decision-making technique. This study applies seven of these approaches (Table 3) to calculate relative weight in multicriteria decision-making.

Table 3. Determination weight factor approaches.

Approaches	Description
Rating scale [15]	$\omega_j = \dfrac{\sum\limits_{k=1}^{l} \omega_{jk}}{\sum\limits_{j=1}^{n} \sum\limits_{k=1}^{l} \omega_{jk}}$ (where, $\omega_{jk} = r_{jk} / \sum\limits_{j=1}^{n} r_{jk}$) (3.1)
Churchman-Ackoff [16]	$\omega_j = \dfrac{J}{\sum\limits_{j=1}^{n} j} = \dfrac{2J}{n(n+1)}$ (3.2)
Eigenvector [17]	$A\omega = \lambda_{\max}\omega$ (3.3)
Rank order centroid weights [18]	$\omega_j = \dfrac{1}{n} \sum\limits_{k=k}^{n} \dfrac{1}{k}$ (3.4)

Note. ω_j = weighting factor of the j-th attribute, j = attribute (j = 1, 2, ... , n), n = number of attributes, k = respondent (k = 1, 2, ... , l), l = number of respondents, r_{jk} = rating of respondent k, J = rank of the importance of the j-th attribute, A = positive pairwise comparison reciprocal matrix, $\lambda_{\max}$ = maximum eigenvalue of A.

## 3. Applications and Results

3.1. Study Networks

This study proposes a framework for improving WDSs robustness: Optimal valve installation. To optimally install a valve, the priority segment to be divided is determined using the weighted utopian approach that considers the weights of each factor considered in the multicriteria decision techniques. A new valve location is then determined considering pipe failure analysis and the valve operation success ratio.

To verify the proposed technique, a well-known benchmark (i.e., the Pescara network) and real-world water distribution networks (i.e., the G-city network) are studied.

Pescara network

The Pescara Network was first proposed by Bragalli et al. [20]. This network consists of three reservoirs, 99 pipes, 71 nodes and 498.28 (LPS) total system demand. The network is reconstructed to apply the optimal valve installation technique proposed in this study by randomly arranging 67 valves and socially important facilities. The Pescara network's layout is shown in Figure 6.
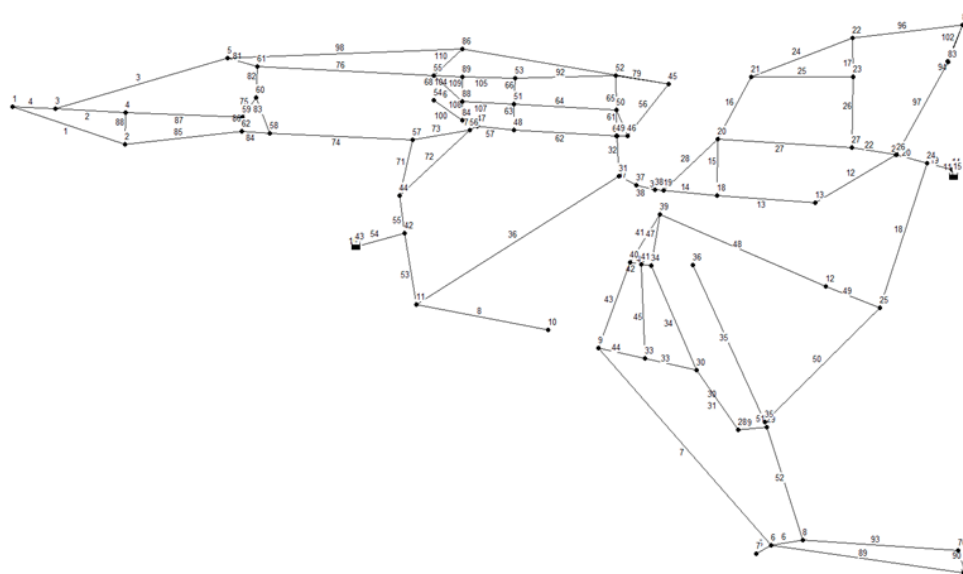
Figure 6. Layout of the Pescara network.

