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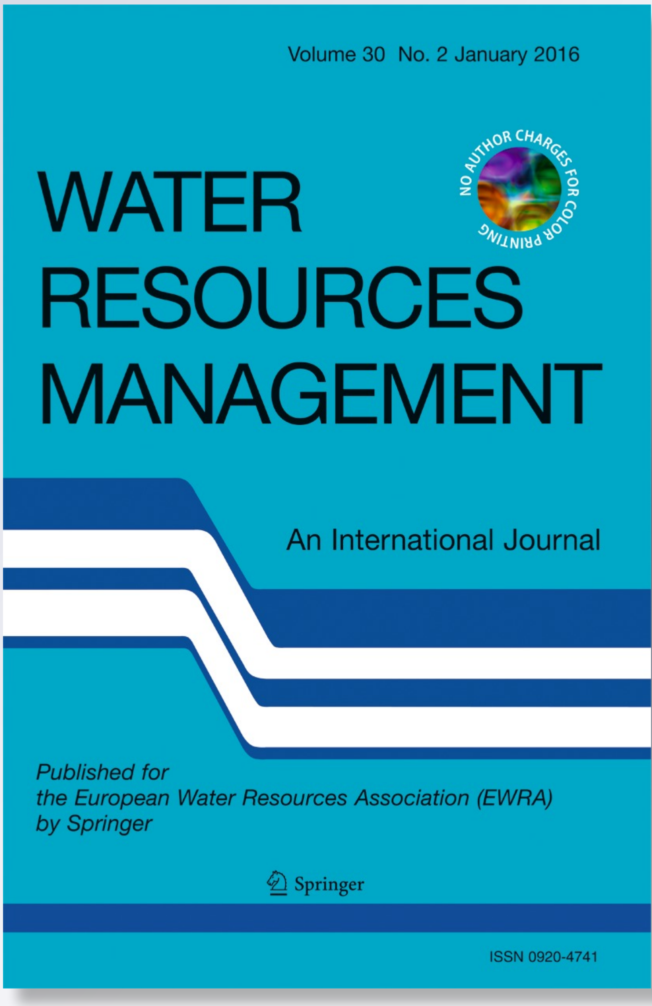

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Multiobjective Optimal Design of Sewerage Rehabilitation by Using the Nondominated Sorting Genetic Algorithm-II

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Abstract Application of multiobjective optimization in sewerage rehabilitation management is not widespread due to the limitation of data collection and complex optimization process. Thus, a few researches in literature focused on sewerage rehabilitation optimization, and only considered two-objective optimization usually between the service life and the direct cost instead of a social cost. A sewerage rehabilitation multiobjective optimization decision support system (SRMOS) was developed for sewerage rehabilitation management in this study. The nondominated sorting genetic algorithm-II was used to design a set of Pareto surfaces with desirable rehabilitation effectiveness at the lowest cost by providing optimal plans comprising a construction method and substitute material. The SRMOS was applied to a real sewerage system to provide tradeoff solutions for three conflicting objectives, which are minimizing rehabilitation cost, maximizing pipe service, and minimizing traffic disruption. Compared with the experts' manual estimation, the plan derived from the SRMOS enables saving nearly 20 % of the rehabilitation cost. The contours of the rehabilitation cost show the equivalent relation between the traffic disruption and service life of pipes. The results indicate that increasing the number of objectives can make up the drawback of cost hard to be quantified and can also facilitate deriving practical plans for reference in decision-making.

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Keywords Sewerage rehabilitation · Multi-objective optimization · Non-dominated sorting genetic algorithm (NSGA-II) · Pareto surface (PS)

1 Introduction

The construction of municipal sewerage systems is an essential sustainable development indicator for water reuse; however, internal hydrogen sulfide corrosion and complex external surroundings cause cracks in sewer pipes and deteriorate their conditions (Wirahadikusumah et al. 1998). When pipe defects are identified by image processing on closed-circuit television images (Yang and Su 2006; Yang and Su 2008; Yang and Su 2009; Yang et al. 2011a; Yang et al. 2011b; Su and Yang 2014), the appropriate construction methods and substitution materials for defected pipes are the most crucial factors affecting the cost effectiveness of a rehabilitation plan (Sen Gupta et al. 2001). The conventional rehabilitation plan relies on the expertise of professional engineers, and decision-makers generally adopt a simple rehabilitation plan that involves allotting rehabilitation capital to "critical sewers" (Fenner 2000; Ward 2012). Under various conditions, such as budget constraints and highly stringent environmental regulations, decision-makers encounter a difficult challenge on necessitating exploration of cost-effective strategies for managing sewerage systems (Marzouk and Omar 2013; Nicklow et al. 2010). An optimization decision support model can give decision-makers comprehensive knowledge and provide an appropriate sewerage rehabilitation plan (Lee et al. 2009).

Nicklow et al. (2010) reported genetic algorithm (GA) as a flexible tool in sewerage system design for single objective optimization. However, decision-makers may not only consider the budget as an exclusive objective but also consider other indirect costs such as environmental impact. A previous study used GA and weight method to determine the optimal tradeoff curve between construction cost and greenhouse gas emissions for pipe network design (Dandy et al. 2008; Wu et al. 2009), but determining the weight is challenging because it is dependent on the decision-maker's subjective preferences (Tabari and Soltani 2013).

Recently, several multiobjective optimizers, such as nondominated sorting genetic algorithm-II (NSGA-II) and multiobjective artificial bee colony algorithm, were used to determine a "Pareto front (PF)", "Pareto surface (PS)", or hypersurface (for more than three objectives) between competitive objectives (Ahmadi et al. 2014; Liao et al. 2014; Nouiri et al. 2015; Yazdi and Neyshabouri 2014). The famous NSGA-II was commonly used for optimizing water distribution design and monitoring network problem involving discrete integer and hybrid variables (Dhar and Patil 2012; Qi et al. 2014).

