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ADVANTAGES OF USING GENETIC ALGORITHMS OVER DETERMINISTIC METHODS IN OPTIMAL DESIGN OF THE WATER NETWORKS REHABILITATION

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Abstract. Water supply and distribution systems are key elements of any urban development or sustainable agricultural development in the case of the irrigation systems. It is not surprising then that various analyses and design techniques for the economic and efficient design of hydraulic networks have received attention over the years. A possible approach to increasing the hydraulic capacity of water supply and distribution systems is to add loops (thereby providing alternative pathways) and increase their hydraulic capacity with minimum capital investment. However, optimal design of looped hydraulic networks belongs to the class of large combinatorial optimisation problems which are very difficult to handle using conventional operations research techniques. In recent years some successful attempts to apply modern heuristic methods to this problem have been published. The main part of the paper deals with applying such a technique, namely the genetic algorithm methodology, to network rehabilitation optimisation considering both technical and economic aspects of the problem. A case study of the sprinkler irrigation system Šala-Kolárovo 13 (south-west part of Slovakia) is presented.

1. Introduction. The linear programming (LP) method has long been accepted as an approach for the optimal selection of diameters for pipes in branched irrigation networks. However, problems with adapting mathematical programming methods to looped network problems have restricted the use of LP to branched layouts only. Although there are some examples of efforts to use models for the design of looped networks, mainly by using mathematical programming (non-linear programming, dynamic programming), such a problem is still considered to be difficult to solve, particularly if one decides to tackle complex, real life networks.

These problems in applying optimising techniques contributed significantly to the situation in Slovakia where the majority of pressurised irrigation systems with large area coverage was designed with a branched layout. At first glance this seems to be a mistake because from both hydraulic and operational viewpoint looped networks are usually preferred to branched networks. The main disadvantage of branched networks is that they provide only one route to the delivery point. Paradoxically, networks without loops in the original configuration may be viewed as an advantage in the case of rehabilitation and strenghtening the systems since they may be improved by introducing loops. It represents a precious potential of branched networks, especially nowadays when there is need to increase their hydraulic capacity as a part of rehabilitation of irrigation networks.

This option is even more valuable when we consider the fact that in previous decade several papers appeared in the scientific literature, presenting modern heuristics capable of providing solutions to optimisation problems where previous-

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ly deterministic algorithms have failed (Simpson et al 1994, Savič et al 1997, Čistý et al 1999). One of the heuristic methods, which are best suited for purposes of design, rehabilitation or calibration of pressurised pipe networks, is the genetic algorithm (GA).

In the majority of cases the requirement to increase the hydraulic capacity of the water distribution systems is based on the following demands:

- To increase pressure and take off at demand points due to the irrigators upgrade (with increased demand).
- To provide sufficient pressure within the pipeline system with a larger number and modified locations of demand points as well as their grouping in selected parts of an irrigation system.
- To expand the system by adding new branches.
- To eliminate system deficiencies due to its aging.

2. Methodology. Genetic algorithms are stochastic search methods that mimic the process of natural selection and mechanism of population genetics. They were first introduced by Holland (1975) at the University of Michigan and later developed further and popularised by Goldberg (1989) at the University of Illinois. Genetic algorithms are used in a number of different application areas ranging from function optimisation to solving large combinatorial optimisation problems. The GA is an algorithmic model of Darwinian evolution that begins with the creation of a set of solutions referred to as a *population of individuals*. Each individual in a population consists of a set of parameter values that completely describes a solution. A solution is encoded in a string called a *chromosome*, which is consists of *genes* that can take a number of values (*alleles*). Initially, the collection of solutions (*population*) is generated randomly and at each iteration (also called *generation*), a new generation of solutions is formed by applying genetic operators analogous to ones from natural evolution (*crossover, mutation, selection, reproduction*). Each solution is evaluated using an objective function (called a *fitness function*), and this process is repeated until some form of convergence in fitness is achieved. The goal of the optimisation process is to minimise or maximise the fitness. The following pseudo-code shows how a GA works:

```
BEGIN /* genetic algorithm*/
        Generate initial population;
        Compute fitness of each individual;
        WHILE NOT finished DO LOOP
                BEGIN
                        Select individuals from old generations for mating;
                        Create offspring by applying recombination and/or
mutation
                        to the selected individuals ;
                        Compute fitness of the new individuals;
```