G-city network

The G-city network consists of three blocks. As shown in Figure 7, A block mostly consists of housing, some apartments and a commercial district and most of the water supplied to this block is obtained from the Noon Reservoir. B block mostly contains apartments and commercial districts centering on the Haan/Chulsan Reservoir, and C block consists of housing, apartments and commercial and industrial districts supplied by the Soha Reservoir.
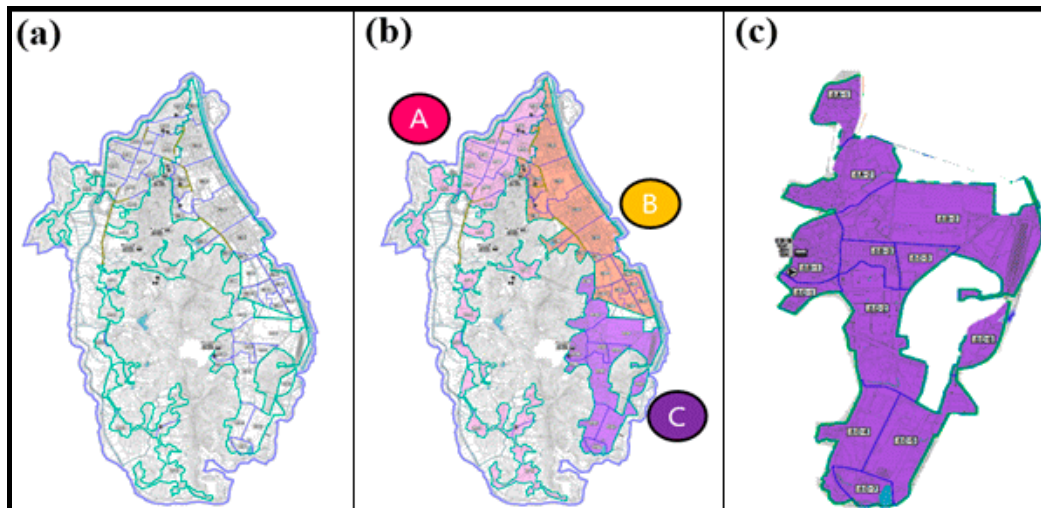

Figure 7. Layout of the G-city network: (**a**) map of G-city city; (**b**) three subnetworks; (**c**) selected subnetwork (C block).

The proposed technique to enhance the robustness of the WDSs in this study is applied to C block to assess the technique's application to various water use types. As shown in Figure 7c, C block consists of one reservoir, 648 pipes with a total length of 69,494.3 m and 511 nodes. Total system demand is 14,097.96 CMD and each pipe is installed from 11 commercial pipe sizes available (80, 100, 150, 200, 250, 300, 400, 500, 600, 800, 1000 mm). This block has approximately 46,900 water supply users and 531 valves. The valve construction cost is calculated using the construction costs of the WDSs function (Clark et al., [21]) as following Equation (1). The construction costs function accounts for the pipe material and installation in Table 4.

$$y = a + b(x^c) \tag{1}$$

where y = the valve construction cost ($); x = the pipe diameter in inches (1 in. = 2.54 cm); and a, b and c are component specific parameter values estimated using regression analyses.

Table 4. Valve construction cost parameters based on Clark et al. [21].

Frequency of Installation	Pipe Diameter	Parameters			R^2
		a	b	c	
Low [a]	10.16–91.44 cm (4–36 in.)	4.4	0.48	0.62	0.99
Medium [a]	10.16–91.44 cm (4–36 in.)	9.8	0.02	1.8	0.58
High [a]	10.16–91.44 cm (4–36 in.)	18.3	0.081	1.8	0.90
Low [b]	30.48–182.88 cm (12–72 in.)	5.4	0.0	0.0	0.99
Medium [b]	30.48–182.88 cm (12–72 in.)	15.7	0.0	0.0	0.99
High [b]	30.48–182.88 cm (12–72 in.)	32.7	0.001	2.7	0.81

Note. [a] Ductile iron fittings, [b] Steel fittings.

3.2. Benchmark Network: Pescara Network

First, the segment is identified based on valve location, pipe and node information. A valve deficiency matrix was generated by calculating the difference between the node-arc matrix that represents the relationship between the pipe and the node and the valve location matrix that represents the location of the valve.

Based on the three matrices, the segment identification algorithm was applied and the results are presented in Table 5. The whole network was divided into 35 segments based on randomly installed 67 valves.

Table 5. Criteria of segment priority.

