Optimising the design of sewer networks using genetic algorithms and tabu search

Lou Y. Liang
Russell G. Thompson and
David M. Young

The authors

Lou Y. Liang, **Russell G. Thompson** and **David M. Young** are all based at the Department of Civil and Environmental Engineering, The University of Melbourne, Victoria, Australia.

Keywords

Optimization techniques, Programming and algorithm theory, Waste disposal, Water

Abstract

This paper describes the application of heuristic techniques for designing gravity wastewater collection systems. Designing sewer networks can be a time-consuming task that is largely based on trial and error where suitable pipe diameters and slopes combinations for all pipelines between manholes must be identified. Since there is a large range of possible slopes, diameters and roughness coefficients of pipes, only a small number of combinations of these parameters are usually analyzed in traditional design processes. Identifying a minimum cost design is an important issue when constructing sewer networks. In this paper, genetic algorithms and tabu search techniques are implemented to solve this difficult optimization problem. An adaptive rule and a dynamic search strategy were developed to assist the search procedures find better solutions.

Electronic access

The Emerald Research Register for this journal is available at
www.emeraldinsight.com/researchregister

The current issue and full text archive of this journal is available at
www.emeraldinsight.com/0969-9988.htm

Emerald

Engineering, Construction and Architectural Management
Volume 11 · Number 2 · 2004 · pp. 101–112
 · ISSN 0969-9988
DOI 10.1108/09699980410527849

Introduction

The design of gravity wastewater collection systems (GWCS) traditionally involves using trial and error procedures that are time consuming. If the initial design is poor, several iterations maybe necessary before a good design is found. Sewer design requires to engineers generate a broad set of feasible options and make an intelligent selection from that set. However, there are few effective modelling and simulation tools available for aiding the design of GWCS, particularly for conceptual design. Current design processes are not systematic enough to ensure that construction costs are minimised. Large complex networks have more potential for unnecessary costs to be incurred.

Traditional methods for designing GWCS can result in over-design, wasting substantial public funds (Gupta *et al.*, 1976). Numerous models of GWCS have been proposed and applied. One important problem is to determine an optimal sewer system design for a given network layout. In this case, the discharge in each pipe is fixed and adequate pipe sizes and slopes to meet the physical and hydraulic requirements must be determined. A number of mathematical programming techniques have been applied to determine optimal sewer networks, including linear programming (Elimam *et al.*, 1989), dynamic programming (Gupta *et al.*, 1983; Walsh and Brown, 1973), non-linear programming (Dajani *et al.*, 1973; Gupta *et al.*, 1976) and heuristic programming (Desher and Davis, 1986).

Although a range of mathematical programming techniques have been applied to minimise the costs of constructing wastewater systems, they generally have difficulty in dealing with large networks. For example, using a penalty function method with a small computer memory for sewer optimisation may ignore good feasible solutions and obtain near optimal solutions. Dynamic programming has been limited to separate iterations for a number of sub-processes in the sewer network. Other methods neglect diameter progression, but it is

The authors wish to express their gratitude to the Department of Changbin Coastal Construction at Sinotech Engineering Consultants Ltd (SEC) for their important comments and useful suggestions regarding this research.

important that such relationships be specified in order to satisfy the hydraulic constraints. It is often assumed that all pipes are flowing full to set trial slopes, but this fails to consider the partially full condition when determining practical flowing slopes.

Hydraulic principle in design

A GWCS is usually made of steady uniform flow in pipelines with a mean velocity from one section to another (Wallingford and Barr, 1998). Conduits with the surface of the sewage exposed to normal atmosphere pressure are classified as open channels. With a free surface this also implies a constant cross-section and depth. The normal depth is dependent on the channel characteristics and discharge. Sewage is considered to have similar flow characteristics to that of water. Several equations are generally used to evaluate the hydraulic friction head loss. Conduits that are used for conveying sewage are usually designed to operate in partially-full pipe conditions. Thus, consideration of flow velocity and discharge at various depths other than full flow conditions are important in sewer networks design. Manning's equation is used extensively to find a theoretical velocity distribution across the conduit section. It is a semi-empirical equation for uniform steady state flow of water in an open channel (Chow, 1959):

$$V_{\mathrm{f}} = \frac{1}{n} R^{2/3} S^{1/2} \quad \text{SI system} \qquad (1)$$

where n is Manning's roughness coefficient of friction, V_{f} is the flow velocity at full flow, R is the hydraulic radius, and S is the slope of the hydraulic wastewater line.

This equation can be readily expressed in graphical form as design charts. The velocity and discharge at various depths of flow can be derived from this relationship (see Appendix). Let Q_{p}, and V_{p} be the flow discharge and velocity in partially full pipe conditions, respectively, d be the depth of flow and D, Q_{f}, and V_{f} be the hydraulic diameter, discharge, and flow velocity for full flow, respectively. Using these relationships presented in the Appendix, values of $Q_{\mathrm{p}}/Q_{\mathrm{f}}$ and $V_{\mathrm{p}}/V_{\mathrm{f}}$ for various partial depths of flow can be calculated. When sewer pipes are flowing partly full, the same principle that governs flow in open channels can be used, provided the pressure on the surface of the flow is maintained at the atmosphere's level throughout. The shape of the flow section is accounted for by using the hydraulic radius and area. For circular pipes running partly full, it is relatively easy to find the appropriate ratio of depth.

