Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2017.20260

65 (2017) 153–162
February

Optimal design of a new water distribution network using a water supply risk assessment

Taeho Choi[a], Cheolho Bae[a], Hwisu Shin[b], Jayong Koo[b,*]

[a]*K-water Research Institute, Korea Water Resources Corporation, 125, Yuseong-daero, 1689 beon-gil, Yuseong-gu, Daejeon, 34045, Republic of Korea, emails: choistarth@kwater.or.kr (T. Choi), baech@kwater.or.kr (C. Bae)*
[b]*Department of Environmental Engineering, University of Seoul, Seoulsiripdae-ro 163, Dongdaemun-gu, Seoul, 02504, Republic of Korea, Tel. +82-2-6490-2866; Fax : +82-2-6490-5465; emails: twinklev007@uos.ac.kr (H. Shin), jykoo@uos.ac.kr (J. Koo)*

Received 13 March 2015; Accepted 15 October 2016

ABSTRACT

This study considered water supply risk (WSR) as well as the cost of a water distribution network (WDN) design, and developed an optimized model of pipe diameters and gate valves within the WDN. Thus, a multipurpose algorithm was used to implement an optimal WDN design that minimizes both WDN establishment costs and the Block WSR. The algorithm adopted was non-dominated sorting genetic algorithm II, which has most frequently been used. The optimal model was applied to Block A2, and the results showed that the Block WSR of each pipe after $Prob_{PB}$ was changed to 0.2 (case/km/year) from that of the existing design method. As a result, the Block WSR of the existing network design was 0.306 m^3/year, but that of the optimal network design was reduced by 10.1% to 0.275 m^3/year. The construction cost of the existing network design was 139,600,000 won, but that of the optimal network design was reduced by 59.7% to 56,300,000 won. While the construction cost of the network with the optimal design is much lower than that of the network with the existing design, the optimal design method can also reduce the Block WSR; thus, the optimal design model was proven effective. In addition, apart from construction costs, the Block WSR reduction effect due to the optimal design showed that the daily water cut-off of 8.8 persons/year can be prevented by the conversion of 296 L/Lpcd.

Keywords: Water supply risk; Water distribution network; Optimal design; NSGA II; Interpretive structural modeling

1. Introduction

The focus of water pipe facility infrastructure has mainly been on safety and the stability of the water supply. However, infrastructure designed with excessive focus on stability raise issues of extravagant use of resources and poor efficiency. In the past, economics were a partial consideration when water pipe facilities were planned, but currently, risk management of the water-cut-off scale and the water-cut-off duration in terms of service is not successfully conducted. Within the range that meets the water supply stability and the redundancy rate of an emergency, the suggestion of adequate design factors would enable the curtailment of resources and the economical operation of facilities. If the costs saved by using a minimum-cost design are earmarked for maintenance, repair, and management of facilities, then the durability of the facilities will be enhanced. So far, the design of a new water distribution network (WDN) has included an optimization method for an efficient water supply and construction expenditure curtailment. During such a design process, an optimal alternative, similar to an optimal solution, was to be selected by considering various scenarios and constraints. However, since this type of design is solely focused on cost efficiency of the new WDN, it is a design that considers only water suppliers, not water consumers.

* Corresponding author.

In order to improve the satisfaction of water supply services, careful management, starting from the design stage of the WDN, is required; therefore, the concept of water supply risk (WSR) should be considered.

This study aimed to design a new WDN model that minimizes construction costs and Block WSR. The focus was to derive optimal WSR values under various constraining conditions. To this end, this study used the non-dominated sorting genetic algorithm (NSGA II). NSGA II is a genetic algorithm used in two or more objective functions when it is difficult to standardize the relationship between objective functions to the same unit. Therefore, using NSGA II, the model development for WSR minimization was conducted to ensure feasible risk management for service improvements as well as an economical design of the WDN.

2. Literature review

In the optimization of the design of a water pipe network (WPN), the design has a single purpose; yet, due to the complexity of the pipe network, researches on an optimal design that considers multiple purposes such as cost, reliability, and risk have been actively undertaken during the twenty-first century. Walski [1] emphasized the necessity of new model development not only to minimize network costs but also to maximize the network function. The pipe network designer should design the head according to cost constraints, if possible, beyond the minimal head that is allowed at the node of the water supply system; the remainder head is used to overcome the head loss that increases under the conditions of demand or failure. In addition, Walski suggested the necessity of studies that apply purposes besides cost, such as a reliability index, to an objective function. Based on this point of view, literature trends were examined and reviews regarding single-purpose and multipurpose optimization techniques are arranged in Table 1.

In the existing studies, a genetic algorithm was most commonly used for the optimal design of the WPN. It was recently found that researches regarding the optimal design of a WPN using a multipurpose genetic algorithm have been actively conducted. However, to date, a multipurpose optimization technique for the optimal design of a WPN has not frequently been used, but when used, cases that applied the concept of WSR that took into account the consumers' side of WPN management were insufficient. Therefore, in this study, using the multipurpose genetic algorithm from among multipurpose optimization techniques, an optimal model of a new WDN for the minimization of establishment costs and the Block WSR was developed.

3. Research methods

This study considered WSR as well as the cost of WDN design, and developed a model of optimization of pipe diameters and gate valves within the WDN. Thus, a multipurpose algorithm was used to implement a WDN optimal design that simultaneously minimizes WDN establishment costs and the Block WSR. The algorithm adopted was NSGA II, which has most frequently been used. Our model was created based on Microsoft Visual C# 2010. To begin, for the WDN of the target area, optimal pipe diameters were designed using NSGA II and the EPANET 2.0 toolkit and, with regard to the WDN with the completed optimal pipe diameter using the above method, the optimal position of the gate valves was designed. NSGA II and the EPANET 2.0 toolkit were also used in the design of the gate valve. Constraints of the optimal design of pipe diameters were water velocity of pipes and node water pressure, whereas the constraint of the optimal location design of gate valves was the installment cost of the gate valves. The objective functions in the optimal diameter design and optimal location design of gate valves were Block WSR and installment costs. The process used in this study is shown in Fig. 1.