The application of multiobjective optimization to sewerage rehabilitation management is not widespread due to the limitation of data collection and complex optimization process. Most applications of urban sewer/drainage optimization were carried out in the field of water distribution networks design by considering only two-objective functions, in which the objective usually is a quantifiable direct cost instead of a social cost quantified by currency (Barlow and Tanyimboh 2014; García et al. 2014). In a few literatures related to sewerage rehabilitation management, researches focused on two-objective optimization, such as Yang and Su (2006) and Marzouk and Omar (2013), by maximizing the sewerage network service life and minimizing the maintenance cost. Service life and cost depend on the construction method and substitution material of pipe in sewerage systems (Reyna 1993; Sen Gupta et al. 2001). Due to the limitation of data collection, the optimization processes were often applied to hypothesized study cases in the literature.

Hence, this study proposes a sewerage rehabilitation multiobjective optimization decision support system (SRMOS) for sewerage rehabilitation management. In the

SRMOS, the NSGA-II multiobjective algorithm was employed to achieve a tradeoff between two or among three conflicting objectives, namely minimizing the rehabilitation budget, maximizing the service life of pipes after rehabilitation, and minimizing traffic disruption during the rehabilitation period. Cost, pipe service life, and traffic disruption are included in optimized objectives, in which the last objective is a social impact from pipe rehabilitation and a novel objective function originally employed in this study. In addition, this study applied SRMOS to a real sewerage rehabilitation case for demonstration, and the cost efficiency and parameter sensitivity analysis were investigated to illustrate the feasibility of the SRMOS for decision-making references.

2 Methodology

2.1 Study Case and Sewerage System

The sewerage system of the 15th district of Kaohsiung City in southern Taiwan (Fig. 1) was used as the study site. This sewerage system covers an area of approximately 0.5 km^2 and serves 12 000 people. Figure 1 shows the layout of the sewerage system, which has a design underground depth of between 1.5 and 3.0 m and pipe diameters ranging from 200 to 700 mm. The average traffic flow on the main roads above the failed sewer pipe, Wumiao Road and Jianming Road, is 2743 and 1480 vehicles/h, respectively. Most of these pipes were composed of reinforced concrete pipes (RCPs) because of their low cost; Table 1 shows a summary of the characteristics of the pipes in the system and several failed pipes. In addition to RCPs, acrylonitrile butadiene styrene (ABS), glassfiber-reinforced plastics (GRPs), and vitrified clay pipes (VCPs) are currently common candidate materials. Table 2 lists the costs and service lives of these candidate materials; these data were obtained by conducting a survey of the Taiwan market.

2.2 Optimal Algorithm and Sewerage Rehabilitation Optimization Model

As illustrated in Fig. 2, the first process in the SRMOS involves collecting the required information related to sewerage rehabilitation and determining objectives based on the requests of the decision-

Fig. 1 Layout of the sewerage in studying case

Table 1 Characteristics of the sewer pipe and traffic flow in study area

PIPE No.	Diameter (mm)	Pipe length (m)	Cover depth (m)	Failed length (m)	Average traffic flow (vehicle/h)	PIPE No.	Diameter (mm)	Pipe length (m)	Cover depth (m)	Failed length (m)	Average traffic flow (vehicle/h)	PIPE No.	Diameter (mm)	Pipe length (m)	Cover depth (m)	Failed length (m)	Average traffic flow (vehicle/h)
1	200	48.5	2.3	25.53	26	24	200	29.8	2.6	22.35	308	47	500	65	3.2	48.75	3295
2	200	30.4	2.5	30.4	24	25	200	33.5	2.2	23.19	1480	48	200	16.7	3	9.54	224
3	200	37.2	1.9	2.48	224	26	200	33.4	2.1	17.98	1480	49	350	52.6	3.2	15.03	3295
4	200	17.7	2.2	5.06	26	27	200	55.3	2.5	27.65	2775	50	500	62.2	3.1	36.28	3295
5	200	35.9	2.3	25.64	24	28	200	15.9	1.9	10.6	296	51	200	23	3.1	10.22	119
6	200	36.3	2.4	26.62	322	29	200	80.5	2.3	70.44	383	52	250	24.2	3.3	14.52	1744
7	200	73.2	2	22.72	148	30	200	65.5	2.2	47.87	308	53	200	56.6	3.6	41.16	3295
8	200	30.6	1.8	12.75	224	31	200	18.5	2.4	10.28	119	54	200	69	3	49.83	119
9	200	80.5	1.8	30.19	247	32	200	48.2	2.3	10.15	2775	55	250	46.7	2.8	15.57	3295
10	200	25.5	2.4	15.3	195	33	200	18.7	1.6	16.03	296	56	500	56.6	3.2	37.73	3295
11	200	33.4	2	20.55	1480	34	200	33.5	1.7	28.35	87	57	200	28.8	3.2	23.56	925
12	200	55.7	1.9	20.25	1480	35	200	21	2.1	10.5	1480	58	250	26.6	2.7	15.96	1744
13	200	51.5	2.6	49.05	322	36	200	18.7	2.2	16.03	2775	59	200	36.4	2.8	29.12	290
14	200	38.1	1.9	30.48	1480	37	200	26.1	2.2	15.66	164	60	200	13.7	2.7	8.22	2775
15	200	16.2	1.6	13.5	195	38	200	21.3	1.4	15.98	296	61	200	65.8	3	24.37	290
16	200	25.9	2.2	23.31	32	39	200	25.8	1.7	18.06	87	62	200	21	2.7	13.13	148
17	200	25.7	2.4	16.35	322	40	200	75.9	1.6	15.18	87	63	200	74	3	49.33	290
18	200	26.2	2.2	13.1	322	41	200	77.2	1.6	4.83	87	64	200	23.5	2.7	14.1	148
19	200	65.7	2.5	45.48	925	42	300	60.5	3.1	9.16	3295	65	200	29.6	2.4	0	24
20	200	21.1	1.4	18.46	87	43	500	41.4	3	36.23	1744	66	700	60	3.5	0	6458
21	200	28.3	1.4	20.58	195	44	200	25.7	3.2	17.99	224	67	700	70	3.4	0	6458
22	200	26	2.4	15.6	296	45	300	41.3	3.2	17	1744	68	700	80	3.3	0	6458
23	200	25.8	2.3	20.64	322	46	200	28.4	2.8	7.75	26	69	300	12	3.2	0	1744