Design criteria

Designers must be able to find feasible solutions using design criteria in a GWCS. There are numerous requirements that act as constraints when designing the layout of sewer networks. For example, conditions relating to the cover depth of pipes, the amount of flow can be conveyed by each link, the continuity of each link and the flow velocity to be accomplished for each link must be considered. Designers must choose parameters from available choices until all the constraints are met. There are two types of constraints that tend to dominate the design of GWCS. First, hard, non-negotiable constraints exist explicitly in the problem statement and are set by design standards. These constraints such as the cover depth of pipe and flow velocity, involve an attribute of the elevation being set. Secondly, soft, negotiable constraints are to be satisfied and are expressed as limits, such as diameter progression in design. These represent design rules or planning guidelines rather than feasibility conditions. However, these constraints have to be considered during the design of GWCS.

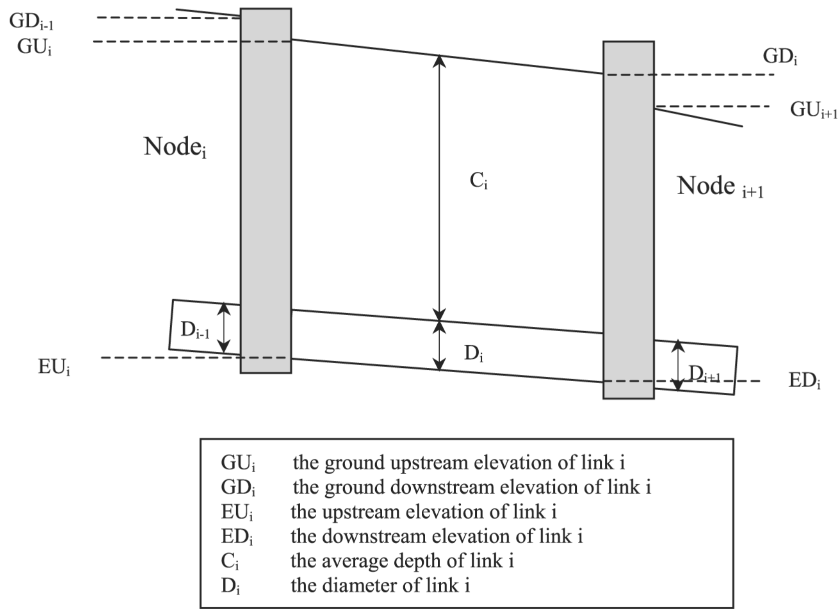
Figure 1 shows the pipeline elevation relationships for two consecutive nodes. The following section describes the constraints and analysis used in the modelling procedures developed.

Cover depth

For underground sewers, it is often necessary to have adequate depth cover. However, construction work is more difficult if a sewer is buried too deep underground. Pipelines are normally designed for a specific range of depth and requires sufficient strength to resist external forces. The average depth of a link should be less or equal to the maximum cover and greater or equal to the minimum cover. The cover depth relationship is represented by:

$$C_{\max} \geq C_i \geq C_{\min} \quad \text{for } i = 1, 2, \ldots, n \qquad (2)$$

Figure 1 Relations of two consecutive nodes



where n is the number of links, $C_{\min}$ is the minimum depth cover, $C_{\max}$ is the maximum depth cover, and C_i is the depth cover of link i.

Velocity limits

Clearly, when designing a sewer pipeline it is important to ensure that it will be capable of conveying sewage with the maximum or minimum velocity resulting from gradient adjustment and other factors. The velocity of flow in a sewer has to be sufficient to prevent deposition of solids. If the velocity is insufficient, solids will settle in the invert of the sewer and remain there. However, high flow velocity in the sewer can cause erosion from dirt in the sewage. Hence, a minimum self-cleaning velocity and maximum velocity must be considered as design criteria:

$$V_{\max} \geq V_i \geq V_{\min} \quad \text{for } i = 1, 2, \ldots, n \qquad (3)$$

where n is the number of links, V_i is the flow velocity in link i, $V_{\min}$ is the minimum flow velocity, and $V_{\max}$ is the maximum flow velocity.

Diameter progression

Usually, sewer diameters on upstream links will be less than or equal to those diameters of downstream links. Although this constraint in sewer network design is not hard, i.e. the sewage will still be conveyed if diameter progression is violated on some links, it is a desirable design criteria. Here, violation will affect the search for optimal solutions by reducing the number of alternative designs considered. Hence, the upstream diameter D_i should be less or equal than the downstream diameter D_{i+1} (Figure 1):

$$D_i \leq D_{i+1} \quad \text{for } i = 1, 2, \ldots, \ n-1 \qquad (4)$$

where n is the number of links, D_i is the diameter of link i, and D_{i+1} is the diameter of link i+1.

Invert level progression

In order to ensure that the outgoing sewage of upstream links reaches the next downstream link, the invert level has to follow a progression rule. For gravity flow, the elevation of upstream inverts of outgoing links must be greater or equal to the downstream elevation of the invert of the incoming link. This relation is represented by:

$$EU_i \geq EU_{i+1} \quad i = 1, 2, \ldots, \ n-1 \qquad (5)$$

where n is the number of links, EU_i is the invert elevation of link i, EU_{i+1} is the invert elevation of link i+1.

Meta-heuristic techniques

In this study, two meta-heuristic techniques have been applied to the design of GWCS.

The practical aspects of adapting genetic algorithms (GA) and tabu search (TS) techniques are described. In order to generate feasible solutions efficiently, an adaptive rule was developed for the GA and a dynamic strategy was constructed for the TS technique.

GA

The ideas of biological evolution based on natural selection were adapted to solve complex systems during the 1960s. These concepts were first applied to engineering problems in the late 1980s (Goldberg and Kuo, 1987). GA usually require the decision variables to be represented as binary digits and concatenated together to form a chromosome. Although it is common to use binary coding for decision variables, integer coding can also be used.