The Weight Factor Approaches / The Criteria of Segment Priority		Rating	Churchman-Ackoff	Eigenvector	Rank Order Centroid Weights
Hydraulic Importance	Undelivered demand (the number of water users)	0.225	0.250	0.521	0.250
	Incensement of head loss for isolation of segment	0.141	0.146	0.112	0.146
	Number of valves to isolate of segment	0.096	0.104	0.081	0.104
Social Importance	Important facilities	0.119	0.117	0.085	0.117
	Composition of ages	0.035	0.066	0.017	0.066
	Restoration infrastructure (equipment, person, system)	0.079	0.029	0.013	0.029
Socio-economic Importance	Average income level	0.086	0.080	0.028	0.080
	Characteristics of the water user (residential district, commercial district, industrial district)	0.086	0.087	0.024	0.087

After segment identification, the priority of the segments was determined using the multicriteria decision-making model to improve the robustness of the existing WDSs (i.e., the weighted utopian approach). The result of calculating weights are presented in Table 5. Using this approach, the priority of the segments that need to be divided are determined the undelivered demand and the number of important facility and Table 6 shows the priority factors (i.e., the undelivered demand and the number of important facility) in each segment.

As the weight of each criterion differs according to the approach, four approaches were used for the calculations and the final weight factor of each criterion is an average value. The final segment division priority is shown in the final column of Table 7. As the weighting approaches were different, excellence cannot be judged but the sensitivity of the weighting must be considered.

Based on the calculated segment division priority in Table 7, segment 10 ranks first. The location of segment 10 corresponds to the blue shaded area in Figure 8. It contains 12 nodes and 16 pipes. The undelivered demand for segment 10 is 91.19 LPS and this segment could cause the greatest damage among all segments if one pipe fails.

To minimize undelivered demand, segment 10 is divided into two segments if one valve is installed in the direction of node 12 of pipe 49, as shown in Figure 9. As a result, the maximum undelivered demand decreased from 91.19 to 72.1 LPS and the length-weighted average undelivered demand decreased from 35.88 to 26.11 LPS.

Table 6. Segment identification result of Pescara network.

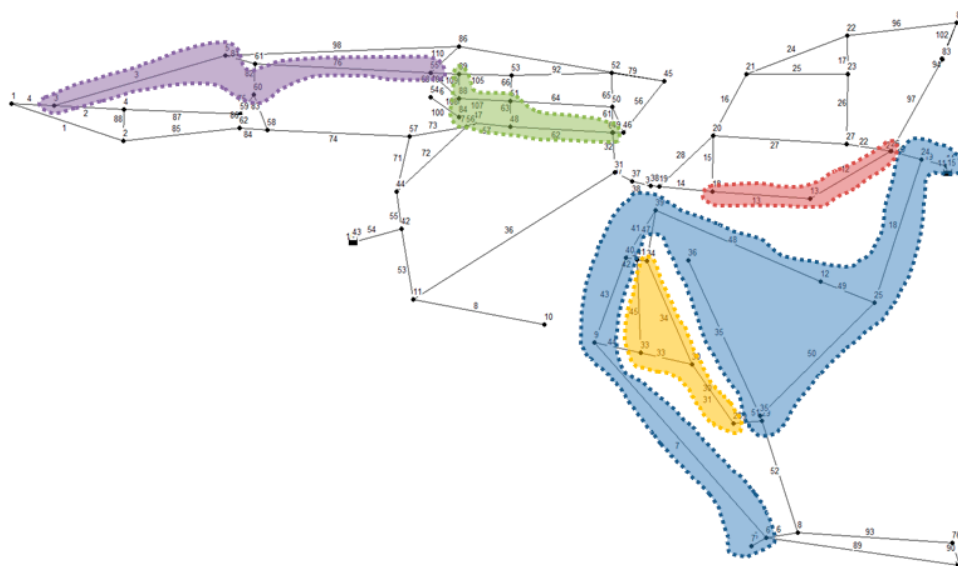| Segment No.	Node No.	Pipe No.	Undelivered Demand (LPS)	Important Facility
1	-	15	0	0
2	-	25	0	0
3	-	29	0	0
4	-	48	0	0
5	-	60	0	0
6	-	61	0	0
7	-	79	0	0
8	1, 2, 59	1, 77, 78	29.88	0
9	4	80	8.5	0
10	6, 7, 9, 12, 14, 22, 23, 27, 33, 34, 37, 38	5, 7, 9, 16, 17, 26, 32, 37, 39, 40, 43, 44, 45, 46, 47, 81	91.19	0
11	8	6	33.6	0
12	10, 11	8, 33	46.17	0
13	13, 15, 16, 24	10, 11, 13, 18, 19, 88	18.07	0
14	17	12, 36	4.81	0
15	18, 19	14, 22	37.98	0
16	20, 61, 62, 64	21, 85, 86, 87, 91	10.79	1
17	21	23	2.17	0
18	25	20, 24	5.32	1
19	26, 28, 31, 32, 39	27, 28, 30, 31, 38, 41, 42	18.41	1
20	30, 43, 47	52, 54, 55, 56, 57	19.26	1
21	35	34	12.64	1
22	36	35	12.64	1
23	40, 41	49, 51, 65	12.13	1
24	42	72,	6.21	1
25	44, 53, 54	64, 66, 67	12.33	1
26	45, 46, 48, 63, 67, 68	53, 58, 59, 62, 95, 96, 97, 98	24.35	1
27	49, 50	71, 94	8.98	0
28	51	90	0	1
29	3, 5, 52, 62	2, 3, 4, 63, 73, 83, 89, 93, 99	31.92	2
30	56, 57	69, 74	6.02	2
31	58	70	5.14	1
32	60	84	0	0
33	70	50	0	0
34	29	68, 75, 76, 82, 92	6.4	0
35	66	92	25	0