Table 2 Characteristics of the pipe materials

Material	Diameter (mm)	200	250	300	350	500	700
RCP[a]	Cost ($NTD/m)	841	954	1239	1300	2043	3200
	Service life (Year)	25					
ABS[b]	Cost ($NTD/m)	769	1199	1900	2300	3924	6042
	Service life (Year)	30					
GRP[c]	Cost ($NTD/m)	1080	1435	1800	2400	4170	7750
	Service life (Year)	50					
VCP[d]	Cost ($NTD/m)	1180	1545	1910	2500	5815	13,000
	Service life (Year)	100					

$ unit of price is NTD (New Taiwanese Dollar); 1 NTD = 0.033 US dollar

[a] Reinforced concrete pipe

[b] Acrylonitrile Butadiene styrene

[c] Glassfiber Reinforced Plastic

[d] Vitrified Clay Pipe

makers; this is followed by adjusting the NSGA-II procedures to design the sewerage rehabilitation plans and determine the optimal tradeoff. The NSGA-II is mainly based on a nondominated sorting (NDS) mechanism. The nondominated solutions in NDS provide a range of alternative options that offer choice and flexibility to the sewer system controllers to enable the best control settings (Rathnayake and Tanyimboh 2015). Some of NSGA-II parameters are used in conducting a sensitivity analysis to demonstrate their effect on the tradeoff solution. Objectives in the SRMOS can be set as a function of a quantifiable direct cost or an unquantifiable societal cost, and the decision variable comprises the construction method and substitute material for the pipe.

In this study, the first objective was to minimize the total rehabilitation cost (TRC), and is expressed in Eqs. (1)-(6). The TRC is a function of the pipe diameter, pipe material, and construction method. The cost was quantified by currency and estimated according to an official report (Government KC 1999).

$$\text{Minimize } TRC = CM + CR \tag{1}$$

$$CM = \sum_{r=1}^{BNP} C_r L_r \tag{2}$$

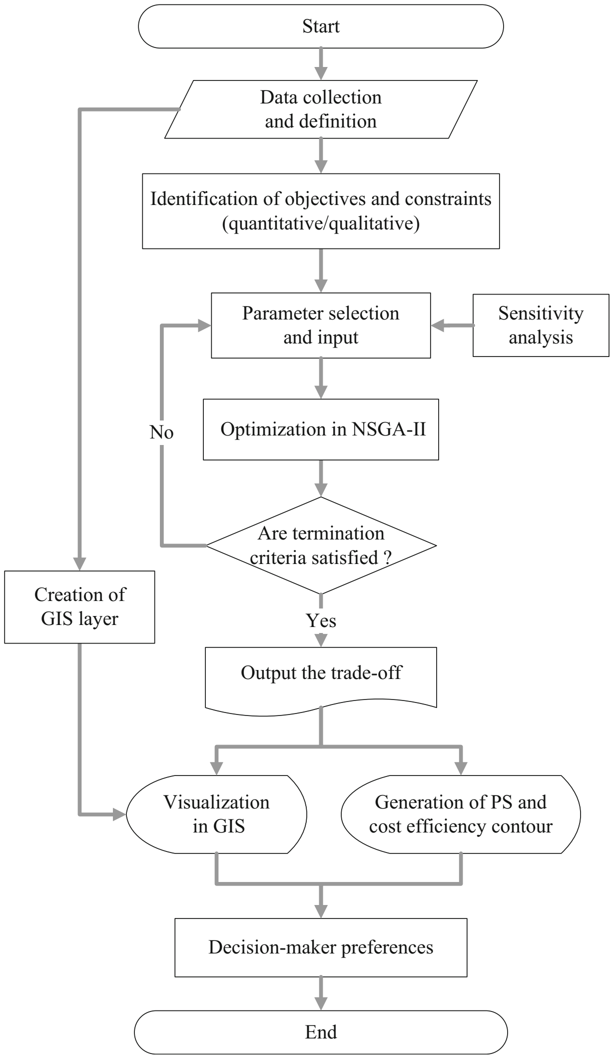
For trenchless replacement

$$CR = \sum_{r=1}^{BNP} (30D_r + 16300) \tag{3}$$

For excavation replacement

$$CR = \sum_{r=1}^{BNP} \left(0.01180D_r^2 + 742.7{H_r}^2 + 1.18D_rH_r - 1578.5H_r + 1.9D_r + 5810\right) \tag{4}$$

Fig. 2 Flowchart of the proposed SRMOS



For renewal

$$CR = \sum_{r=1}^{BNP} (74.1 \times D_r + 20660) \tag{5}$$

For renovation

$$CR = \sum_{r=1}^{BNP} (60 \times D_r + 5400) \tag{6}$$

where CM is the total cost (New Taiwan Dollar, NTD) of the substitute material for the pipes, C_r is the unit cost (NTD/m) of the substitute material for the rth pipe, L_r is the rehabilitated length or replaced length (m) of the rth failed pipe, and BNP is the number of failed pipes. The cost of the substitute material varies according to the pipe categories shown in Table 2. Furthermore, *CR* represents the total construction cost (NTD), $D_{r.}$ is the diameter of the *r*th failed pipe (mm), and H_{r} is the depth (m) under the ground of the *r*th failed pipe. The excavation and trenchless replacement methods both involve replacing existing pipes with new pipes. The trenchless construction method is adopted in both the renewal and renovation processes, resulting in less traffic disruption.