In this study, a combination of both representations were used. Pipe sizes and gradients were used to represent the pipeline network within the optimisation procedure. An algorithm was used to convert the decision variables to binary digits consisting of a specific number of bits. The sub-string ϕ was formed from the set of pipe diameters. The sub-string θ was formed from the gradients. Both sub-strings were used to construct each chromosome that was used as the basic unit $f(\phi, \theta)$. The ϕ and θ sub-strings consist of binary codes that can be transformed into integers to represent the diameter variables and gradient variables, respectively. Only four types of commercial pipes were considered and represented as both binary and integer codes (Table I) in this study. Binary codes were used to represent the hydraulic gradients of links. Integer codes were used to represent solutions after binary coding when applying the adaptive rule. This improved the optimisation process by not violating any of the constraints within the network. The chromosomes were decoded to identify the discrete pipeline diameters and pipeline gradients.

Table I Binary and integer coding

Diameter (m)	Pipe type	Binary coding	Integer coding
0.25	VCP	00	1
0.30	VCP	01	2
0.40	RRCP	10	3
0.50	RRCP	11	4

Adaptive design rules

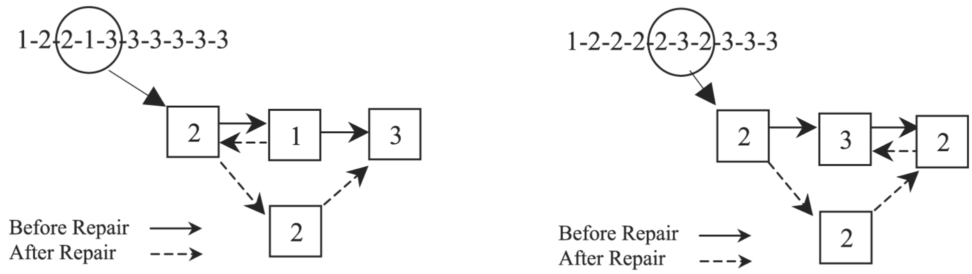
One way to reduce the likelihood of generating infeasible solutions in GA is to incorporate a penalty function within the objective function. This reduces the chance of infeasible solutions surviving beyond the generation they were created. However, this method is inefficient in multi-criteria problems such as, GWCS design problem. Hence, it is important to find a procedure that allows GA methods to be employed, but also ensures that constraints are not violated. Specialised rules can be developed to incorporate constraints within the GA procedures to ensure that only feasible solutions are generated. An adaptive rule was developed to repair "bad" genes. When the crossover and mutation operators lead to "bad-behaviour" genes (ie. genes that violate any constraint), this rule was used to produce "well-shaped" genes. This rule only modified components of solutions to ensure feasibility.

The adaptive rule developed involved choosing a suitable chromosome representation, i.e. choice of the diameter variable being coded. In this study, the integer coding process becomes active after each binary gene was transformed to represent the hydraulic parameters of the sewer network. A chromosome string may not satisfy the diameter progression constraints, for example, the chromosome $\{A\}$ having 10 genes $\{A\} = (1-2-2-2-2-3-2-3-3-3)$ is infeasible because the value of the sixth gene is three and its adjacent gene for corresponding nodes is two. This will cause an illegal progression connection (2-3-2). Figure 2 shows the adaptive upstream and downstream rule used to repair chromosomes that fail to satisfy the diameter progression criteria. The upstream repair rule replaces violating genes with upstream genes, while the downstream repair rule replaces violating genes with downstream genes.

TS

The TS technique was also adapted to optimise the design of GWCS. TS is an artificial intelligence technique that allows flexible memory structures with respect to strategic restrictions and aspiration levels to be defined for exploiting previous solutions

Figure 2 Adaptive GA rules



(a) Upstream-Based Repair **(b)** Downstream-Based Repair

(Glover, 1986; Glover and Laguna, 1997). TS is based on generating neighbourhood solutions from a current feasible solution. Neighbourhood solutions are feasible solutions that are generated from the current feasible solution using a simple operation such as a small variation to one design parameter. For GWCS networks, the neighbourhood can be defined by considering changes to the hydraulic diameters and gradients. The neighbourhood includes subsets with two variables, one subset with the diameter variable and the other subset with the hydraulic gradient variable for which both can be incremented or decremented.

Here, $\Phi(d, s)$ represents a solution, ie. a GWCS network in terms of diameters and gradients. $\phi(d_n, s_n)$ represents the solution in terms of the diameter and gradient for link n in the network. Each solution component $\phi(d_n, s_n)$ has an associated set of neighbourhood solutions $\boldsymbol{N}[\phi(d_n, s_n)]$, where each solution $\phi\left(d_n^\star, s_n^\star\right) \in \boldsymbol{N}[\phi(d_n, s_n)]$ can be reached directly from $\phi(d_n, s_n)$ by an operation called a move, and $\phi(d_n, s_n)$ is said to move to $\phi\left(d_n^\star, s_n^\star\right)$ when such an operation is performed. Thus, $\Phi(d^{\text{trial}}, s^{\text{trial}}) = \Phi(d^{\text{now}}, s^{\text{now}}) \pm (\Delta d^\star, \Delta s^\star)$. Here, $\Phi(d^{\text{now}}, s^{\text{now}})$ is an existing network solution from which trial solutions are generated and $\Delta d^\star$ and $\Delta s^\star$ are incremental or decremental changes to the network solutions. Each trial solution must satisfy all the hydraulic constraints. If the solution $\Phi(d^{\text{trial}}, s^{\text{trial}})$ is better than $\Phi(d^{\text{now}}, s^{\text{now}})$, then the solution $\Phi(d^{\text{now}}, s^{\text{now}})$ is updated with the solution $\Phi(d^{\text{trial}}, s^{\text{trial}})$. After many iterations, the optimal solution of network problem $\Phi(d^{\text{best}}, s^{\text{best}})$ will be updated by the solution $\Phi(d^{\text{now}}, s^{\text{now}})$.