Kill old individuals to make room for new chromosomes and insert offspring in the new generation;
IF Population has converged THEN finishes := TRUE ;
END
END

Genetic Algorithm raises again a couple of important features. First it is a stochastic algorithm; randomness has an essential role in genetic algorithms. Both selection and reproduction needs random procedures. A second very important point is that genetic algorithms always consider a population of solutions. Keeping in memory more than a single solution at each iteration offers a lot of advantages. The algorithm can recombine different solutions to get better ones and so, it can use the benefits of assortment. The robustness of the algorithm should also be mentioned as something essential for the algorithm success. Robustness refers to the ability to perform consistently well on a broad range of problem types. There is no particular requirement on the problem before using GAs, so it can be applied to resolve any problem. All those features makes GA a really powerful optimisation tool.

In the case of the pipe network rehabilitation the optimisation problem can be stated as: minimise the cost of upgrading the network subject to satisfactory performance. Rehabilitation options can include pipe removal and replacement (with pipes of any one of a set of available diameters), pipe insertion with the same size or smaller inserts (die drawing), pipe duplication with pipes of any diameter, pipe cleaning, pipe lining or taking no action. The chromosome can be a binary or integer string of numbers (representing possible decisions), which thus defines the network design.

Completely new networks or schemes to strengthen existing networks can be designed. Pipes, valves, pumps and reservoirs can be added (or removed), and their size and capacity chosen on an overall optimal basis by the GA. Even modifications to existing pumps or reservoirs can be considered as options within the overall system. Care must be taken, however, to incorporate all reasonably possible choices for each component in the system, with an appropriate set of costs from which all schemes can be priced. In general, the more choices and flexibility in the design options allowed at this stage, the greater the savings will be for the optimised design.

A model is first set up, incorporating all the options for individual network components. The GA then generates trial solutions, each of which is evaluated by simulating its hydraulic performance. Any hydraulic infeasibility, for example failure to reach a specified minimum pressure at any demand point, is noted, and a penalty cost is calculated. Operational (e.g. energy) costs can also be calculated at this point if required. Penalty costs are then combined with predicted capital and operational costs to obtain an overall measure of the quality of the trial solution. From this quality measure the fitness of the trial solution is derived. The process will continue for many thousands of iterations, and a population of good feasible solutions will evolve (Fig.1) .