Figure 8. Five segments above the dividing priority.

Table 7. Priority of segment division.

| Segment No.	Undelivered Demand	Important Facility	Priority
1	0	0	27
2	0	0	27
3	0	0	27
4	0	0	27
5	0	0	27
6	0	0	27
7	0	0	27
8	29.88	0	6
9	8.5	0	18
10	91.19	0	1
11	33.6	0	4
12	46.17	0	2
13	18.07	0	11
14	4.81	0	24
15	37.98	0	3
16	10.79	1	16
17	2.17	0	25
18	5.32	1	22
19	18.41	1	10
20	19.26	1	9
21	12.64	1	12
22	12.64	1	12
23	12.13	1	15
24	6.21	1	20
25	12.33	1	14
26	24.35	1	8
27	8.98	0	17
28	0	1	26
29	31.92	2	5
30	6.02	2	19
31	5.14	1	23
32	0	0	27
33	0	0	27
34	6.4	0	21
35	25	0	7
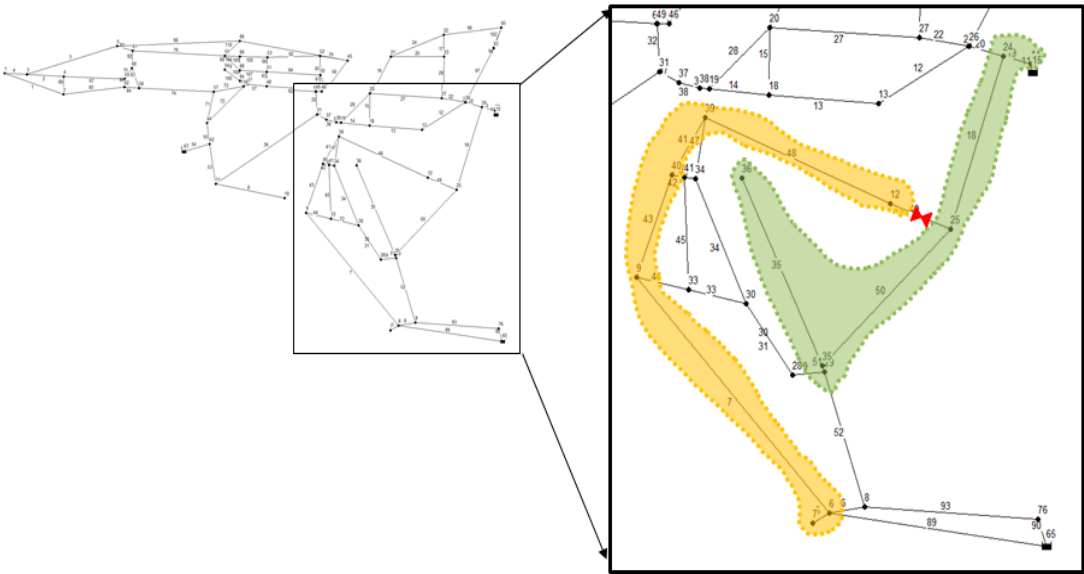
Figure 9. Result of optimal valve installation for segment division.

Similarly, one valve was installed to the five segments with the highest division priority and each segment was divided into two. The 35 segments were divided into 40 by the addition of five new valves and this segment division simultaneously decreased damage. Table 8 shows the optimal valve installation for dividing the top five segments.

Table 8. Result of optimal valve installation after top five segment divisions.