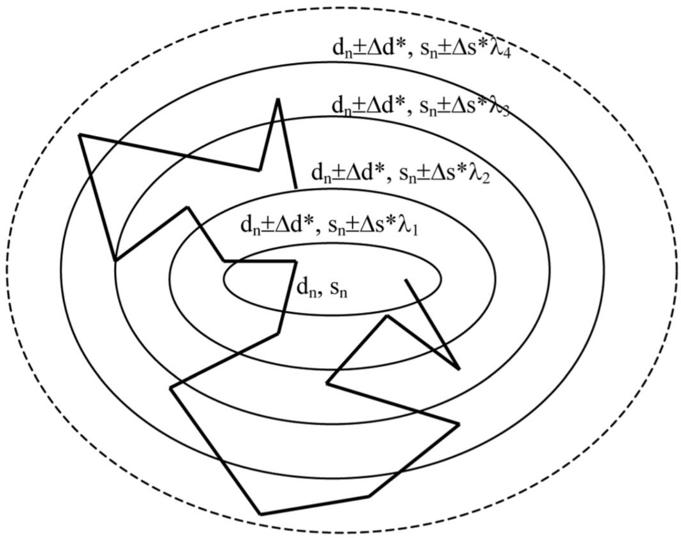
In this search procedure, steps for generating moves can be made more efficient in searching structures that move from one solution to a new one in its neighbourhood set. This consists of determining how many parameters or variables to optimise and what range of values to consider for each parameter. As stated above, if the move $(\Delta d^\star, \Delta s^\star)$ is accepted, then the move is added to the tabu list (TL). Recent moves remain in the TL for at least the number of iterations specified by the tabu tenure. Tabu tenure can vary for different types or combinations of attributes. After the number of tabu tenure iterations have been performed, recently added moves will be removed from the TL. In this study, a dynamic search strategy was developed to implement more efficient moves in the GWCS design.

Dynamic search strategy

A flexible procedure was developed to generate neighbourhood solutions. Here, the moves from the current solutions were adjusted dynamically as a function of the number of iterations. An oscillation factor (λ_t) allows moves to be flexible. Once the diversification effect of the search is achieved, this parameter was no longer used. A common concern of dynamic search strategies is that they can result in generating many infeasible solutions at the end of search. If the oscillation factor is too gentle, the search may converge to a non-optimal feasible solution. Conversely, if it is too harsh, the final stage of the search may result in generating many infeasible solutions. Therefore, the oscillation factor typically requires validation for each specific problem.

Dynamic search strategies are flexible methods that can be used to overcome the problem of premature convergence. Figure 3 shows the dynamic search strategy of a move.

Figure 3 The dynamic search strategy of TS



For certain d_n, s_n ($n = 1, 2, \ldots$, number of links), the search route can be made more flexible by using random values of an oscillation factor λ_t in the relative diameter and gradient moves $\Delta d^\star$, $\Delta s^\star$. A dynamic search strategy was developed using flexible parameter rules that were exchanged between different parameter values randomly. This allowed either an increase or a decrease of the imposed move using a random seed. For the intensification strategy, the parameters $\Delta d^\star$, $\Delta s^\star$ and λ_t were examined in this study. This involved determining of the appropriate value of $\Delta d^\star$, $\Delta s^\star$ and λ_t to decompose the optimisation and periods of search process. Here, the maximum value of the oscillation parameter $\lambda_{\max}$ was used to represent the maximum random integer used in the dynamic search strategy.

This type of intensification approach called intensification by decomposition allowed a more concentrated focus on other parts of the feasible region. Strategic oscillation was applied to avoid cycling. This involved varying the diameter and gradient variations $\Delta d^\star$ and $\Delta s^\star$ applied in the network when evaluating a move. It was also introduced when the value of the objective function did not improve after several iterations.
This strategy swaps the moves between different parameters according to the values of the diameter, gradient variation and random oscillation factors.

Construction cost

The main costs associated with constructing a GWCS are associated with:
- land acquisition,
- overheads,
- labour,
- false-work,
- materials, and
- earthworks.

Land acquisition, overheads and labour costs usually involve many local factors and were not considered in this model. False-work costs were also not included since safety standards would be assumed to be met.

Material and earthwork costs were included in this model. Material costs including all pipes and manholes materials and stores used during the construction can represent about 11 percent of the total construction cost (Walsh and Brown, 1973). Earthwork costs including excavation and backfill often dominate the project cost and can represent around 80 percent of the total cost. The costs of GWCS can be significantly affected by the design of the network in terms of the gradients and diameters of pipes. The cost function used here is based on direct costs relating to a series of activities such as excavation, backfill and dumping:

$$f(c) = \sum_{j=1}^{m} \sum_{i=1}^{n_j} (SC_{ij} + EC_{ij} + BC_{ij} + DC_{ij}) \quad (6)$$