3.1. Target area

To estimate the WSR, this study used geographic information system data of total pipes, registers of leakage recovery, and water supply data of Block A2, WDN District

Table 1
Studies for single-objective and multiobjective optimization methods

Single-objective optimization methods		Multiobjective optimization methods	
References	Method	References	Method
[2]	Linear programming and pipe network analysis	[3]	Multiobjective genetic algorithm (structured messy genetic algorithm)
[4]	Quasi-Newton search and backtracking line search	[5]	Multiobjective genetic algorithm (vector evaluated genetic algorithm)
[6–12]	Genetic algorithm	[13]	B/C analysis
[14,15]	Simulated annealing	[16]	Multiobjective genetic algorithm (NSGA)
[17]	Evolutionary design algorithm and genetic algorithm	[18]	Latin hypercube

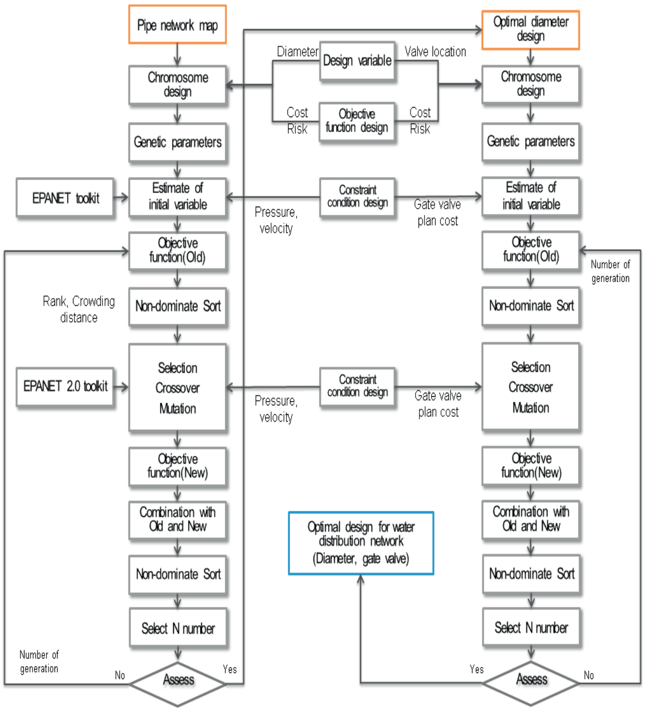

Fig. 1. Flow chart of optimal design model development for new water distribution network.

K in City S, and applied construction standard production unit system and related construction data in order to estimate embedment costs per pipe diameter. The number of pipes in Block A2 was 84, the number of connections was 237, and the pipe length was 5,706 m. The total demand of this area was 813.34 m^3/day, and Block A2 was adjacent to Blocks A1, B3, B5, and C7.

3.2. Model development of optimal pipe diameters

In developing a model with optimal pipe diameters that minimizes WSR, the pipe diameter was set as a design variable to design the chromosome for NSGA II, and pipe embedment cost and WSR were set as objective functions. Next, genetic parameters were determined and, using the EPANET 2.0 toolkit, the chromosome initial value was estimated with constraints (water velocity of pipes and node water pressure). Then, using the algorithm NSGA II, the pipe diameter that minimizes the embedment cost and Block WSR was determined. Detailed methods are as follows.

3.2.1. Chromosome design

In chromosome design using NSGA II, the pipe diameter is a design variable and pipe embedment cost and Block WSR are objective functions. Genes of chromosomes are expressed as whole numbers, and according to the whole numbers, the size of the diameter is determined. Genes according to diameter are expressed in Table 2.

The Block WSR, from among the objective functions, was defined by Choi and Koo [19], and it is estimated by the WSR estimation model. The estimation method of Block WSR can be described by using the following equations. WSR is the demand shortage of the pipe burst probability (Prob_{PB}) and is calculated as the product of Prob_{PB} and the impact of a pipe burst (Imp_{PB}). A Prob_{PB} function was produced by applying logistic regression. Logistic regression can be used to obtain the Prob_{PB} of each pipe unit, whereas previous statistical approaches predicted bursts in pipe groups that have similar characteristics. In addition, Imp_{PB} is classified into the impact on leakage duration time (LDT), from pipe burst to gate-valve closure, and on repair work time (RWT), from gate-valve closure to repair completion. Therefore, the WSR of each pipe is calculated as shown in Eq. (1).

Table 2
Gene representation of variables

Diameter (mm)	Gene
80	1
100	2
150	3
200	4
250	5
300	6
350	7
400	8

$$\text{Risk}_{pi} = \text{prob}_{pi} \times \left\{ \left(\text{impact}_{pi}^{1st} \times T^{1st} \right) + \left(\text{impact}_{pi}^{2st} \times T^{2st} \right) \right\} \quad (1)$$

where Risk_{pi} is the WSR of pipe i (m^3/year); prob_{pi} is the Prob_{PB} of pipe i (No./year); impact_{pi}^{1st} is the demand shortage in LDT for burst of pipe i (m^3/day); impact_{pi}^{2st} is the demand shortage in RWT for burst of pipe i (m^3/day); T^{1st} is the duration of LDT (day); and T^{2st} is the duration of RWT (day).

In order to estimate the WSR for each block, WSR values of pipes in the same block were averaged using Eq. (2).

$$\text{Risk}_b = \frac{\sum_{i=1}^{n} \text{Risk}_{pi}}{n} \quad (2)$$

where Risk_b is the Block WSR (m^3/year) and n is the pipe number in block.

The WSR of a WDN can be defined as the product of Prob_{PB} and Imp_{PB}. Prob_{PB} is estimated by logistic regression analysis using factors affecting pipe bursts and records of previous pipe bursts. However, since the target pipes are new, Prob_{PB} is set at 0.2 (case/km/year) in the current study. This is the minimal value among all Prob_{PB} of all pipes in the target area. Also, the WSR assessment model of the WDN is expressed as the product of Prob_{PB} and the Imp_{PB}. Imp_{PB} was classified into an impact index of LDT and an impact index of RWT. The sum of these two indexes was treated as the total impact index of the pipe burst. The assessment model was developed to estimate the impacts of water supply cut-offs and water supply cut-downs based on valve installation positions, pipe positions, and emergency connective pipes. Prob_{PB} was calculated using logistic regression analysis, and the impact of LDT was calculated using the EPANET 2.0 emitter. On the assumption that the leakage amount is proportional to the pressure of the node reached by each pipe, after leakage production, the demand shortage at all nodes was calculated in order to estimate the impacts. The impact on RWT was calculated using interpretive structural modeling and a concept of a "segment" based on the gate-valve boundary. To repair a pipe burst, the closest gate valve is closed, and "segments" are then made. Imp_{PB} on RWT was estimated by calculating the total demand shortage of "segments" caused by gate valves that were closed for pipe repair. LDT and RWT for each pipe were estimated by multiple regression analysis, and were then multiplied by the impacts of LTD and RWT in order to quantify the volume.