Segment No.	Node No.	Pipe No.	Undelivered Demand (LPS)
1	-	15	0
2	-	25	0
3	-	29	0
4	-	48	0
5	-	60	0
6	-	61	0
7	-	79	0
8	1, 2, 59	1, 77, 78	29.88
9	4	80	8.5
10	6, 7, 9, 12, 14, 22, 23	5, 7, 9, 16, 17, 26, 32, 37	29.52
11	27	39	33
12	33	40, 43	8.79
13	34, 37, 38	44, 45, 46, 47, 81	19.88
14	8	6	33.6
15	10	8	16.4
16	11	33	29.77
17	13, 15, 16, 24	10, 11, 13, 18, 19, 88	18.07
18	17	12, 36	4.81
19	18	14	21.04
20	19	22	16.94
21	20, 61, 62, 64	21, 85, 86, 87, 91	10.79
22	21	23	2.17
23	25	20, 24	5.32
24	26, 28, 31, 32, 39	27, 28, 30, 31, 38, 41, 42	18.41
25	30, 43, 47	52, 54, 55, 56, 57	19.26
26	35	34	12.64
27	36	35	12.64
28	40, 41	49, 51, 65	12.13
29	42	72,	6.21
30	44, 53, 54	64, 66, 67	12.33
31	45, 46, 48, 63, 67, 68	53, 58, 59, 62, 95, 96, 97, 98	24.35
32	49, 50	71, 94	8.98
33	51	90	0
34	3, 5, 52, 62	2, 3, 4, 63, 73, 83, 89, 93, 99	31.92
35	56, 57	69, 74	6.02
36	58	70	5.14
37	60	84	0
38	70	50	0
39	29	68, 75, 76, 82, 92	6.4
40	66	92	25

From Table 9, we can confirm that with the optimal valve location approach, the damage caused by WDSs failure can be significantly mitigated even though supplemental source is not added by the efficient installation of the valve to find the critical segment causing serious damage in the pipe failure.

Table 9. Comparison of the results between original design and improved design.

Comparison Criteria	Original Design	Improved Design
The number of segments	35	40
Maximum undelivered demand (LPS)	91.19	33.60
Length weighted average undelivered demand (LPS)	35.88	18.44

3.3. Real-World Network: G-City Network

The robustness improvement technique proposed in this study was verified by applying it to the previous benchmark WDSs. This chapter evaluates the influence of the optimal valve installation technology for segment division by applying it to a real-world network (i.e., G-city Network).

Using the information from the G-city WDSs in Section 3.1, a total of 383 segments of the entire network were identified by their valves. Unintended isolation occurred in 40 of these segments. As shown in Figure 8, four large-scale segments that affected more than 5% of the total water users during pipe breakages were identified. The results of the large-scale segment analysis are presented in Table 10. In Figure 10, there are four important facilities in this area: two hospitals, one elderly center and one fire station.
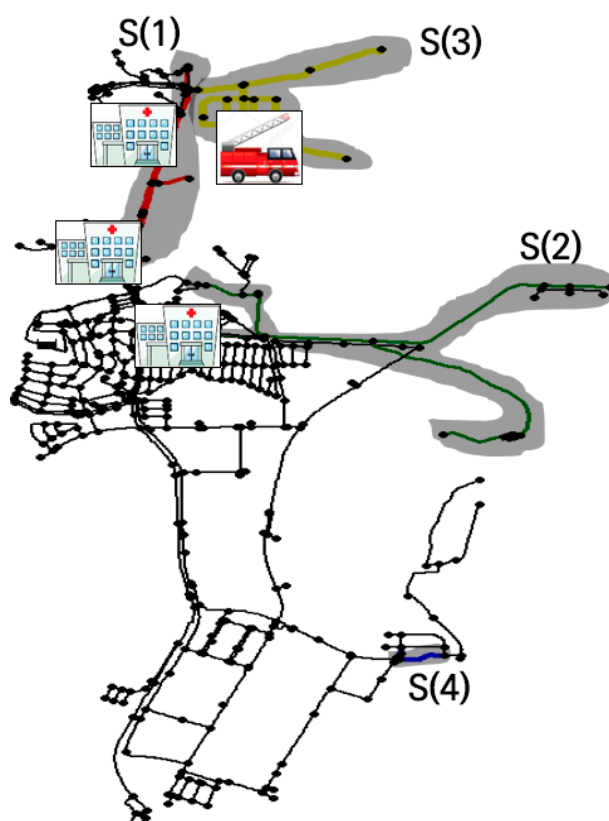
Figure 10. Location of the large-scale segment and important facilities.