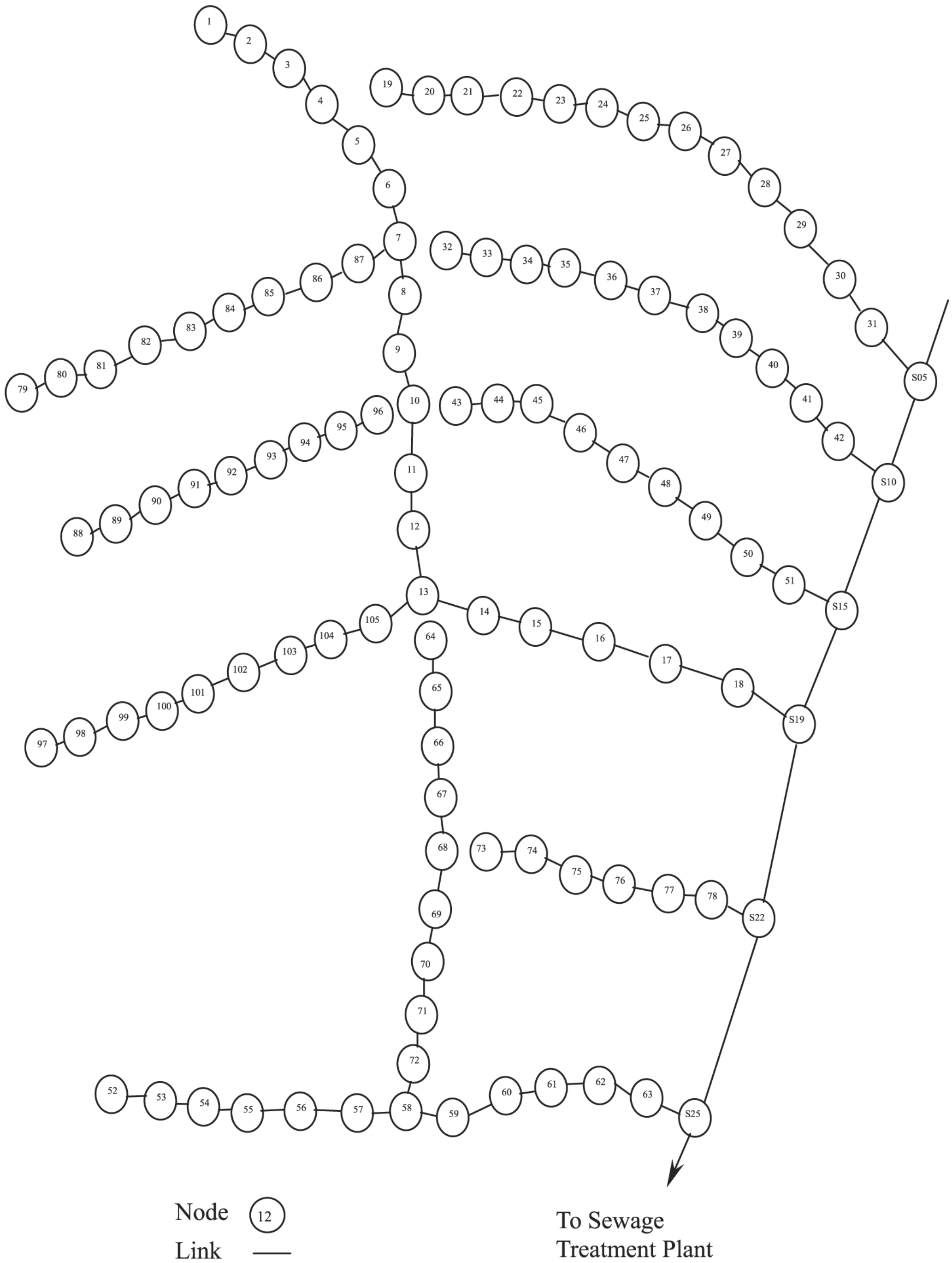
where n_j is the number of sewer links for pipeline j, m is the number of pipelines in the network, SC_{ij} is the material cost of link i of pipeline j, EC_{ij} is the excavation cost of link i of pipeline j, BC_{ij} is the backfill cost of link i of pipeline j, DC_{ij} is the soil dump cost of link i of pipeline j.

Case study

The East-I Wastewater Collection Engineering (EIWCE) project was constructed in 1992 as part of the Changbin Industrial Park Project in the suburb of Changbin adjacent to Taichung Harbour in Taiwan. The EIWCE project consists of a 6.2 km network sewer pipelines used to convey sewage from factories as shown in Figure 4. The original design of the EIWCE project contained 105 links and ten junction manholes with pipeline materials and earthwork

Engineering, Construction and Architectural Management
Volume 11 · Number 2 · 2004 · 101–112

Figure 4 Basic pipeline layouts for the EIWCE project



costing a total of NT$ 12.9 million (1US$ = 34NT$).

Materials cost

The cost of materials used to construct the sewer network depend on the size and type of the pipes used. The cost and specifications of four types of pipe materials that were used in the project are shown in Table II (Changbin, 1992).

Earthwork cost

The earthwork costs associated with construction work not only includes the cost of digging holes but also the cost of disposing excavated material. Therefore, proper selection of sewer trenches becomes an important consideration. The optimal design for GWCS requires an analysis of the construction components and an examination of all

Table II Pipe specifications

Pipe type	Price/m (NT$)	Thickness (cm)	Excavation width (m)	Roughness coefficient
VCP (ϕ250)	1,280	2.2	0.79	0.012
VCP (ϕ300)	1,710	2.5	0.85	0.012
RRCP (ϕ400)	2,100	6.3	1.03	0.013
RRCP (ϕ500)	3,056	7.1	1.14	0.013

Notes: VCP – vitrified clay pipe; RRCP – resin reinforced concrete pipe; and NT$ – new Taiwan dollars

possibilities for use. The unit costs that were used to determine the earthwork costs for the EIWCE are presented in Table III.

Analysis and results

Computational requirements as well as the overall construction cost are important performance measures for evaluating optimisation algorithms. Computation time however, depends on the computers processing speed. Here, the most important performance measure was considered to be the number of solutions generated to identify the best solution.