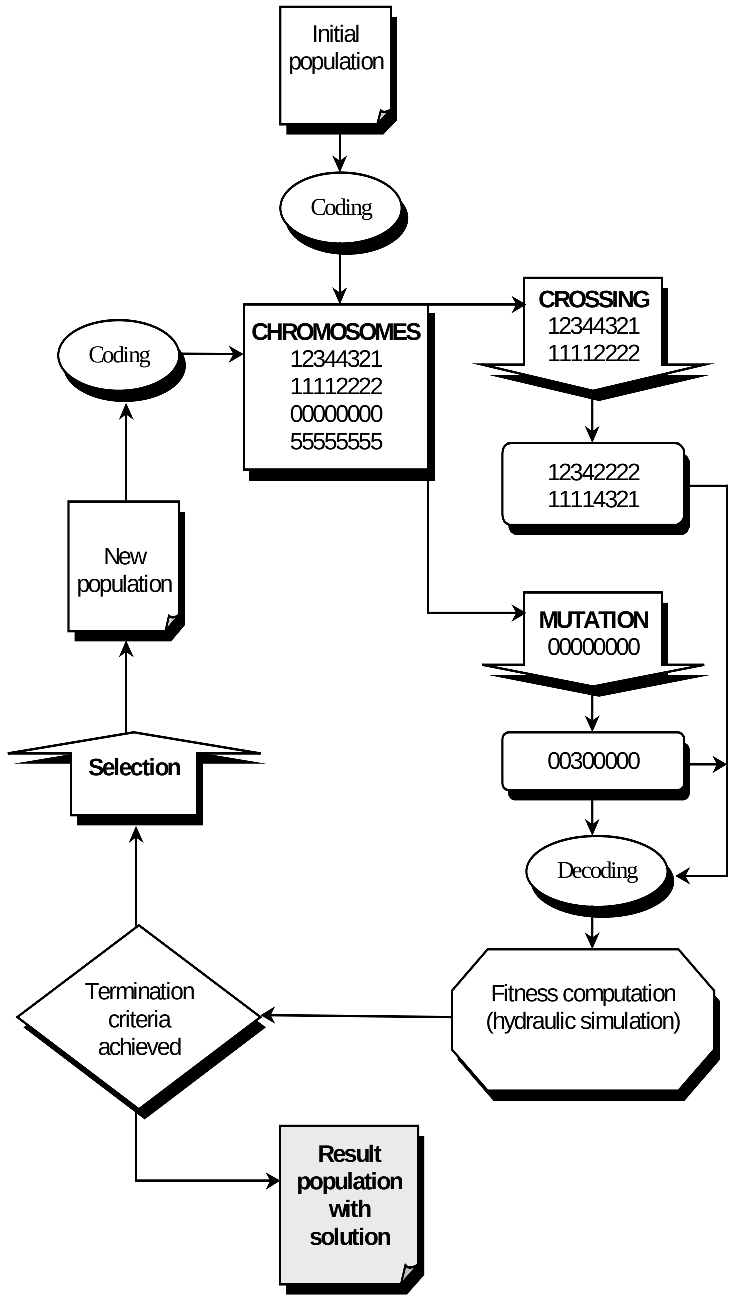

Figure 1 GA Flowchart

3. The ga parameters. Population size is a very sensitive parameter for the GA process because with too small a population the GA will converge rapidly to a local optimum, while with a large one there will be a long waiting time for an improvement in the process. A population size of 100 solutions was found suitable for the current work.

GA supports binary integer and real coding. Standard GA uses a binary alphabet (i.e. 0's or 1's) to form chromosomes, which are sets of character strings analogous to the chromosomes found in DNA. In this work, instead of a simple binary code integer interpretation of the bit string is used for decoding.

Crossover describes the process by which parents' coded data strings are combined to form new coded strings for their offspring. In its simplest form, a single point along the coded string is selected at random, and the code strings from two parents are broken at this point. The tail ends are switched and the strings recombined to form the codes for two offspring. In this work was used crossover operator that randomly selects two crossover points within a chromosome then interchanges the two parent chromosomes between these points to produce two new offspring.

Occasional random alteration of digits protects the GA process against premature loss of potentially useful genetic material. Each digit of an offspring's string is altered with a low probability p_m, usually held constant throughout the evolution in a GA.

4. Results and discussion. The described methods of optimal pipeline network rehabilitation were applied to the irrigation system Šala-Kolárovo. This is one of the first irrigation facilities with large area coverage in Slovakia, with applied sprinkler irrigation and an underground pressurised water network. Its construction was completed at the beginning of the sixties and thus the whole facility is coming close to the end of its service life and hence it can serve as a suitable model for testing the proposed rehabilitation methods.

The irrigated area amounts to 772 ha. The irrigation system consists of irrigation water take off complex located at the irrigation inlet to the irrigation pump station, pump station itself, pressurised network for the delivery of irrigation water and sprinklers. For the purpose of this study we will describe in detail only the pipeline network. The pump station and sprinklers influence only marginally the operation of the analysed system and therefore their detailed technical specification is not necessary. Only the basic parameters (pressure and output of the pump station, required pressure and sprinklers take off) are taken into account.

The design of the system was substantially based upon the concept of hand-move laterals. Since this approach is now abandoned, its use is not producing required benefits. This is the reason why we have decided to review the rehabilitation proposals based on the concept of irrigation with non-specific hose-reel irrigators with an optimum output of 8,5 ls^{-1} and optimal inlet pressure 0,4-0,7 MPa (0,47-0,50 MPa was used as allowed minimal pressure in computations). In addition to that it is assumed that a battery of such sprinklers will be used, i.e. there will be a serial set of six machines. The original network is unable to comply with hydraulic requirements for such operation. The configuration of irrigators could be chosen arbitrarily without any impact on the calculation procedure presented in this paper.

4. 1. Optimisation of the Branched Network Using Linear Programming. For the clarity purposes we briefly describe the optimisation procedure of the pipeline network rehabilitation using linear programming. The mathematical formulation of this problem is as follows:

$X_{11} + X_{12} + ...+ X_{1n} = B_1$
$X_{21} + X_{22} + ...+ X_{2n} = B_2$
etc.
$X_{m1} + X_{m2} + ...+ X_{mn} = B_m$ (1)

$A_{11} X_{11} + A_{12} X_{12} + ...+ A_{xy}X_{xy} \leq C_1$
etc.