Imp_{PB} used in the model of optimal pipe diameters was the impact in LDT because it is not possible to estimate the impact in repair time that is influenced by gate valves during this design procedure of optimal diameters. As above, the WSR per pipe is expressed as the product of $Prob_{PB}$ and Imp_{PB}, which means the probable demand shortage due to a pipe burst. The Block WSR is calculated as the arithmetic mean of the WSRs per pipe. The second objective function, the pipe embedment cost, was regarded as the sum of material cost and construction cost. This total cost, detailed in Table 3, was used as the pipe embedment cost per pipe diameter.

Accordingly, the chromosomes were designed, as outlined in Table 4. These were used as the chromosomes of NSGA II for the model of optimal pipe diameters.

The initial values of chromosomes were estimated using a random function and the genes of integers converted from pipe diameters were set per pipe diameter though a random function. The set WDN was examined to verify if it was fit to the constraints using the EPANET 2.0 toolkit. Other pipes unfit to the constraints were reset using a random function. In particular, if the water velocity was found to be less than the minimal value of a constraint, the pipe diameter was reset using a random function within the range that is smaller than the diameter of the pipes determined by the random function. However, if the water velocity was found to be over the maximum value of a constraint, the pipe diameter was reset using a random function within the range that is larger than the diameter of the pipes determined by the random function. In the same way, the initial chromosome values were set to correspond to the initially set population.

Table 3
Total laying cost for each pipe diameter

Diameter (mm)	Cost (won/m)
80	148,200
100	156,700
150	183,500
200	205,600
250	235,300
300	264,800
350	293,200
400	314,900

3.2.2. Non-dominated sorting

Non-dominated sorting is one of the methods that find the most optimal chromosomes from among those with more than two objective functions. Non-dominated sorting consists of two stages: non-dominated sorting and crowding distance sorting. In the non-dominated sorting stage the absolutely superior groups (ranks) are determined, whereas in the crowding distance sorting stage, the superior chromosomes are selected in the same group. First, non-dominated sorting begins with the comparison of relationships between all chromosomes. When exploring the minimal objective function value, if the objective function values of specific chromosomes are smaller than those of other chromosomes, it can be said that the specific chromosomes are dominant, and thus the chromosomes with smaller objective function values are assigned lower ranks. For example, as seen in Fig. 2, since chromosome 4 has a smaller value than chromosome 5 for both objective functions, it is dominant and is assigned a higher rank. In the same way, through non-dominated sorting, Fig. 3 can be produced.

In order to determine the priority between the chromosomes in the same rank, crowding distance sorting is conducted. In this way, the smaller the values of the crowding distance of specific chromosomes, the higher the priorities. Therefore, the distance is the right-angled distance of chromosomes that are nearest to each other toward the objective function of each chromosome.

3.2.3. Genetic operation

The genetic operation is an essential part of the genetic algorithm in which are found the initial chromosomes with numbers as big as the population size that undergo selection, crossover, and mutation to find dominant genes. This essential genetic operation was used and applied based on the algorithm (NSGA II). The initial chromosomes are sorted out, through non-dominated sorting and crowding distance sorting, in the order of the chromosomes for which the values of the two objective functions become minimal. These chromosomes can be considered parental chromosomes, and offspring chromosomes are produced through selection, crossover, and mutation. Then, for both types of chromosomes with numbers twice the population size,

Table 4
Chromosome design for pipe diameter optimal design

Chromosome	Pipe 1	Pipe 2	Pipe 3	…	Pipe *n*	Objective 1	Objective 2
Population 1	Dai (1,1)	Dai (1,2)	Dai (1,3)	...	Dai (1,*n*)	Cost (1,1)	Risk (1,2)
Population 2	Dai (2,1)	Dai (2,2)	Dai (2,3)	...	Dai (2,*n*)	Cost (2,1)	Risk (2,2)
...	...	...	...	...	...	...	...
Population *m*	Dai (*m*,1)	Dai (*m*,2)	Dai (*m*,3)	...	Dai (*m*,*n*)	Cost (*m*,1)	Risk (*m*,2)

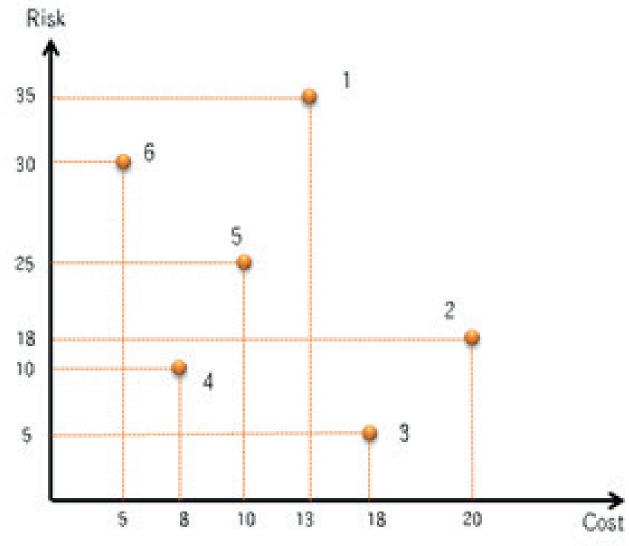

Fig. 2. Example of non-dominated sorting.

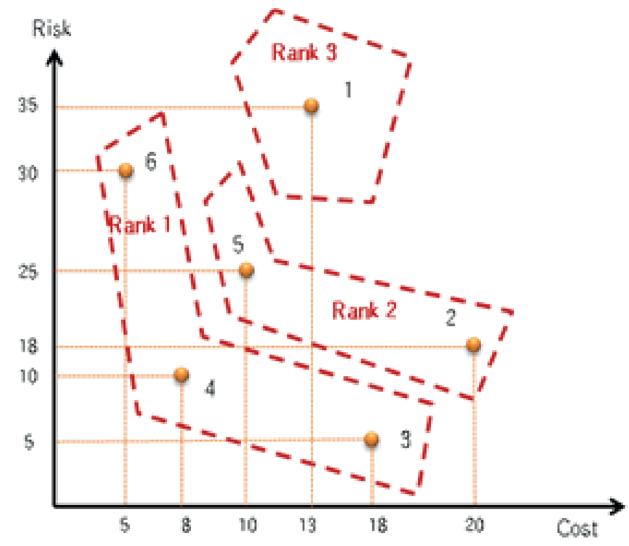

Fig. 3. Result of non-dominated sorting.

non-dominated sorting and crowding distance sorting are performed. The sorting is repeated as many times as the number of generations. These steps are summarized in Fig. 4.