The second objective was to maximize the average service life of the pipes after rehabilitation and is expressed in Eq. (7); the defected pipe is assumed to recover its remained official service life after damage rehabilitation. The service life of the pipe (Y_i) depends on the pipe material as well as the pipe position and underground environment. Ideally, a prediction deterioration models is a solution to consider the impact of underground environment on shortening service life. However, model establishment is restricted by the limited condition monitoring data and the direct assessment of structural deterioration. Currently, the service life varying with pipe materials is adopted according to official product reports. In Table 2, a pipe with a long service life is usually associated with a high cost. The third objective to minimize traffic disruption is a social cost that has difficult in quantitative analysis by currency. Different construction methods may result in various levels of traffic disruption. For example, open trench construction method would force the diversion of vehicles, thereby generating considerable traffic disruption. Therefore, the change in the traffic flow on a section of the road is determined as the traffic disruption so that the third objective is expressed in Eq. (8).

$$\text{Maximize } SL = \frac{1}{BNP}\sum_{r=1}^{BNP} Y_r \tag{7}$$

$$\text{Minimize } TD = \sum_{r=1}^{BNP} f_r \tag{8}$$

where *SL* is the service life (years), Y_i is the service life (years) of the *r*th failed pipe after rehabilitation, *TD* is the traffic disruption, and f_r is the average traffic flow (vehicle/h) on the road above the *r*th failed pipe (Table 1). A longer service life leads to higher sewage treatment and water reuse rates. A lower change in the traffic flow results in a lower increase in the vehicle travel time and lower social costs. Both the second and third objectives are considered indirect costs and conflict with the rehabilitation costs (i.e., the first objective). These conflicting objectives are incommensurable, compared with each other directly and summed with a weight (Fu and Butler 2008). Therefore, the NSGA-II was used to resolve the three-objective design of sewerage rehabilitation.

The chromosome of the NSGA-II is encoded in binary numbers (Fig. 3). The code of the construction method can be one of the following values: 1 (trenchless replacement), 2 (excavation replacement), 3 (renewal), or 4 (renovation); the code of the substitute material can be one of the following values: 1 (RCP), 2 (ABS), 3 (GRP), or 4 (VCP). The fitness of the chromosome is expressed by three objective values. Finally, the tradeoff solutions were visualized in a geographic information system (GIS).

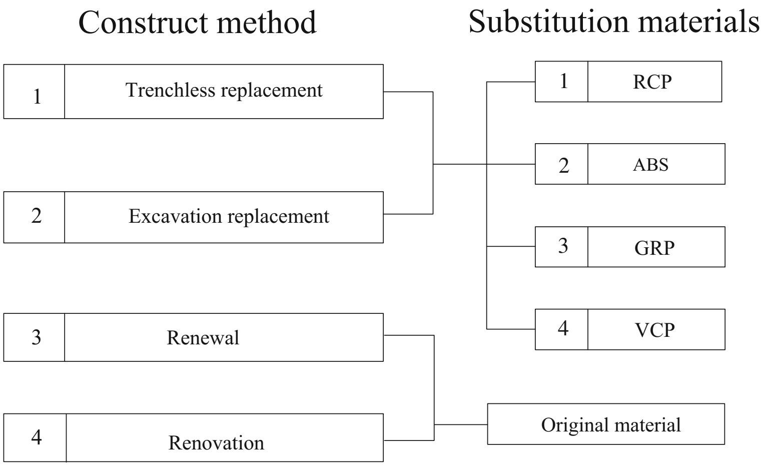


Fig. 3 Encoding rule for available rehabilitation methods and substitution materials

3 Results and Discussion

3.1 Tradeoff Curve for two and Three Objectives

A total of 64 failed pipes must be evaluated for one of the alternative construction methods and one of the alternative substitute materials. Thus, in the case study, the solution space comprised approximately 6.28 × 10^{57} possible rehabilitation plans. Figure 4 depicts the optimal tradeoff solutions (plans) for two objectives, which are minimizing the rehabilitation cost and maximizing the service life or minimizing traffic disruption; the parameters that were set in the NSGA-II are outlined as follows: 1200 generations, a crossover rate of 0.9, a mutation rate of 0.1, and a population size of 400. In addition, the PF consists of the optimal tradeoff solutions, and each of these solutions represents a rehabilitation plan associated with a maximum service

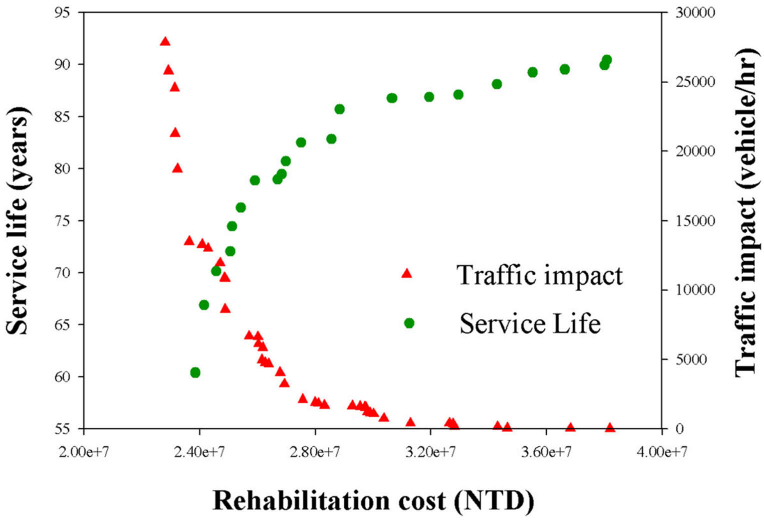


Fig. 4 Optimal trade-off for two objectives

life or minimum traffic disruption at a specific rehabilitation cost. As expected, increasing the rehabilitation cost increased and reduced the total service life and traffic disruption, respectively. VCP materials and the trenchless construction method were mostly adopted in the rehabilitation plans associated with high rehabilitation costs. Compared with the plan associated with the highest pipe service life, the service life of the pipes in the plan involving the lowest service life was lower by 26.6 years; however, in this plan, a rehabilitation budget of 1.4 million NTD was saved. Similarly, in the plan involving the lowest traffic disruption, a rehabilitation budget of 1.5 million NTD was spent on reducing the traffic disruption of 28 000 vehicles/h. Only 22 or 38 candidate optimal plans (5.5 % or 9.5 % of the population size) were obtained, respectively, indicating that determining the optimal design of complex sewerage rehabilitation is difficult. Generally, the cost estimated in the rehabilitation plans (solutions) ranged from 23 million NTD to 38 million NTD depending on the adopted construction method and material. Compared with the estimated rehabilitation cost (nearly 28 million NTD) in the experts' manual plan (Government KC 1999), the SRMOS can offer a complete rehabilitation plan set and the minimum cost was lower by 20 %. This result indicates that the SRMOS can provide acceptable and sophisticated rehabilitation plans at a lower cost for reference in decision-making.