$D_1 X_{11} + D_2 X_{11} + ...+ D_j X_{mn} = \min$ (3)
Solution has to comply with inequalities:
$X_{11} > 0$; $X_{12} > 0$ etc. up to $X_{mn} > 0$ (4)

Where X_{ij} is unknow length of selected diameter j on section i
B_i total length of section
A_{mn} hydraulic loss in section m and diameter n
C_i allowable total loss for section
D_i price of pipeline with diameter number i

When in order to resolve pipeline networks rehabilitation task we apply linear programming, unknown will be the lengths of individual pipeline diameters. In conditions (1) we must mathematically express the requirement that the sum of unknown lengths of individual diameters in each section has to be equal to its total length. The second type of the equation in constraints (2) represents the request that the total pressure losses in a hydraulic path between the pump station and critical node (the end of the pipeline, extreme elevation inside the network) should be equal or less than the known value. This constraint is based on the maximum network pressure requirement needed for the operation of the system. Given the investment costs minimisation requirement, the objective function (3) sums the products of individual pipeline prices and their required lengths. When we formulate the rehabilitation optimisation, the objective function should provide economical advantage for the choice of original diameters, however it should not discriminate against the choice of a larger diameter (if the hydraulic situation (2) requires so). Four possible diameters are selected for each section. The first possible option is the diameter that is identical with the original one in that section, with the three larger diameters as options for the same section. In the objective function the program assigns the original diameter a minimum unit price and real prices to other diameters. Further details on LP optimisation can be found in available literature (Zdražil, 1965). The computd results are summarised in the Table 1.

4.2. Optimisation of the Looped Network Using Genetic Algorithm. To avoid problems with scaling, premature convergence, and selective pressure of traditional proportional fitness schemes (for example, roulette wheel selection), rank selection is used to choose parents for next generation. The population is ordered according to the computed fitness values and parents are selected with a probability based on their rank in the population. A *linear ranking* selection is used for this optimisation study. Two-point crossover was selected and the probability of a selected pair of strings being subjected to the crossover operator was taken as p_c=0.95. The mutation rate is usually set very low, e.g., $p_m \in (0.01, 0.10)$. For the Šaľa-Kolárovo problem the mutation rate is set to be p_m= 0.02, or on average, only two chromosomes will be mutated out of the total population of one hundred.

TABLE 1. *Assessment of Calculation Results*

	Branched alternative by LP		Branched alternative by GA		Looped alternative by GA	
Diameter (mm)	Length (m)	Cost US$	Length (m)	Cost US$	Length (m)	Cost US$
500	58	3 767	58	3 767	7	455
400	0	0	281	14 553	0	0
350	967	41 500	226	9 716	334	14 326
300	0	0	292	9 711	529	17 579
250	1 147	25 924	1 952	44 116	1 212	27 385
200	1 869	33 635	1 661	29 905	735	13 232
150	0	0	0	0	964	13 589
Sum	4 041	104 825	4 472	111 769	3 781	86 567

5. Summary and conclusions. Economical and hydraulic effectiveness of the rehabilitation of the sprinkler irrigation systems highly depend on the effectiveness of their pipe network rehabilitation. Irrigation pipe networks are often branched and an obvious approach to increase the hydraulic capacity of such systems while keeping capital investment at minimum is to convert these systems to looped networks.

Because of their complexity and inability to cope well with discrete, non-linear combinatorial problem, such as pipe network optimisation, the conventional optimisation techniques are poorly suited for solving this task. This was again confirmed in this study by applying a classical optimisation methodology, linear programming, and the genetic algorithm (GA) to network rehabilitation. The main practical advantages of the genetic algorithm approach are:

- Ease of dealing with the complexity of network components (i.e., every part of the system that can be simulated could also be the subject of optimisation).
- Relatively simplicity of the methodology (compared to conventional methods of mathematical programming).
- The method can be used also for other, otherwise difficult tasks in this field, such as the design of a new network, calibration of hydraulic systems, optimal layout selection of networks, optimal pump scheduling, etc.

The linear programming method was used first with new diameters being available at a cost to the existing network so it could satisfy the increased demand conditions with an unchanged topology (network stays branched). When the GA was used to design the looped version of the network rehabilitation the full advantage of this approach was achieved. Economical comparison of branched and looped option is given in Table 1, which shows that the looped option is some 17% cheaper.

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