In the case of segment S(1), more than 10% of all water users could be affected by abnormal conditions, such as system failure. In addition, the segment division priority was determined considering the segment priority criteria given in Table 6. Therefore, S(1), S(2) and S(3), where the expected impact is the greatest and important facilities are located, were selected as priority areas for segment division. The design was then reinforced with additional valve installation.

Expected damage was minimized through reinforcing system design according to segment division priority. To effectively determine the position and number of additional valves, the sensitivity analysis was conducted by changing the number of valves and their installation locations.

Table 10. Analysis results for large-scale segments.

| Segment ID	S(1)	S(2)	S(3)	S(4)
# Direct Customers	2103	2588	632	226
# UI Customers	2503	622	1374	1765
# Total Customers	4606	3210	2006	2001
# Valves	17	7	2	5
# Pipes	33	17	8	6
# UI Pipes	53	9	17	15
# Total Pipes	86	26	25	21

For an analysis of the valve location sensitivity, the candidate valve locations are set based on engineering knowledge from among all potential locations. In case of G-city network, 30 valve location candidates (30 locations) are selected among all possible valve installation locations (116 locations) based on engineering knowledge. Using the selected valve location candidates, the additional valve is installed sequentially and calculate the maximum number of damaged customers, according to the additional valve installation in the whole segment during pipe failure analysis. After then, the effect (the maximum number of damaged customers) of valve installation is compared for different location and determine the optimal valve location. After the first optimal valve location determination, repeat from Step 1 to find the second valve location. To verify the efficiency of the additional valve, the valve operation rate (assuming 90%) and pipe failure analysis was performed. Valves operate for maintenance in the abnormal condition, such as pipe failure. However, if the valve does not work at this time, the damaged segment will expand. Therefore, to evaluate the reasonable damage in the present WDSs, the valve operating rate was considered. To determine the number of additional valves, the relationship between the number of additional valves and the maximum number of customers affected under pipe failure situations was checked as shown in Table 11 and Figure 11. Table 11 presents the impact of valve installation with the maximum damage owing to the increasing number (≈ the valve construction cost) of valves in the 30 candidate locations. The valve construction cost is calculated using the Equation (1) and the installation condition assumes as the medium frequency in Table 4.

The number of valves was gradually increased and the damage reduction effect was evaluated. Then, the number of appropriate valves was determined from the number of marginal valve numbers in Figure 11 that yield optimal efficiency with additional valve installation. In the case of the Gwangmyung network, as the number of additional valves increases, the maximum number of affected customers was reduced and the greatest damage reduction effect could be achieved by installing eight additional valves. The eight valves are installed on the 300, 400, and 600 mm pipes. It means that installing a valve on the main pipeline is a good efficiency.

Therefore, eight additional valves were installed in the top three of the priorities of segment dividing (Segment S(1) to S(3)). As a result, the expected water user damage caused by large-scale segments decreased to less than 5%. In addition, three large-scale segments were divided into eight small segments through eight valves. Table 12 shows the result of adding eight new valves. Compared with the installation of additional valves, the maximum number of affected water users in segment S(1) was reduced from 4606 to 1986 (56.8%) by the installation of four additional valves. Likewise, S(2) and S(3) were installed three and one additional valve(s) and the expected damage decreased by 17.8 and 67.9% respectively.

Table 11. Effect of damage reduction by increasing the number of additional valves in G-city network.