In real applications, evaluating only two objectives usually cannot satisfy the request of decision-makers, and the quantifiable direct cost is usually estimated inappropriately. Consequently, three conflicting objectives were optimized simultaneously [Eqs. (1)–(8)] to determine the most appropriate sewerage rehabilitation plan. Figure 5 illustrates the optimal tradeoff solutions for the three conflicting objectives; these solutions were computed using a population size of 400 and 1200 generations, and the PS consists of these solutions in a 3D space. As clearly depicted, a higher rehabilitation budget is spent in simultaneously satisfying the other two objectives. Depending on the requests of decision-makers, numerous optimal tradeoff solutions [Fig. 5a] can be visualized to provide decision-makers with various appropriate plan choices. For example, if a total traffic interference of approximately 10,500 vehicles/h is considered in a plan, a service life of 70.7 years can be achieved for 2.69 million NTD, and a service life of 85.4 years is possible for 3.81 million NTD. Remarkably, several alternative plans associated with no traffic disruption are indicated in Fig. 5a, and these reasonable plans mean that the trenchless construction method is applied in rehabilitating all failed pipes despite the higher cost. By contrast, such plans could not be determined in the optimization of the two objectives (Fig. 4). This result indicates that fewer objectives are not conducive for obtaining a practical plan, and this is possibly because of the difficulty involved in fully quantifying the rehabilitation cost. In other words, increasing the number of objectives can make up the drawback of cost hard to be quantified and can also facilitate deriving practical plans for decision-making references.

3.2 Parameter Sensitivity Analysis in Sewerage Rehabilitation Plans

Figure 5b illustrates the tradeoff ranked in optimal and suboptimal solutions after the evolution of fewer generations. The suboptimal solutions were dominated by the optimal solutions, and the suboptimal solutions would approach the optimal solutions after a higher number of evolutions; this illustrates the nature of the NSGA-II ranking selection method. Furthermore, to illustrate the effect of generation evolution on solution improvement, the tradeoff was determined by setting the same population size as that in the preceding tests, a crossover probability of 0.9, and a mutation probability of 0.1 after different generation evolutions

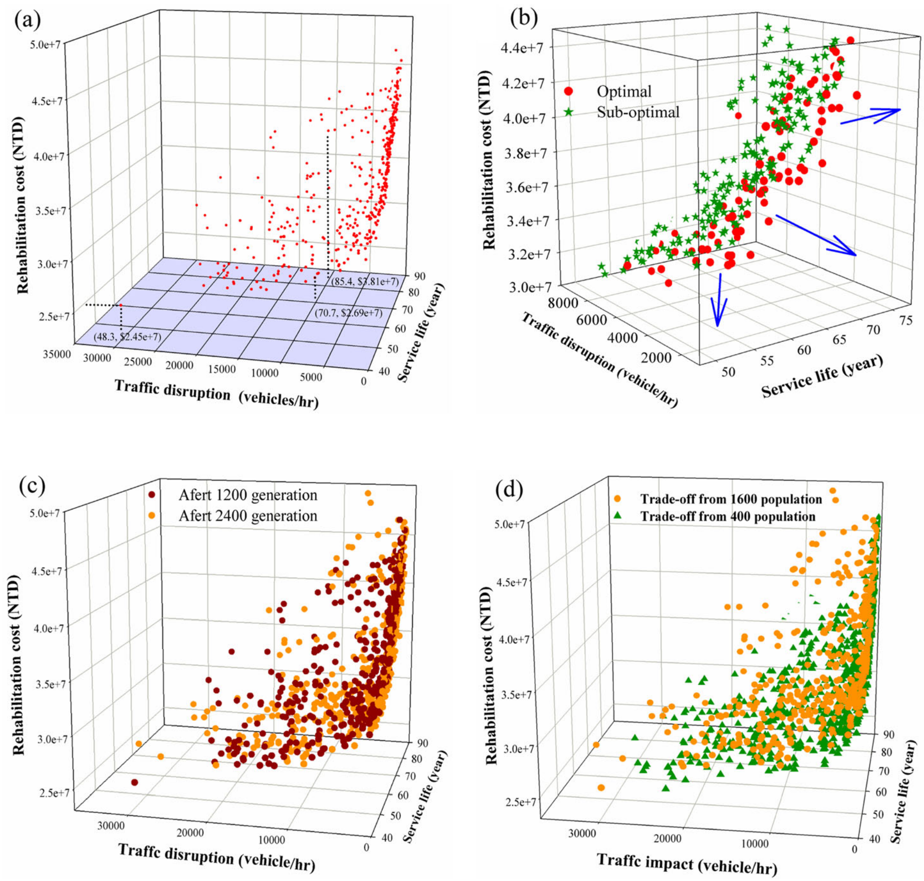


Fig. 5 **a** Optimal trade-off for three objectives. **b** Evolution of Trade-off. The effect of **c** generation and **d** population parameter on trade-off

(Fig. 5c). This similar tradeoff indicates that the solution cannot be improved further after the 1200 generation, which is three times the population size in the NSGA-II. Similarly, to explore the effect of the population size on the number of tradeoff solutions, the tradeoff was calculated by setting different population sizes after a generation evolution of three times the population size. Figure 5d depicts 400 and 600 optimal tradeoff solutions obtained for population sizes of 400 and 1600, respectively. These results indicate that the number of solutions did not increase considerably even when the population size increased fourfold. In other words, an infinite tradeoff solution does not exist in the solution space for this discrete optimization problem.