3.3. Model development of the optimal location of gate valves

3.3.1. Chromosome design

In chromosome design, the gate valve location is a design variable, and the installment cost of gate valves and the Block WSR are objective functions. Genes of chromosomes are expressed as 1 and 0. If the gene is 1, then 1 and 0 mean that the gate valve is installed and not installed, respectively. Block WSR among the objective functions is identical to that of the aforementioned WSR assessment model. The Imp_{PB} used was the impact in RWT since it is the impact according to the location of gate valves. The second objective function,

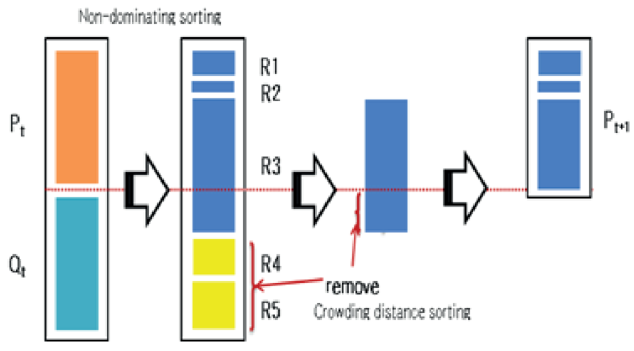

Fig. 4. Basic procedure of NSGA II.

Table 5
Total laying cost for each valve diameter

Diameter (mm)	Cost (won)
80	1,782,121
100	1,926,134
150	2,499,089
200	2,938,469
250	3,863,459
300	5,489,096
350	7,079,579
400	9,292,996

the gate valve embedment cost, was regarded as the sum of material costs and construction costs per pipe diameter of the gate-valve embedment. The total cost, detailed in Table 5, was used as the gate-valve embedment cost per pipe.

Accordingly, the chromosomes were designed, as seen in Table 6. These were used as the chromosomes of NSGA II for the model of the optimal location of gate valves.

The initial value of chromosomes was estimated using a random function. The value was set as 0 or 1 depending on the presence or absence of a gate valve. Only in the position expressed as 1 in the pipe–node matrix was the value 0 or 1. The budget for the gate valves to be installed was a constraint condition. If the installment cost of all gate valves exceeded the budget, then starting from the pipes where two gate valves were installed, one gate valve was deleted from each of the pipes in sequence. On the contrary, if the installment cost of all gate valves was more than the budget, then starting from the pipes where no gate valves were installed, one gate valve was added from each of the pipes in sequence.

In addition, non-dominated sorting and genetic operation were used in the model of the optimal location of gate valves as in the model of optimal pipe diameters.

4. Results and discussion

In this section, as one applicable application of the Block WSR for the optimal design of the WDN, a model of optimal diameters and the optimal location of gate valves was developed, using NSGA II and the EPANET 2.0 toolkit. The results of the model development of the optimal design of the WDN are as follows.

Table 6
Chromosome design for valve location optimal design

Chromosome		Pipe 1	Pipe 2	…	Pipe i	Objective 1	Objective 2
Population 1	Node 1	Val (1,1)	Val (1,2)	...	Val (1,i)	Cost (1,1)	Risk (1,2)
	Node 2	Val (2,1)	Val (2,2)	...	Val (2,i)		
	...	...	...	...	...		
	Node j	Val (j,1)	Val (j,2)	...	Val (j,i)		
...							
Population n	Node 1	Val (1,1)	Val (1,2)	...	Val (1,i)	Cost (n,1)	Risk (n,2)
	Node 2	Val (2,1)	Val (2,2)	...	Val (2,i)		
	...	...	...	...	...		
	Node j	Val (j,1)	Val (j,2)	...	Val (j,i)		

4.1. Results of model development of the optimal pipe diameter

The design model of optimal pipe diameters to minimize the WSR is an NSGA II model that takes a pipe diameter as a design variable and uses pipe embedment cost and LDT as objective functions. In order to formulate design results of optimal pipe diameters through the developed model, genetic parameters were determined for Block A2. To compare the results according to population size and generation number, the crossover rate and the mutation rate were fixed as 0.9 and 0.1, respectively, to perform the model development. As a result of performing the model of optimal pipe diameters according to population size and generation number, little variation in the values of objective functions was found for more than 200 of the population size and 100 of the generation number. If population size and generation number are increased, the selection of optimal values is more probable, but if the time of repetitive calculation is lengthened, the efficiency of the model operation deteriorates. Thus, population size and generation number were fixed as 200 and 100, respectively.

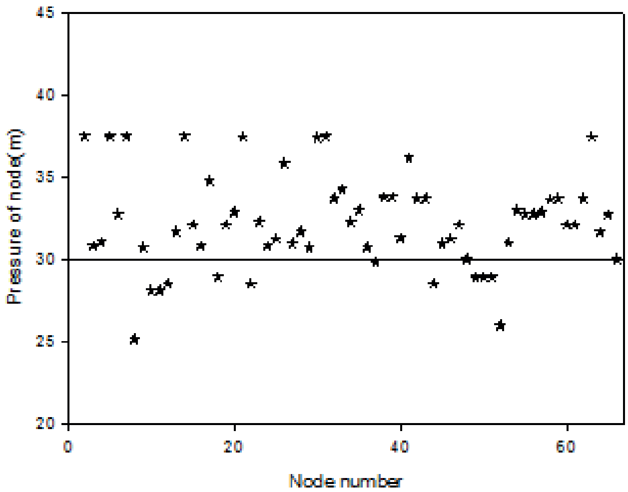

Fig. 5. Pressure by node for the optimal diameter design network.

4.1.1. Application of the model of optimal diameter design

Considering all types of data in Block A2, only the pipe diameter was selected as a design variable. Total pipe embedment cost and Block WSR of LDT were selected as objective functions. When Block WSR of LDT was estimated, leakage hole size was set at 1 cm^2. The target pipes were supposed to be newly installed, and the burst probability of all pipes was assumed to be 0.2 (case/km/year). LDT was set to be 4.2 h for all pipes, which was previously suggested by Choi and Koo [19].