# Total Additional Valve	Maximum Damaged Customers	Valve Construction Cost ($)	# Additional Valve			Maximum Damaged Customers		
			S(1)	S(2)	S(3)	S(1)	S(2)	S(3)
0	4606	0				4606	3210	2006
1	4606	15.7			1	4606	3210	1649
2	3210	31.4	2			3008	3210	2006
3	3210	47.1	2		1	3008	3210	1649
4	3210	62.8	3		1	2103	3210	1649
5	2113	78.5	3	2		2103	2113	2006
6	2103	94.2	3	3		2103	1029	2006
7	2103	109.9	3	3	1	2103	1029	1649
8	1986	125.6	4	3	1	1986	1029	1649
9	1986	141.3	4	3	2	1986	1029	1649
10	1831	157.0	6	3	1	1831	1029	1649
11	1831	172.7	6	3	2	1831	1029	1531
12	1831	188.4	6	3	2	1831	1029	1531
13	1649	204.1	9	3	1	1392	1029	1649
14	1649	219.8	9	4	1	1392	983	1649
15	1649	235.5	9	5	1	1392	891	1649
16	1392	251.2	9	3	4	1392	1029	1001
17	1392	266.9	10	3	4	1392	1029	1001
18	1029	282.6	11	3	4	975	1029	1001
19	1001	298.3	11	4	4	975	983	1001
20	1001	314.0	11	5	4	975	891	1001
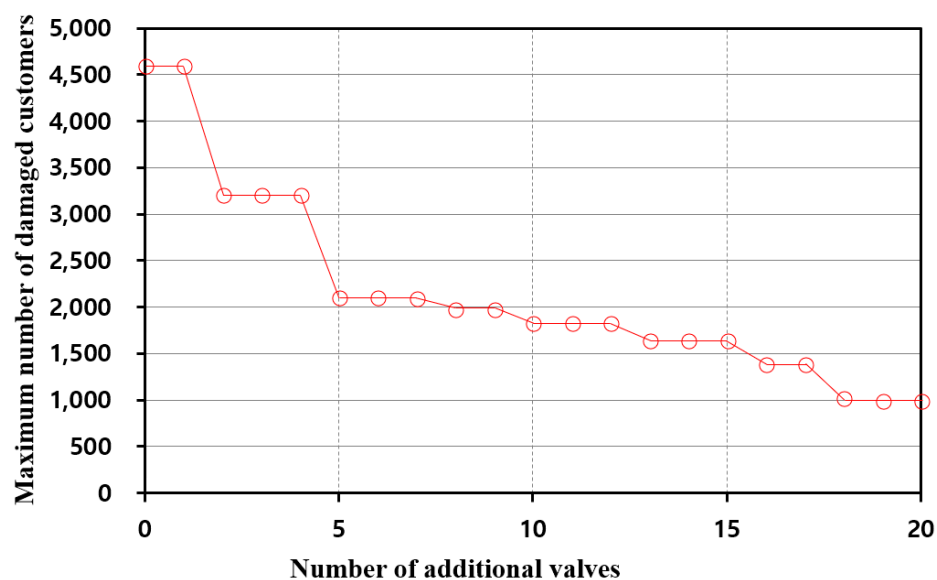
Figure 11. Relationship between the number of valves and maximum number of customers affected in G-city network.

Table 12. Comparison number of affected water users in the reinforcement design.

Segment ID	Original Design	Improved Design	# Additional Valve
S(1)	4606	1986	4
S(1)	3210	1029	3
S(2)	2006	1649	1

4. Conclusions

This study investigated the framework of improving WDSs robustness by the installation of additional valves. For this objective, three approaches were applied, namely segment finding algorithm, critical segment selection technique and valve location determination. Using the segment finding algorithm, the segment and the unintentional isolation were identified. To select the segments to be divided, a multicriteria decision technique considering the hydraulic, social and socio-economic

criteria was used as a technique for evaluating the critical segment selection technique. In this study, a questionnaire survey analysis was applied to the experts in the field of WDSs for evaluating the relative importance and among the criteria, the undelivered demand and the location of important facilities were selected for identifying the priority of the segment. To improve the segment robustness, a new valve location determination technique was proposed that could replace the engineer's experience. This technique performed pipe and valve failure analysis and the analysis of the trade-off relationship between the number of additional valves and the maximum damage for determining optimal valve locations and number of additional pipes. To verify the results, two WDSs were applied. Simulation results of the relationship between the number of additional valves and the maximum damaged customers showed that for the G-city network, the maximum damage of water users in the segment can be reduced by more than 50% by the installation of eight additional valves. This result is because the priority of dividing segment is determined to the undelivered demand and the important facility by multi-criteria decision-making approach. In other words, if you apply different criteria for other networks, the results of valve installation that can improve robustness will be changed. For example, if the composition of ages is selected as an important criterion, the additional valves are installed around the elderly care facility and the residence for elderly people to reduce the damage of shut off the water.

In conclusion, this study verified the framework of improving WDSs robustness and using the optimal valve location approach proposed in this study, we confirmed that the damage caused by WDSs failure can be significantly mitigated, without adding any supplemental source. This study had several limitations that future research should address. A hydraulic analysis (i.e., pressure driven analysis) for additional valve installation should be performed to investigate its effect and confirm the findings of this study. In case of changing the system total demand or network isolation (e.g., the additional valve installation or segment isolation), the demand driven analysis (DDA) is not suitable. Because in the abnormal conditions, DDA model may produce unrealistic outputs such as negative pressure. Therefore, future studies will develop more realistic valve installation techniques considering the pressure driven analysis.