Analysis of optimisation techniques

In order to assess the performance of the various parameters associated with the optimisation procedures, part of the pipeline network was used. The performance of the GA was investigated by varying the values of three parameters, population size (X), probability of crossover (Pc) and probability of mutation (Pm). With the TS technique the effects of varying the size of the TL and maximum oscillation values (λ_{max}) were explored. The TL size was defined in terms of the percentage of the neighbourhood size.

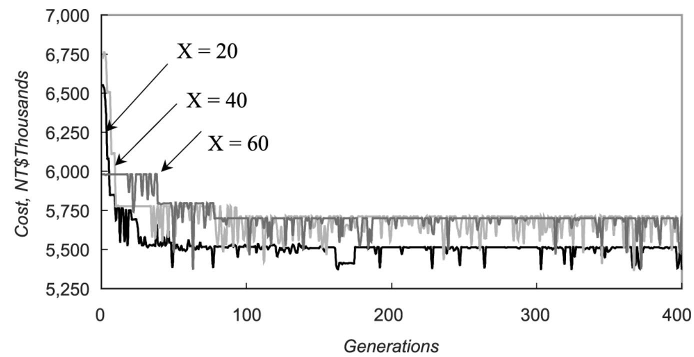
GA

The effects of population size on the performance of the GA are shown in Figure 5.

Table III Unit costs for earthwork activities

Description of work	Unit cost per cubic meter (NT$)	Remarks
Excavation	35	Depth < 4 m
Excavation	88	4 m ≤ depth < 8 m
Backfill	160	Hamper = 100 kg
Dump	53	Distance = 1.5 km

Figure 5 Solution quality and population size



Here, the best value identified in each generation is shown. Higher fluctuations in performance were experienced when a population of 40 was adopted. The smallest population size (20) consistently found better solutions. Moderate levels of the crossover probability (0.4) achieves best results earliest in the search process (Figure 6). The mutation rate had a significant effect of the performance of the GA, with a rate of 0.005 performing much better than the other rates considered (Figure 7).

TS

The effect of TL size on the performance of the TS technique was investigated using the same gradient variance and oscillation factor

Figure 6 Solution quality and crossover probability

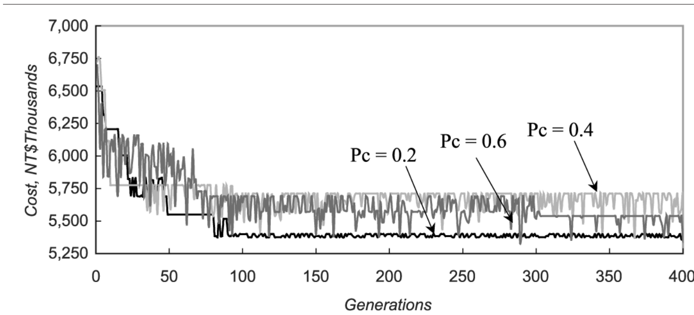
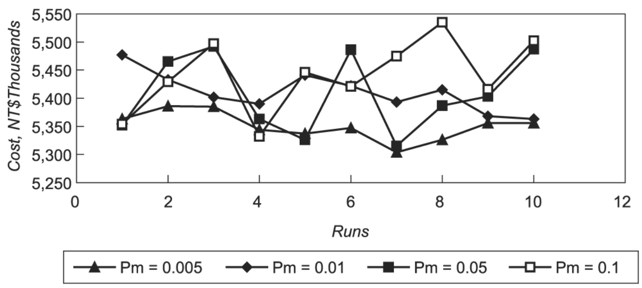


Figure 7 Solution performance and probability of mutation



(Figure 8). The performance of the algorithm was not consistent with a TL size of 80 percent indicating that larger TL size does not necessarily result in identifying better solutions.

The effect of the oscillation factor parameter on solutions can be seen in Figure 9. In this experiment, the maximum oscillation factor, λ_{max}, was set at 2, 3, 4 and 5, respectively. This indicates that the oscillation factor has a significant effect on the performance of the algorithm. It should be noted that the curve is clearly inconsistent at the highest level (5). The performance of the procedure at this level is more likely to be controlled by the maximum oscillation factor parameter. The effects of the maximum oscillation factor parameter on solutions obtained are evident at the higher level. Again, the best-cost curve at each level of oscillation factor is shown in Figure 10.