To explore the effects of other NSGA-II parameters on the tradeoff solution, several SRMOS runs were performed with different parameters. Three indicators in Table 3 were used to evaluate the effects of the parameters. These indicators include the numbers of optimal solutions, suboptimal solutions, and the solutions representing the rehabilitation plan associated with no traffic disruption. In the generation test, when the number of generations increased, the solutions clearly converged to the optimal solution until the number of generations reached three times the population size. After the 1200th generation, the number of optimal solutions changed regularly and the number of plans associated with no traffic disruption approached a steady state. This can be attributed to the

Table 3 Sensitive analysis result for NSGA-II parameter

Control parameter of NSGA-II*		Number of optimal solution (Proportion)	Number of sub-optimal solution (Proportion)	Number of plan with no traffic disruption
Generation	200	216 (54 %)	184 (46 %)	0
	400	249 (62 %)	151 (38 %)	3
	800	332 (83 %)	68 (17 %)	2
	1200	400 (100 %)	0 (0 %)	3
	1600	328 (82 %)	72 (18 %)	5
	2000	369 (93 %)	31 (7 %)	6
	2400	400 (100 %)	0 (0 %)	4
	2800	353 (88 %)	47 (12 %)	3
	3600	364 (92 %)	36 (8 %)	3
Population size	200	200 (100 %)	0 (0 %)	2
	400	400 (100 %)	0 (0 %)	3
	800	349 (44 %)	451 (56 %)	5
	1200	422 (35 %)	778 (65 %)	2
	2400	446 (19 %)	1954 (81 %)	5
Crossover probability	0.8	310 (78 %)	90 (22 %)	3
	0.85	337 (84 %)	63 (16 %)	4
	0.9	400 (100 %)	0 (0 %)	3
	0.95	349 (87 %)	51 (13 %)	5
Mutation probability	0.05	400 (100 %)	0 (0 %)	2
	0.1	400 (100 %)	0 (0 %)	3
	0.15	261 (65 %)	139 (35 %)	0

*Other input parameter is constant

mechanisms of diversity-convergence balance in the NSGA-II and may depend on the request in different generation stages for each problem (Ishibuchi and Shibata 2004). When the number of generations was set as 1200 in a series of population size tests, increasing the population size did not increase the proportion of optimal solutions when the population size exceeded 400 (one-third of the total generation). However, the obvious increase in the number of suboptimal solutions indicates that solutions in a larger population require more generations to evolve. In the crossover probability test, solutions with a high crossover probability resulted in a high number of optimal solutions. However, excessive crossover causes solutions to converge rapidly, thereby losing their diversity; the appropriate probability is thus 0.9. Finally, the result of the mutation probability test indicated that a higher mutation probability clearly reduced the number of optimal solutions as well as the number of plans associated with no traffic disruption. In summary, an appropriate number of generations, high crossover probability, and low mutation probability for this sewerage rehabilitation case are the major factors influencing optimization.

3.3 Cost-Effectiveness Analysis of Sewerage Rehabilitation Plans

Cost efficiency contour is commonly used for strategic planning and potential to describe cost reduction for a product. To implement a thorough cost-effectiveness analysis of a sewerage rehabilitation plan, the feasible PS comprised 554 optimal tradeoff solutions in 3D (Fig. 6a).

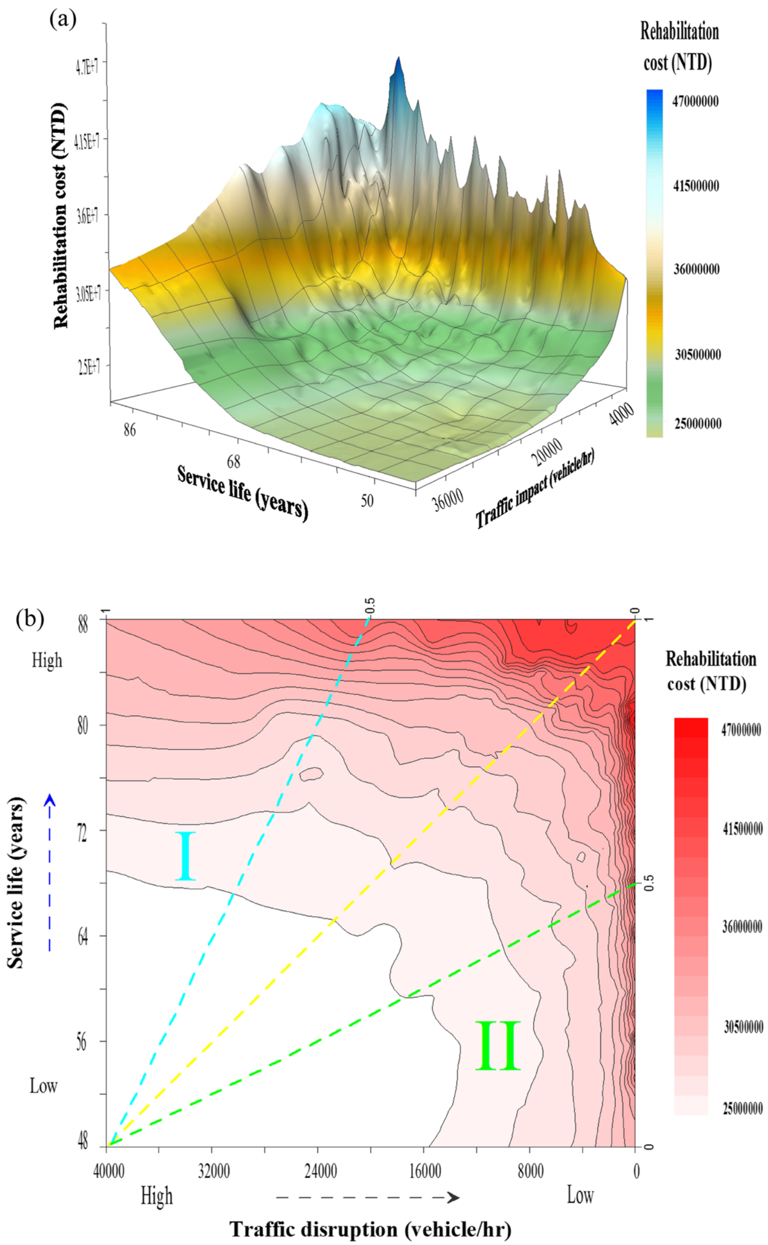


Fig. 6 **a** 3D Pareto surface (PS) for study case and **b** 2D cost-efficiency curve derived from the PS

