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A Genetic Algorithm Search for the Optimal Design of Water Distribution Systems

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1 Introduction

This thesis presents an application of the relatively new and powerful genetic algorithm search to the problem of the optimisation of the design (and operation) of water distribution systems.

1.1 Water Distribution Systems

A water supply system is a fundamental component of the infrastructure of a community. A water supply system for water transmission and distribution is essentially a network of pipes connecting sources (such as reservoirs, wells or connections to adjacent systems) of water to demand points (nodes). To facilitate efficient and reliable operation, the sources are connected to the demand nodes via a complex arrangement of system components such as pipes, pumps, balancing tanks (often used to store water for peak demand periods and emergency conditions), and control devices such as pressure reducing valves (often used to separate a system into pressure zones).

1.2 System Expansions

A community's water use patterns increase and diversify with population and economic growth. The water supply authority responsible for the ongoing maintenance and operation of a water distribution system assesses the reliability and the quality of service provided by their system and periodically updates plans for future system expansions to meet projected future demands. Recommendations for future system expansions may include a host of design and operational decisions such as:

- the identification of future sources of water such as wells
- the upgrade of water treatment facilities (since the capacity of the source is constrained by the capacity of the water treatment facility)
- the sizing of pumps and their pumping schedules
- the settings and operating rules of pressure regulating valves
- the expansion or rehabilitation of a water distribution pipe network,
- the location and capacity of system storages

The design of future system expansions and / or changes to the operation of existing facilities to meet changing demand patterns is the responsibility of the water authority. For complex city systems, and even for simple residential subdivisions sub-systems or irrigation systems, the number of alternative designs is very large. The number of combinations of options to meet the

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1.3 Hydraulic Simulation of Water Distribution Systems

A prerequisite step to optimisation is the accurate hydraulic simulation of proposed pipe network designs to assess hydraulic feasibility. A hydraulic simulation model predicts water distribution system behaviour, including flow and pressure distributions, given some instantaneous or time-dependent pattern of water demands.

The hydraulic simulation of a water distribution system is itself a complex mathematical problem. Methods of hydraulic analysis are reviewed in this thesis in Chapter 2 in a search for a reliable and efficient analysis. The hydraulic simulation model is a very important part of the genetic algorithm formulation developed in this thesis.

There are a number of commercial packages available for the hydraulic analysis of water distribution systems. In engineering practice, the designer develops a pipe network design by considering a handful of trial and error hydraulic simulations of proposed designs using a commercial hydraulic simulation package. Proposed designs are based on local knowledge of the design and operation of the system, engineering judgement, design guidelines and rules of thumb. The designer uses a simulation model to determine workable solutions which are then compared in terms of cost, reliability and other objectives.

1.4 Optimisation of the Design of Water Distribution Systems

The optimisation of a water distribution system design attempts to achieve the best possible design (and operation) for a specified level of system performance such that system expansion costs (and life-cycle operating costs) are a minimum. The pipe network optimisation problem is defined in Chapter 3.

Usually, the foremost objective of the optimisation is to minimise the initial construction costs of new system components and the present value of system operation costs for the lifetime of the design. Millions of dollars are spent annually expanding or rehabilitating water supply system infrastructure. Jeppson (1985) reported the 40,000 water services in the U.S.A. had invested $200 billion in water supply facilities and were investing in new facilities at the rate of $2 billion per year. The ongoing costs of operating water supply systems are also significant (and will depend on the system layout and the capacity of system components). In the U.S.A., the electricity consumed by water supply utilities (for pumping water) makes up about 7% of all the electricity consumed in the country (Ormsbee et al., 1989).

In addition to network design and operating costs, there are usually several other competing objectives (some non-quantifiable) such as system reliability and possible future system expansions that should be considered in the optimisation.

The decision variables of the optimisation are the physical and operational characteristics of the system components to be defined in the design such as: the pipe network layout; the diameters of new pipes; the cleaning, duplication or deletion of existing pipes; the introduction of new pump station installations or the upgrade of existing pump stations; the capacity and proposed operating policies for individual pump units; the location, volume and operating water levels of new storage tanks; and valve settings.

The water distribution system design is subject to a series of demand conditions at the nodes such as: peak instantaneous flows; emergency flows for fire fighting or in the event of a pipe breakage; and/or time-dependent peak day or peak week demand patterns. The design is required to exhibit a specified system performance for the demand patterns considered. Some system performance constraints which may be considered include: minimum allowable pressure heads achieved at the nodes for all demand conditions; tanks refill by the end of some demand period in preparation for the next demand period; and pumps operate within their limits of operation. A design which does not meet the system performance constraints is said to be an infeasible solution.