The constraint conditions were 3.0 m/s of the maximal velocity, 0.1 m/s of the minimal velocity, and 30 m of the minimal node water pressure. Genetic parameters for NSGA II were 200 of the population size, 100 of the generation number, 0.9 of the crossover rate, and 0.1 of the mutation rate. The model of optimal pipe diameters for Block A2 was operated as follows. Fig. 5 shows the water pressure distribution of each node, and Fig. 6 shows the water velocity distribution of each pipe.

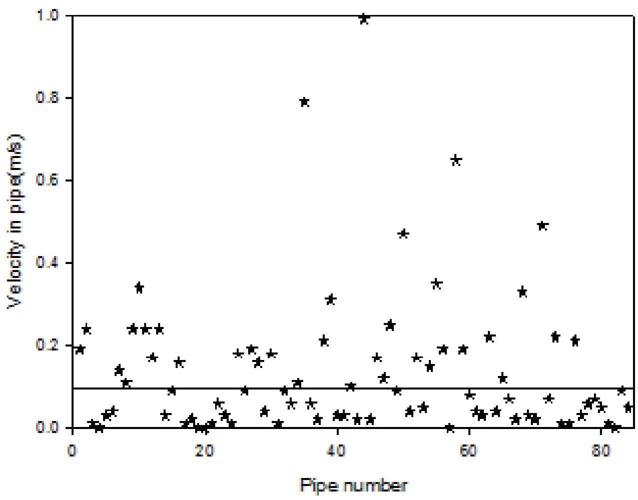

Fig. 6. Velocity by pipe for the optimal diameter design network.

When the node water pressure, which is a constraint of the WPN, with optimal diameters satisfied 30 m, the number of nodes was 54 out of 66, and the number of pipes that satisfied 0.1 m/s of the minimal velocity was 36 out of 84. During optimal pipe design, constraints of minimal node water pressure and minimal pipe water velocity were not always satisfied at all nodes and pipes because the node

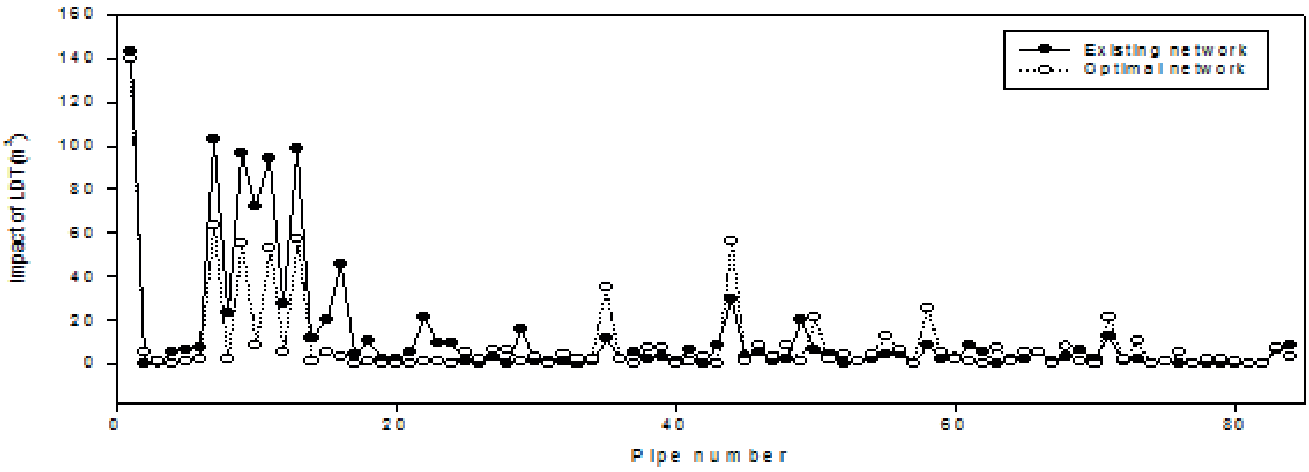

Fig. 7. Comparison of impacts of LDT for existing and optimal diameter design networks.

demand on the existing network was much less than the pipe diameters, and the number of pipes that satisfied 0.1 m/s of pipe water velocity was only three. Thus, it was found that the network created in the model of optimal diameters was optimally designed under the current conditions of node demand. In addition, the construction cost and the impact in leakage duration were estimated, as follows, after applying the model of optimal pipe diameters for Block A2.

4.1.1.1. Estimation results of construction costs of optimal diameters Conduction of the model of optimal diameter design showed that most pipe diameters were smaller than the existing pipe diameters. In the existing pipe network, pipes with a diameter of 400 mm are plentifully distributed, but after conducting the model of optimal diameter design, the pipes with a diameter of 250 mm were designed as the biggest pipes, and the pipes with a diameter of 80 mm were most frequently included. In the case of the exhibiting network, an uncertain forecast of water demand seemed to have been made. Therefore, in designing the optimal pipe diameter, an accurate forecast of water demand is required. In conclusion, after conducting the model of optimal diameter design, since the pipe diameters were decreased, the total pipe embedment cost was reduced by 62.4%, from 1,219,373,257 to 458,838,079 won.

4.1.1.2. Impact estimation of LDT The Imp_{PB} of LDT of the optimal design network and the Imp_{PB} of LDT of the existing design network were compared, and the results are shown in Fig. 7.

The comparison of the Imp_{PB} of LDT between the existing design network and the optimal design network showed that 45 of 84 pipes had a reduced Imp_{PB} of LDT and that 39 had an increased Imp_{PB} of LDT. Based on this finding, even in the optimal design network, Imp_{PB} of LDT can decrease or increase, depending on pipes. Thus, the optimal model of the WDN is distinguished from the existing models of diameter minimization in that it can consider diameter augmentation as well as diameter reduction. Thus, the developed optimal model of the WDN was proved to be effective. However, since the Block WSR of LDT, which is an objective function, is minimized during the conduction of the design model of optimal diameters, Imp_{PB} of LDT for all blocks could be reduced.