Figure 8 Solution performance and TL size

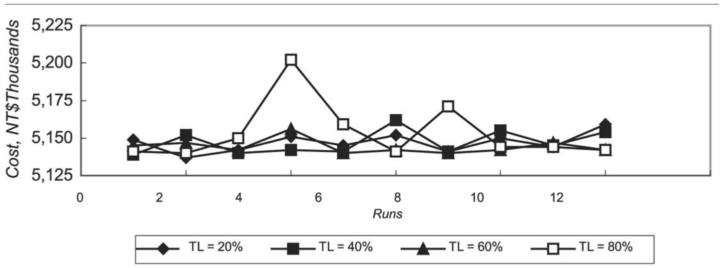


Figure 9 Solution performance of maximum oscillation values

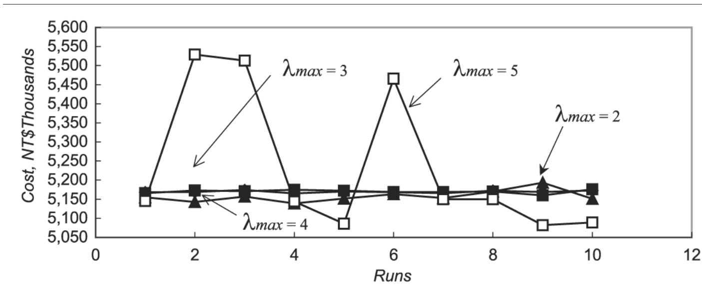
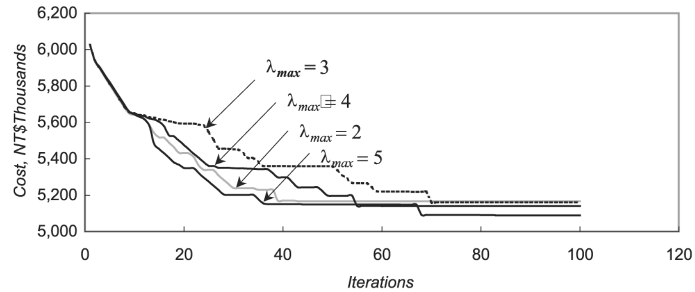


Figure 10 Convergence and maximum oscillation values



The results indicate that the highest parameter level (5) has the steepest slope among them.

Comparison of designs

The design profile for one pipeline (links 1-31) of the EIWE project is presented in Table IV. The conventional design of links 1-18 shows, that pipelines have an average slope of 0.245 percent. The average slopes in pipeline for the best designs obtained from the GA and TS techniques are 0.256 and 0.267 percent, respectively. The conventional design of links 19-31 shows that pipelines have an average slope of 0.244 percent. The average slopes in pipeline design for GA and TS are 0.240 and 0.232 percent, respectively. The traditional design has deeper elevations downstream compared with both GA and TS designs. GA tends to have larger diameters compared with TS for many links.

In order to get a better appreciation of the performance of the GA and TS techniques, the construction costs were compared with those using the conventional methodology (Table V). It can be seen that the designs produced using both GA and TS techniques achieve a significant reduction in construction costs. Overall, the best GA and TS designs achieved a cost savings of 9 and 16 percent, respectively. Costs were reduced for all pipelines for both techniques. However, TS consistently achieved larger cost savings than GA.

Conclusions

This paper has described how GA and TS methods can be applied to overcome the problems faced by the current trial and error

Engineering, Construction and Architectural Management
Volume 11 · Number 2 · 2004 · 101–112

Table IV Design dimensions

Link no.	Conventional design		GA design		TS design	
	Diameter (m)	Gradient (percent)	Diameter (m)	Gradient (percent)	Diameter (m)	Gradient (percent)
1	0.30	0.25	0.25	0.19	0.25	0.27
2	0.30	0.24	0.25	0.17	0.25	0.18
3	0.30	0.24	0.25	0.18	0.25	0.21
4	0.30	0.24	0.25	0.18	0.25	0.27
5	0.30	0.24	0.30	0.18	0.25	0.27
6	0.30	0.23	0.30	0.19	0.25	0.26
7	0.40	0.19	0.40	0.13	0.30	0.21
8	0.40	0.18	0.40	0.21	0.30	0.22
9	0.40	0.18	0.40	0.24	0.30	0.27
10	0.40	0.17	0.40	0.16	0.40	0.17
11	0.40	0.17	0.40	0.21	0.40	0.16
12	0.40	0.18	0.40	0.25	0.40	0.18
13	0.50	0.16	0.50	0.13	0.40	0.31
14	0.50	0.18	0.50	0.20	0.50	0.10
15	0.50	0.16	0.50	0.14	0.50	0.14
16	0.50	0.14	0.50	0.11	0.50	0.14
17	0.50	0.13	0.50	0.24	0.50	0.14
18	0.50	0.13	0.50	0.10	0.50	0.14
19	0.30	0.28	0.25	0.23	0.25	0.23
20	0.30	0.24	0.25	0.19	0.25	0.21
21	0.30	0.24	0.25	0.20	0.25	0.18
22	0.30	0.24	0.25	0.18	0.25	0.18
23	0.30	0.24	0.25	0.20	0.25	0.18
24	0.30	0.24	0.30	0.15	0.25	0.23
25	0.30	0.24	0.30	0.22	0.25	0.29
26	0.30	0.24	0.30	0.20	0.25	0.33
27	0.30	0.24	0.30	0.18	0.30	0.15
28	0.30	0.22	0.30	0.22	0.30	0.17
29	0.30	0.20	0.30	0.20	0.30	0.19
30	0.30	0.20	0.30	0.21	0.30	0.24
31	0.30	0.08	0.30	0.12	0.40	0.11

Table V Cost comparisons of EIWCE

Segment	I	II	III	IV	V	VI
Link No.	1-18, 79-105	19-31	32-42	43-51	52-72	73-78
Conventional (NT$ thousands)	6001	1490	1324	903	2588	624
GA (NT$ thousands)	5304	1417	1209	848	2438	505
TS (NT$ thousands)	5061	1328	1100	745	2218	483
GA saving (percent)	11.6	4.9	8.7	6.1	5.8	19
TS saving (percent)	15.6	10.8	16.9	17.5	14.3	22.5

methodology used in designing sewer networks. Specialised procedures were developed for improving the efficiency of both techniques. An adaptive rule was constructed for ensuring that diameter progression constraints were satisfied for the GA. A dynamic search strategy was implemented for the TS that allowed a more diverse range of solutions to be explored in order to avoid premature convergence. Both procedures were able to improve the performance of the meta-heuristic techniques.

A case study was used to demonstrate the savings in construction costs that would be achieved by implementing the designs produced by GA and TS. Overall, significant reductions in construction costs were estimated, 9 percent for the GA and 16 percent with TS. Both techniques produced optimal designs with shallower pipe elevations downstream compared with the traditional design. Pipelines produced using GA often contained pipes with larger diameters than TS. The TS technique consistently identified lower cost designs than GA.