The solutions were determined by setting the population size to 1200, number of generations to 3600, crossover probability to 0.9, and mutation probability to 0.1; this can enable decision-makers to perceive the tradeoff between service life and traffic disruption at a given rehabilitation cost. As expected, increasing the system service life or reducing the traffic disruption both increased the rehabilitation cost. Multiple peaks and valleys were observed for one of the objectives when the other two objectives were varied. This result clearly indicates that sewer pipe rehabilitation optimization problems containing discrete variables are highly nonconvex; resolving such problems by using conventional optimization techniques is thus not ideal. However, interpreting the PS in 3D as shown in Fig. 6a is quite cumbersome; therefore, the PS was projected onto a plane as a cost-efficiency contour (Fig. 6b). The contour represents the isoline of the sewerage rehabilitation cost, and indicates different combinations of inputs that lead to the same rehabilitation budget. When a system traffic disruption of 24 000 vehicles/h and system service life of 65 years are required, the investment cost is approximately 25 million. NTD When the traffic disruption is lower than approximately 3000 vehicles/h, the intensive isoline indicates that the traffic disruption dominates the investment cost. This result also implies that the cost benefit declines after this threshold (i.e., 3000 vehicles/h) under a limited budget. Similarly, the rehabilitation cost increases rapidly in the region in which the pipe service life is higher than 80 years or traffic disruption is lower than 16 000 vehicles/h.

The straight lines illustrated in Fig. 6b represent the relative importance (weight) between two objectives at a certain rehabilitation budget and provide various choices for decision-makers. For example, the blue, yellow, and green line indicates that the weight of Objective 2 to Objective 3 is 1/2, 1/1, and 2/1, respectively. In other words, these lines can be used to quantify the equivalence between two objectives with different units. The yellow line indicates that the value of reducing the traffic disruption by 1000 vehicles/h is equivalent to the value of increasing the system service life by 0.98 years, under the assumption that the decision-maker treats Objectives 2 and 3 with the same importance. When a decision-maker perceives Objective 2 as more important than Objective 3, the tradeoff solution approaches Area I. The rehabilitation cost in Area I increases at an arithmetic ratio as the service life increases. By contrast, the optimal solution approaches Area II when a decision-maker prefers Objective 3, and the rehabilitation cost in Area II increases at a geometric ratio as the traffic disruption decreases.

3.4 Layout of Sewerage Rehabilitation Plans

To provide a user-friendly decision support environment for decision-makers, the rehabilitation plan in the PS set can be visualized in a GIS. Figure 7 depicts the layout of the construction methods and substitute materials for some optimal rehabilitation plans. As shown in Fig. 7a, in the rehabilitation plan involving the highest pipe service life and estimated budget of 43 770 739 NTD, a total service life of 94 years and traffic disruption of 1370 vehicles/h are obtained; in this plan, the employed construction method includes 14 % trenchless replacement, 16 % excavation replacement, 31 % renovation, and 39 % renewal. In the lane with the same and lower traffic flow, such as Pipes #59, #61, and #63, a similar construction method should be adopted; however, the difference in the length of the failed pipes necessitates applying different construction methods and substitute materials for pipes (Figs. 7a and b) to satisfy the three conflicting objectives. Regarding the selected substitute materials, Fig. 7b indicates that only 28 % of the failed pipes are replaced by VCPs to increase the pipe service life, whereas the remaining 72 % of the failed pipes are partially fixed by adopting renewal and renovation methods that maintain the original pipe service life. This result shows that the rehabilitation cost has a considerable effect on maximizing pipe service life and that the empirical cost functions of renewal and renovation

Fig. 7 Layout of **a** rehabilitation method and **b** substitution material in maximum pipe service life plan. Layout of rehabilitation methods in **c** minimum traffic disruption plan and **d** minimum rehabilitation cost plan

[Eqs. (3)–(6)] are both underestimated. When trenchless or excavation replacement is adopted, 89 % of the failed pipes are replaced by VCP materials to approach the maximum service life.

Pipes #59, #61, and #63 in the dead-end lanes at the same traffic flow should be considered to adopt the same method for rehabilitation in practice. However, excavation replacement by using VCPs at a low cost is suggested in rehabilitating Pipes #59 and #61 to minimize the cost, and the substitute material of the highest quality (VCP) is suggested to maximize the service life. Trenchless replacement with a low-cost substitute material (ABS) is suggested because of its longer failure length in rehabilitating Pipe #63. This result also indicates that the cost function tends to dominate the tradeoff plan when practical workflow is not considered. In general, for main roads with high traffic flow, Wumiao Road and Jianming Road, the trenchless method is adopted to minimize traffic disruption.

As illustrated in Fig. 7c, in the rehabilitation plan involving the lowest traffic disruption and estimated budget of 42 716 378 NTD, a service life of 81 years and no traffic disruption are obtained; furthermore, in this plan, the trenchless construction method is adopted and entails performing 19 % trenchless replacement, 44 % renovation, and 37 % renewal. Similarly, in the plan involving the lowest rehabilitation cost (Fig. 7d) and estimated budget of 23 799 322 NTD, a moderate service life (60 years) and severe traffic disruption (22 033 vehicles/h) are obtained. As expected, this plan would adopt the excavation replacement method and a pipe material with a low cost (50 % and 58 %) to satisfy the minimizing rehabilitation cost. Compared with the excavation replacement method, the 0 % trenchless replacement and 3 % renewal in this plan are consistent with the result of high traffic disruption. Visualizing the plan can enable decision-makers to clearly determine appropriate construction methods and substitute materials for failed pipes.