Author Contributions: Y.H.C. wrote the draft of the manuscript and provided this model. D.J. and H.J. carried out the survey of previous studies. Y.H.C., D.J., H.J. and J.H.K. conceived the original idea of the proposed method.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Bruneau, M.; Chang, S.E.; Eguchi, R.T.; Lee, G.C.; O'Rourke, T.D.; Reinhorn, A.M.; Von Winterfeldt, D. A framework to quantitatively assess and enhance the seismicresilience of communities. *Earthq. Spectra* **2003**, *19*, 733–752. [CrossRef]
2. Hashimoto, T.; Stedinger, J.R.; Loucks, D.P. Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. *Water Resour. Res.* **1982**, *18*, 14–20. [CrossRef]
3. Lansey, K. Sustainable, robust, resilient, water distribution systems. In Proceedings of the WDSA 2012: 14th Water Distribution Systems Analysis Conference, Adelaide, Australia, 24–27 September 2012.
4. Jung, D.; Kang, D.; Kim, J.H.; Lansey, K. Robustness-based design of water distribution systems. *J. Water Resour. Plan. Manag.* **2013**, *140*. [CrossRef]
5. Walski, T.M. Water distribution valve topology for reliability analysis. *Reliab. Eng. Syst. Saf.* **1993**, *42*, 21–27. [CrossRef]
6. Goulter, I.; Walski, T.M.; Mays, L.W.; Sekarya, A.B.A.; Bouchart, R.; Tung, Y.K. Reliability analysis for design. In *Water Distribution Systems Handbook*; Mays, L.W., Ed.; McGraw-Hill and American Water Works Association: New York, NY, USA, 2000.

7. Bouchart, F.; Goulter, I. Reliability improvements in design of water distribution networks recognizing valve location. *Water Resour. Res.* **1991**, *27*, 3029–3040. [CrossRef]

8. Hoff, J.W. Maintenance requirements of valves in distribution systems. In Proceedings of the Annual Conference Proceedings AWWA, Toronto, ON, Australia, 23–27 June 1996.

9. Whittaker, A.R.; Arscott, A.W. Development of an intelligent valve key to improve identification and control of distribution system valves. In Proceeding of the Annual Conference Proceedings AWWA, Atlanta, GA, USA, 15–19 June 1997; pp. 229–237.

10. Skousen, P.L. *Valve Handbook*; McGraw-Hill: New York, NY, USA, 1997.

11. Jung, D.; Yoo, D.G.; Kang, D.; Kim, J.H. Linear model for estimating water distribution system reliability. *J. Water Resour. Plan. Manag.* **2016**, *142*. [CrossRef]

12. Jowitt, P.W.; Xu, C. Optimal valve control in water-distribution networks. *J. Water Resour. Plan. Manag.* **1990**, *116*, 455–472. [CrossRef]

13. Araujo, L.S.; Ramos, H.; Coelho, S.T. Pressure control for leakage minimisation in water distribution systems management. *Water Resour. Manag.* **2006**, *20*, 133–149. [CrossRef]

14. Jun, H.; Loganathan, G.V.; Deb, A.K.; Grayman, W.; Snyder, J. Valve distribution and impact analysis in water distribution systems. *J. Environ. Eng.* **2007**, *133*, 790–799. [CrossRef]

15. Yoo, D.G.; Kang, D.; Jun, H.; Kim, J.H. Rehabilitation priority determination of water pipes based on hydraulic importance. *Water* **2014**, *6*, 3864–3887. [CrossRef]

16. Xanthopulos, Z.; Melachrinoudis, E.; Solomon, M.M. Interactive multiobjective group decision making with interval parameters. *Manag. Sci.* **2000**, *46*, 1585–1601. [CrossRef]

17. Eckenrode, R.T. Weighting multiple criteria. *Manag. Sci.* **1965**, *12*, 180–192. [CrossRef]

18. Knoll, A.L.; Engelberg, A. Weighting multiple objectives—The Churchman-Ackoff technique revisited. *Comput. Oper. Res.* **1978**, *5*, 165–177. [CrossRef]

19. Saaty, T.L. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*; McGraw-Hill International Book Co.: New York, NY, USA, 1980; p. 281.

20. Bragalli, C.; D'Ambrosio, C.; Lee, J.; Lodi, A.; Toth, P. On the optimal design of water distribution networks: A practical MINLP approach. *Optim. Eng.* **2012**, *13*, 219–246. [CrossRef]

21. Clark, R.M.; Sivaganesan, M.; Selvakumar, A.; Sethi, V. Cost models for water supply distribution systems. *J. Water Resour. Plan. Manag.* **2002**, *128*, 312–321. [CrossRef]