References

Changbin (1992), *Changbin Coastal Industrial Park Hsien Si Zone East I Wastewater Collection System Engineering Design*, SEC Taiwan (in Chinese).

Chow, V.T. (1959), *Open-Channel Hydraulics*, McGraw-Hill, New York, NY.

Dajani, J.S., Gemmell, R.S. and Morlok, E.K. (1973), "Optimal design of urban wastewater collection networks", *Journal of the Sanitary Engineering Division, ASCE*, Vol. 98, pp. 853-67.

Desher, D.P. and Davis, P.K. (1986), "Designing sanitary sewers with microcomputers", *Journal of Environmental Engineering, ASCE*, Vol. 112, pp. 993-1007.

Elimam, A.A., Charalambous, C. and Ghobrial, F.H. (1989), "Optimum design of large sewer networks", *Journal of Environmental Engineering, ASCE*, Vol. 115, pp. 1171-90.

Glover, F. (1986), "Future paths for integer programming and links to artificial intelligence", *Computers Operations Research*, Vol. 5, pp. 533-49.

Glover, F. and Laguna, M. (1997), *Tabu Search*, Kluwer, Norwell, MA.

Goldberg, D.E. and Kuo, C.H. (1987), "Genetic algorithms in pipeline optimization", *Journal of Computing in Civil Engineering, ASCE*, Vol. 1, pp. 128-41.

Gupta, J.M., Agarwal, S.K. and Khanna, P. (1976), "Optimal design of wastewater collection systems", *Journal of the Environmental Engineering Division, ASCE*, Vol. 102, pp. 1029-41.

Gupta, A., Mehndiratta, S.L. and Khanna, P. (1983), "Gravity wastewater collection systems optimization", *Journal of Environmental Engineering, ASCE*, Vol. 109, pp. 1195-209.

Wallingford, H. and Barr, D.I.H. (1998), *Tables for the Hydraulic Design of Pipes, Sewers and Channels*, Thomas Telford, London.

Walsh, S. and Brown, L.C. (1973), "Least cost method for sewer design", *Journal of the Environmental Engineering Division, ASCE*, Vol. 99, pp. 333-45.

Appendix. The velocities and discharges at various depth of flow

For incompressible flow, ρ is the constant and the discharge will be

$$Q_0 = A_0 V_0 \tag{A1}$$

where Q_0, the discharge, is the volume per unit time flowing and V_0 is the average velocity at the cross-section A_0. The partial flow velocity depends on the property of a pipe section that can be defined entirely by geometry of the pipe section and depth of flow. From Figure A1, the flow depth d of pipe diameter D is flowing and an angle 2θ is made at the center.

$$\theta = \cos^{-1}\left(\frac{D-2d}{D}\right) \tag{A2}$$

$$A_0 = \frac{D^2}{4}\left(\pi\left[1-\frac{\theta}{180}\right] + \left[\frac{\sin 2\theta}{2}\right]\right) \tag{A3}$$

The wetted perimeter P

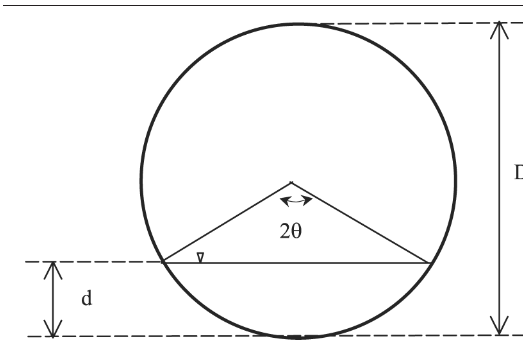
$$P = \left(1-\frac{\theta}{180}\right) \times \pi D \tag{A4}$$

The hydraulic radius R is the ratio of the water area to its wetted perimeter, i.e.

$$R = \frac{A_0}{P} = \frac{\left(\pi\left[1-\frac{\theta}{180}\right] + \left[\frac{\sin 2\theta}{2}\right]\right)D}{\left(4-\frac{\theta}{45}\right)\pi} = \Pi D \tag{A5}$$

where Π is a constant for each partial depth of flow.

Figure A1 Cross-section of pipe in partial filled condition



For the velocity V_p of the partial flow,

$$\frac{V_p}{V_f} = \left(\frac{n_p}{n_f}\right)\left(\frac{R_p}{R_f}\right)^{2/3} = \left(\frac{\Pi_p}{\Pi_f}\right)^{2/3} \tag{A6}$$

here n is assumed as a constant.

Substituting equation (A3) and equation (1) in equation (A1), we obtain

$$Q = \frac{D^2}{4n}\left(\pi\left[1 - \frac{\theta}{180}\right] + \left[\frac{\sin 2\theta}{2}\right]\right)\Pi^{2/3}D^{2/3}S^{1/2}$$
$$= \Omega D^{8/3}S^{1/2} \tag{A7}$$

where

$$\Omega = \frac{\Pi^{2/3}}{4n}\left(\pi\left[1 - \frac{\theta}{180}\right] + \left[\frac{\sin 2\theta}{2}\right]\right)$$

For the discharge Q_p of the partial flow,

$$\frac{Q_p}{Q_f} = \left(\frac{n_p}{n_f}\right)\left(\frac{A_p}{A_f}\right)\left(\frac{R_p}{R_f}\right)^{2/3} = \left(\frac{\Omega_p}{\Omega_f}\right) \tag{A8}$$

here n is assumed as a constant.

The relative depth between the different velocity and discharge can be derived from equations (A6) and (A8), respectively.