4 Conclusions

The proposed SRMOS was applied on a real sewerage system, and results showed the SRMOS provided a acceptable and sophisticated rehabilitation plan with estimations that are 20 % lower than those provided by experts. Such result demonstrated that SRMOS can provide Pareto rehabilitation plans among three novel objectives, which are minimizing the rehabilitation budget, maximizing the service life, and minimizing traffic disruption. Several NSGA-II parameters were determined thorough sensitivity analysis to investigate their effects on the optimal tradeoff solution. Some reasonable plans were observed only in the tradeoff among the three objectives. This indicates that increasing the number of objectives facilitates deriving more practical plans for decision-making references because this study overcame the difficulty of fully quantifying the indirect rehabilitation cost.

In the future, the service life could be considered as a function of the pipe material, pipe position, and underground environment. Furthermore, the NSGA-II could face challenges in dealing with more than three objectives. An extension of NSGA-II optimizer may be employed in the SRMOS while being applied to four objective optimization, such as construction period or environmental impact in addition.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that there is no conflict of interests regarding the publication of this paper.

References

Ahmadi M, Bozorg Haddad O, Mariño MA (2014) Extraction of flexible multi-objective real-time reservoir operation rules. Water Resour Manag 28:131–147. doi:10.1007/s11269-013-0476-z

Barlow E, Tanyimboh T (2014) Multiobjective memetic algorithm applied to the optimisation of water distribution systems. Water Resour Manag 28:2229–2242. doi:10.1007/s11269-014-0608-0

Dandy G, Bogdanowicz A, Craven J, Maywald A, Liu P (2008) Optimizing the sustainability of water distribution systems. Water Distribution Systems Analysis 2008:17–21

Dhar A, Patil R (2012) Multiobjective design of groundwater monitoring network under epistemic uncertainty. Water Resour Manag 26:1809–1825. doi:10.1007/s11269-012-9988-1

Fenner R (2000) Approaches to sewer maintenance: a review. Urban Water 2:343–356

Fu G, Butler D, Khu S-T (2008) Multiple objective optimal control of integrated urban wastewater systems. Environ Model Softw 23:225–234

García IF, Montesinos P, Poyato EC, JAR D (2014) Methodology for Detecting Critical Points in Pressurized Irrigation Networks with Multiple Water Supply Points. Water Resour Manag 28:1095–1109. doi:10.1007/s11269-014-0538-x

Government KC (1999) The report of inspection and rehabilitation of the sewerage in the 29th district. MWH, Inc., Taiwan Branch(In Chinese)

Ishibuchi H, Shibata Y (2004) Mating scheme for controlling the diversity-convergence balance for multiobjective optimization. Genetic and Evolutionary Computation–GECCO 2004:1259–1271

Lee JH, Baek CW, Kim JH, Jun HD, Jo DJ (2009) Development of a decision making support system for efficient rehabilitation of sewer. Systems Water Resour Manage 23:1725–1742

Liao X, Zhou J, Ouyang S, Zhang R, Zhang Y (2014) Multi-objective artificial bee colony algorithm for long-term scheduling of hydropower system. A Case Study of China Water Utility Journal 7:13–23

Marzouk M, Omar M (2013) Multiobjective optimisation algorithm for sewer network rehabilitation. Struct Infrastruct Eng 9:1094–1102. doi:10.1080/15732479.2012.666254

Nicklow J et al. (2010) State of the art for genetic algorithms and beyond in water resources planning and management. J Water Res Pl-ASCE 136:412–432

Nouiri I, Yitayew M, Maßmann J, Tarhouni J (2015) Multi-objective optimization tool for integrated groundwater management. Water Resour Manag 29:5353–5375. doi:10.1007/s11269-015-1122-8

Qi W, Savić DA, Kapelan Z (2014) Hybrid metaheuristics for multi-objective design of water distribution systems. J Hydrol 16:165–177. doi:10.2166/hydro.2013.009

Rathnayake US, Tanyimboh TT (2015) Evolutionary Multi-Objective Optimal Control of Combined Sewer Overflows. Water Resour Manag:1–17

Reyna SM (1993) Optimal planning of sewer systems rehabilitation Ph.D. Thesis, Purdue Univ. W. Lafayette, Indiana, USA

Sen Gupta B, Chandrasekaran S, Ibrahim S (2001) A survey of sewer rehabilitation in malaysia: application of trenchless technologies. Urban Water 3:309–315

Su TC, Yang MD (2014) Application of morphological segmentation to leaking defect detection in sewer pipelines. Sensors 14:8686

Tabari MM, Soltani J (2013) Multi-objective optimal model for conjunctive use management using SGAS and NSGA-II models. Water Resour Manag 27:37–53. doi:10.1007/s11269-012-0153-7

Ward B, Savić DA (2012) A multi-objective optimisation model for sewer rehabilitation considering critical risk of failure. Water Sci Technol 66:2410–2417

Wirahadikusumah R, Abraham DM, Iseley T, Prasanth RK (1998) Assessment technologies for sewer system rehabilitation. Autom Constr 7:259–270. doi:10.1016/S0926-5805(97)00071-X

Wu W, Simpson AR, Maier HR (2009) Accounting for greenhouse gas emissions in multiobjective genetic algorithm optimization of water distribution systems. J Water Res Pl-ASCE 136:146–155

Yang MD, Su TC (2006) Automation model of sewerage rehabilitation planning. Water Sci Technol 54:225–232

Yang MD, Su TC (2008) Automated diagnosis of sewer pipe defects based on machine learning approaches. Expert Syst Appl 35:1327–1337

Yang MD, Su TC (2009) Segmenting ideal morphologies of sewer pipe defects on CCTV images for automated diagnosis. Expert Syst Appl 36:3562–3573

Yang MD, Su TC, Pan NF, Liu P (2011a) Feature extraction of sewer pipe defects using wavelet transform and co-occurrence matrix. Int J Wavelets Multi 9:211–225

Yang MD, Su TC, Pan NF, Yang YF (2011b) Systematic image quality assessment for sewer inspection. Expert Syst Appl 38:1766–1776

Yazdi J, Neyshabouri SAAS (2014) An Optimization Model for Floodplain Systems Considering Inflow Uncertainties. Water Resour Manag:1–19