4.1.2. Results of sensitivity analysis of the model of optimal diameter design

4.1.2.1. The results of the conduction of the model of optimal diameter design according to leakage The model of the optimal diameter design according to the size of leakage holes was conducted to analyze the impact of each pipe leakage volume, and the size of leakage holes was supposed to determine the degree of leakage. In order to analyze the results of the conduction of the model of optimal diameter design according to leakage, the hole size was varied in the unit by 0.1 cm^2. As a result, it was found that the pipe embedment costs of the optimal diameter design were not related to leakage. However, as the size of leakage holes increased, leakage increased, affecting the Block WSR of LDT. The relationship between the size of leakage holes and the Block WSR of LDT is shown in Fig. 8. It was found that the size of leakage holes and the Block WSR of LDT are not in a linearly proportional relationship, but the Imp_{PB} of LDT changes exponentially.

Accordingly, utilizing these results to reduce Block WSR, we can quantify the target leakage reduction of each pipe, and perform WSR management efficiently in the future.

4.1.2.2. The results of the conduction of the model of optimal diameter design according to changes in the constraint of the node water pressure In order to analyze the results of the optimal diameter design according to changes in the constraint of the node water pressure, we altered the node water pressure by 5 m and analyzed variations in the Block WSR of LDT and pipe embedment cost. The results showed that there was no difference in the embedment cost by the node water pressure. This suggests that there was no change in designed diameters. On the contrary, as the node water pressure increased, the Block WSR of LDT tended to increase because demand shortage on the adjacent nodes increased during leakage.

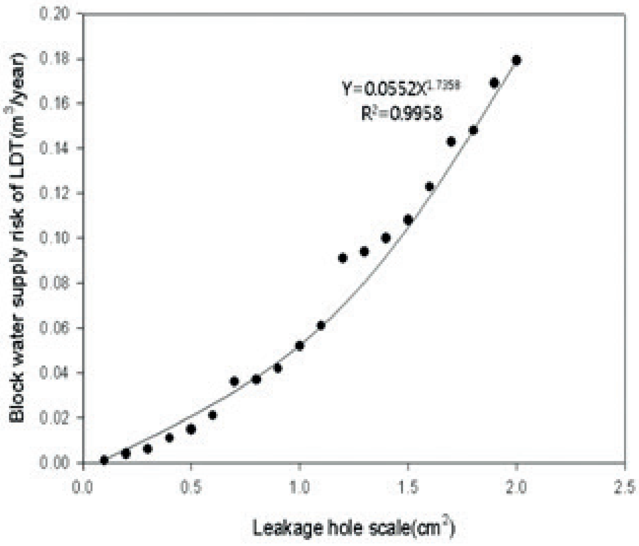

Fig. 8. Block water supply risk of LDT by leakage hole scale.

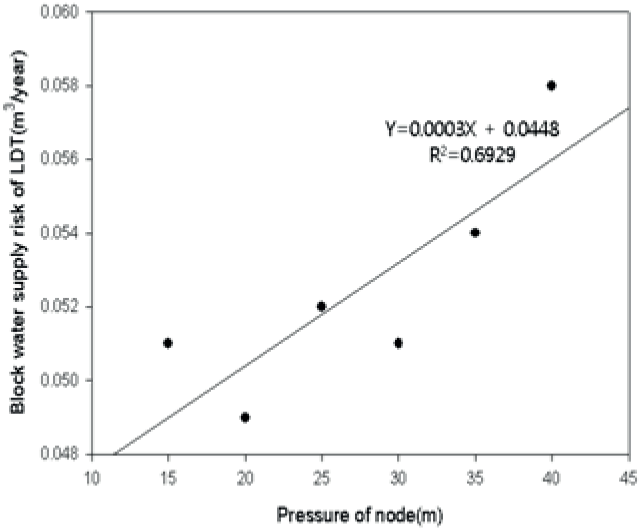

Fig. 9. Block water supply risk of LDT by node pressure.

The relationship between the node water pressure and Block WSR of LDT during the conduction of the model of optimal diameter design is shown in Fig. 9. It was found that as the node water pressure increased, the Block WSR of LDT linearly increased. Based on the results, in the case of the diameter design of the newly constructed WDN, water pressure can be determined in advance, and the WSR of the WDN can feasibly be minimized.

4.2. Results of model development of the optimal location of gate valves

4.2.1. Application of model development of the optimal location of gate valves

This study applied the pipe network map derived from the model of optimal diameters to the model of the optimal location of gate valves. Input values were identical to those of the optimal diameter model. Total installment costs of gate valves and the Block WSR of LDT were selected as objective functions. If gate valves are installed in the WPN derived from the optimal diameter model, a maximum of 165 units can be installed, and the maximum cost was estimated at 310,461,534 won. To compare the existing network design and the optimal network design, the installment cost, as the constraints of the model of optimal location of gate valves, was set at 105,000,000 won, which amounts to 33% of the total cost for 165 units. The genetic parameters of NSGA II used in the model of the optimal location of gate valves were 200 of the population size, 100 of the generation number, 0.9 of the crossover rate, and 0.1 of the mutation rate. The following are the results of the conduction of the model of the optimal location of gate valves.

4.2.1.1. Estimation of the lowest cost in the model development of the optimal location of gate valves The number of pipes installed was 56, and the installment cost of all gate valves was estimated to be 104,747,986 won, which was a 40.7% reduction from 176,673,247 won. The installment cost of gate valves decreased since the diameters of some pipes were decreased due to the optimization of pipe diameters. On the other hand, additional costs occurred due to augmentation of the diameters of some pipes, but ultimately, the cost was reduced, proving the efficacy of the model developed in this study.

4.2.1.2. Imp_{PB} estimation of RWT This study applied the pipe network map derived from the model of optimal diameters to the model of the optimal location of gate valves. Imp_{PB} of LDT was identical to that of the model of optimal diameters. However, Imp_{PB} of RWT is determined by the location of gate valves installed with a 105,000,000 won budget, which is a constraint condition. The Imp_{PB} of RWT of the optimal design network and the Imp_{PB} of RWT of the existing design network were compared, and the results are shown in Fig. 10. The comparison of the Imp_{PB} of RWT between the existing design network and the optimal design network showed that 66 of 84 pipes had a reduced Imp_{PB} of RWT and that 18 had an increased Imp_{PB} of RWT. Based on this finding, even in the optimal design network, Imp_{PB} of RWT can decrease or increase, depending on pipes. However, since the Block WSR of LDT, which is an objective function, is minimized during the conduction of the design model of optimal diameters, Imp_{PB} of RWT for all blocks could be reduced.

4.2.2. Results of sensitivity analysis of the model of the optimal location of gate valves

4.2.2.1. The results of the model of the optimal location of gate valves according to the budget of gate-valve installment While the model of optimal location was conducted, after modifying the budget of the gate-valve installment, which is a constraint condition, the Block WSR of RWT was estimated. During the conduction of the model of the optimal location, when the budget of the gate-valve installment was increased, the Block WSR of RWT was reduced because the possible number of installable gate valves was increased as the budget increased. To express the results as

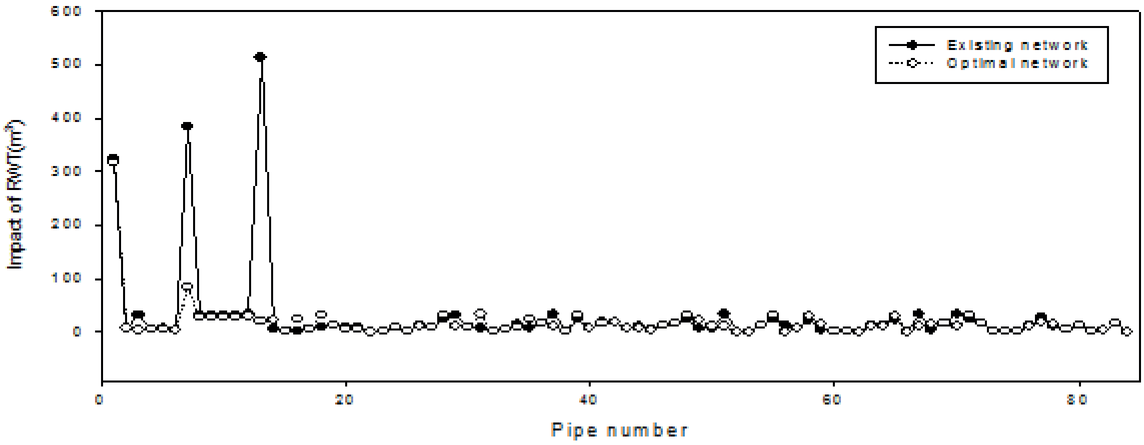

Fig. 10. Comparison of impacts of RWT for existing and gate-valve optimal location design networks.

a quantitative formula, the Block WSR of RWT according to the installment budget of gate valves is diagramed in Fig. 11. As a result, within the range of sensitivity analysis, the effect against costs continued, with a breakpoint occurring at 170,000,000 won of the budget for the gate-valve installment. This study suggests that an optimal investment scale can be determined after calculating the effect against the costs. Thus, the goal of optimization regarding cost/effect analysis will be achieved.

4.2.3. Comparative analysis of WSRs of the existing network and the optimal network

In order to evaluate the appropriateness of the model of optimal design, a comparative analysis was performed between the optimal design network and the existing design network. In both design methods, the $Prob_{PB}$ of each pipe was assumed to be 0.2 (case/km/year). Fig. 12 illustrates the results that evaluated the Block WSR of each pipe after $Prob_{PB}$ was changed to 0.2 (case/km/year) from that of the existing design method.

As a result, the Block WSR of the existing network design was 0.306 m^3/year, but that of the optimal network design was reduced by 10.1% to 0.275 m^3/year. The construction cost of the existing network design was 139,600,000 won, but that of the optimal network design was reduced by 59.7% to 56,300,000 won. While the construction cost of the network of the optimal design is much smaller than that of the network of the existing design, the optimal design method can also reduce the Block WSR; thus, the efficacy of the optimal design model was proved. In addition, apart from the construction cost, the Block WSR reduction effect due to the optimal design showed that the daily water cut-off of 8.8 persons/year can be prevented by the conversion of 296 L/Lpcd.

5. Conclusion

In this study, using NSGA II, a design model was developed in order to minimize the Block WSR of a newly constructed WDN at the minimal design cost. The developed optimal design model to determine pipe diameters and locations of gate valves took the installment costs of pipes and gate valves as objective functions and applied a multipurpose

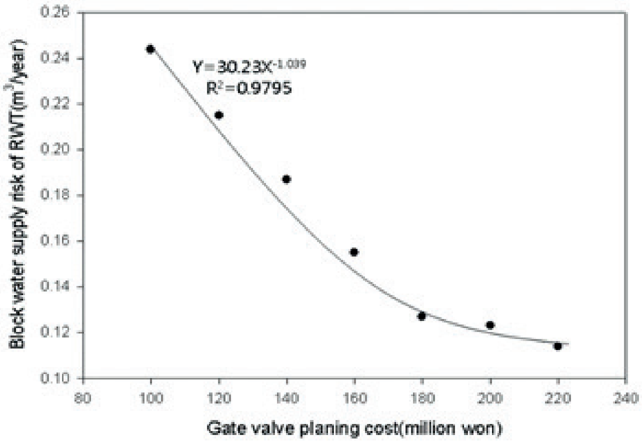

Fig. 11. Variation analysis of block water supply risk of RWT by gate-valve planning cost.

genetic algorithm with the constraints of water velocity of pipes, node water pressure, and installment budget of gate valves. The optimal model was applied to Block A2, and the genetic parameters of NSGA II used in the model were 200 of the population size, 100 of the generation number, 0.9 of the crossover rate, and 0.1 of the mutation rate. The constraints were 3.0 m/s of the maximum velocity, 01 m/s of the minimal velocity, and 30 m of the minimal node water pressure, as well as a 105,000,000 won gate-valve installment budget. $Prob_{PB}$ was set at 0.2 (case/km/year), considering the new construction of pipes.

The results showed that the Block WSR of each pipe after $Prob_{PB}$ was changed to 0.2 (case/km/year) from that of the existing design method. As a result, the Block WSR of the existing network design was 0.306 m^3/year, but that of the optimal network design was reduced by 10.1% to 0.275 m^3/year. The construction cost of the existing network design was 139,600,000 won, but that of the optimal network design was reduced by 59.7% to 56,300,000 won. While the construction cost of the network of the optimal design is much smaller than that of the network of the existing design, the optimal design method can also reduce the Block WSR; thus, the efficacy of the optimal design model was proved. In addition, apart from the

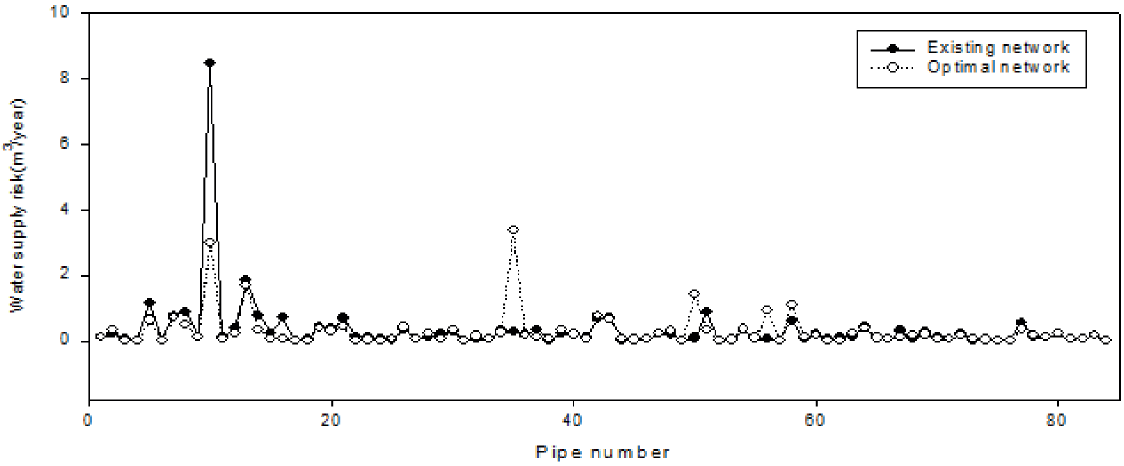

Fig. 12. Comparison of water supply risk for existing and optimal design networks.

construction cost, the Block WSR reduction effect due to the optimal design showed that the daily water cut-off of 8.8 persons/year can be prevented by the conversion of 296 L/Lpcd. On the other hand, after analyzing the variation in leakage volumes and changes in constraints (node water pressure and minimal water velocity of pipes), it was found that there was no significant change in pipe construction costs according to leakage and node water pressure change, and that the Block WSR of LDT is proportional to leakage and node water pressure. Regarding the minimal water velocity of pipes, as the value increased, both the pipe embedment cost and the Block WSR decreased. Based on this finding, it was concluded that leakage volume and node water pressure are not factors that determine diameters, but the minimal water velocity of pipes was a key variable to determine diameters. In addition, it was shown that in the design of the optimal location of gate valves, a higher budget for gate-valve installment further reduces the Block WSR of RWT.

In conclusion, the optimal design model of a newly constructed WDN developed in this study can minimize the Block WSR and can be applied to WDN designs reasonably and effectively. Depending on the leakage of pipes and the constraints (node water pressure, water velocity in pipes, budget for gate-valve installment), the effects differed. Thus, if these results are utilized, construction costs and Block WSR of the newly constructed WDN design can be minimized and, therefore, in the management of a WPN, a more reliable WDN can be designed that considers the needs of consumers as well as water suppliers.

Acknowledgment

This subject is supported by Korea Ministry of Environment as "Global Top Project (2016002120005)".

References

[1] T.M. Walski, The wrong paradigm – why water distribution optimization doesn't work, Water Resour. Res., 127 (2001) 203–205.
[2] D.R. Morgan, I.C. Goulter, Optimal urban water distribution design, Water Resour. Res., 21 (1985) 642–652.
[3] D. Halhal, G. Walters, D. Quazar, D. Savic, Water network rehabilitation with structured messy genetic algorithm, J. Water Resour. Plan. Manage., 123 (1997) 137–146.
[4] O. Fujiwara, D.A. Khang, A two-phase decomposition method for optimal design of looped water distribution networks, Water Resour. Res., 26 (1990) 539–549.
[5] E. Todini, Looped water distribution networks design using a resilience index based heuristic approach, Urban Water, 2 (2000) 115–122.
[6] A.R. Simpson, G.C. Dandy, L.J. Murphy, Genetic algorithm compared to other techniques for pipe optimization, J. Water Resour. Plan. Manage., 120 (1994) 423–443.
[7] G.C. Dandy, A.R. Simpson, L.J. Murphy, An improved genetic algorithm for pipe network optimization, Water Resour. Res., 32 (1996) 449–458.
[8] D.A. Savic, G.A. Walters, Genetic algorithms for least-cost design of water distribution networks, J. Water Resour. Plan. Manage., 123 (1997) 67–77.
[9] I. Gupta, A. Gupta, P. Khanna, Genetic algorithm for optimization of water distribution systems, Environ. Modell. Softw., 14 (1999) 437–446.
[10] M.S. Morely, R.M. Atkinson, D.A. Savic, G.A. Walters, GAnet: genetic algorithm platform for pipe network optimisation, Adv. Eng. Software, 32 (2001) 467–475.
[11] V. Kalanithy, A. Mohammed, Pipe index vector: a method to improve genetic-algorithm-based pipe optimization, J. Hydraul. Eng., 131 (2005) 1117–1125.
[12] M. van Dijk, S.J. van Vuuren, J.E. van Zyl, Optimising water distribution systems using weighted penalty in a genetic algorithm, Water SA, 34 (2008) 537–548.
[13] Z.Y. Wu, A.R. Simpson, A self-adaptive boundary search genetic algorithm and its application to water distribution systems, J. Hydraul. Res., 40 (2002) 191–203.
[14] G.V. Loganathan, J.J. Greene, T.J. Ahn, Design heuristic for globally minimum cost water-distribution systems, J. Water Resour. Plan. Manage., 121 (1995) 182–192.
[15] M.C. Cunha, J. Sousa, Water distribution network design optimization: simulated annealing approach, J. Water Resour. Plan. Manage., 125 (1999) 215–221.
[16] T.D. Prasad, N.S. Park, Multiobjective genetic algorithms for design of water distribution networks, J. Water Resour. Plan. Manage., 130 (2004) 73–82.
[17] G.A. Walters, D.K Smith, Evolutionary design algorithm for optimal layout of tree networks, Eng. Optim., 24 (1995) 261–281.
[18] Z.S. Kapelan, D.A. Savic, G.A. Walters, Multiobjective design of water distribution systems under uncertainty, Water Resour. Res., 41 (2005) W11407.
[19] T.H. Choi, J.Y. Koo, A water supply risk assessment model for water distribution network, Desal. Wat. Treat., 54 (2015) 1410–1420.