1.5 Pipe Network Optimisation Techniques

The optimisation of pipe networks is a problem which has received more attention in recent years. In Chapter 3 of this thesis, a selection of models are reviewed, covering a broad range of approaches to pipe network optimisation. Some models formulate the pipe network optimisation problem using traditional mathematical optimisation techniques such as linear programming, nonlinear programming or dynamic programming. There are other innovative models that are essentially random search methods or enumeration algorithms. Many of the models are hybrid schemes of two or more methods and the models often incorporate heuristic processes. Lansey and Mays (1989b) and Walski (1985) provide comprehensive reviews of the development of pipe network optimisation models in the last 25 years.

Most of the approaches presented in the literature first concentrate on the simpler problem of the optimisation of a gravity-fed distribution network of pipes subject to one critical instantaneous demand pattern and then make recommendations for the treatment of complexities such as pumped systems, multiple demand patterns and the design of other system components such as storage tanks. Often assumptions and simplifications are required due to the complicated nature of the pipe network optimisation problem.

Optimisation approaches which are linked to stand-alone hydraulic simulation models are convenient as proposed designs can be simulated and hydraulic feasibility evaluated in the same way a designer manually simulates and confirms a workable design.

1.6 Genetic Algorithms (GAs)

A genetic algorithm (GA) model for the practical optimisation of the design and operation of water distribution systems is developed in this thesis. The framework for the GA search model is represented by the flowchart of processes in Figure 1.1.

The GA search is a simplified simulation of the evolution process. Evolution is the established optimisation process used by nature, by which species grow and develop from earlier forms and adapt to their environment. A firm theoretical basis for genetic algorithms was established by Holland (1975).

In the natural evolution of a species, a chromosome of genetic information characterises a unique individual. Similarly, in the GA search, trial solutions to the search or optimisation problem are represented by a unique coded structure such as a binary string of 1's and 0's.

In nature, according to Darwin's survival-of-the-fittest philosophy, an individual's chances of survival and reproduction are ultimately regulated by the fitness of the individual. The fitness may be measured relative to the conditions imposed by the environment. The prospect of reproduction can be measured by the fitness of the individual relative to the fitness of fellow members within the competing population. In the artificial evolution of the GA, coded solutions are assigned a value of fitness which measures the worth of the solution relative to a set of objectives.

The GA search employs operators such as selection, crossover and mutation which simulate Darwin's rules of natural selection and genetic mechanisms acting on an evolving population of coded structures. The selection or reproduction operator selects parent coded structures from the current population with some chosen preference to fitter solutions. The genetic code of selected parent coded structures is combined to form offspring coded structures for the new population by the crossover operator. Occasionally, the mutation operator applies subtle genetic variations to the offspring code. Crossover and mutation imitate the exchange of genetic information and the minor variations that occur to genetic information from parent to child.

In nature, useful developments and adaptations are inherited and stored in chromosomes which carry the blueprint of a living thing. In the GA, small pieces of useful code are reproduced and combined with other small pieces of useful code to produce longer pieces of highly fit code.

Over many generations, a population of coded solutions with average fitness (the starting population may be randomly selected) evolves to a population of highly fit coded solutions.

The traditional GA formulation (Holland, 1975) is reviewed in Chapter 4 of the thesis. The simple, yet powerful traditional GA considers populations of strings coded in the binary alphabet and three standard GA operators of selection, crossover and mutation. DeJong (1975) demonstrated the far-reaching possibilities of GAs for function optimisation by applying the traditional GA and some variations to a diverse set of solution spaces (including discontinuous, many-peaked and highly-dimensionality spaces). The simple, robust nature of the GA formulation makes it suitable for a number of applications - some applications for which the best solutions may be difficult to obtain using traditional optimisation techniques. Goldberg (1989) presented a comprehensive review of genetic-based techniques and their applications, and an analysis of the mechanics and the fundamental theory of GAs. Some GA applications of particular interest to this research are reviewed in Chapter 4.

1.7 A Traditional GA for Pipe Network Optimisation

There is a good degree of freedom in the way a GA model may be formulated. DeJong (1985) presents an overview of the issues facing researchers implementing a GA model for a new application area, including the choice of an appropriate coding representation, fitness functions, GA operators and parameters. A traditional GA approach to the pipe network optimisation problem is presented in Chapter 5.

A coding scheme is selected to represent pipe network design solutions as unique coded strings of finite length which simulate chromosomes. The decision variables of the optimisation are represented by genes and the genes are assigned positions in the coded string. A set of unique symbols for a gene (string position) maps to the choices for the corresponding decision variable such as available pipe diameters or allowable PRV settings. The traditional GA uses substrings of binary codes to represent decision variable choices for the pipe network design.

A fitness value provides information about a string's fitness to produce offspring. The fitness of a pipe network design is measured relative to objectives such as low cost and adequate hydraulic performance. The cost of proposed designs may be estimated and penalty costs may be applied to infeasible designs which do not achieve a specified level of system performance. The evaluation scheme of the GA model (in Figure 1.1) is linked to the hydraulic simulation model (developed in Chapter 2) which tests the hydraulic feasibility of the proposed design.

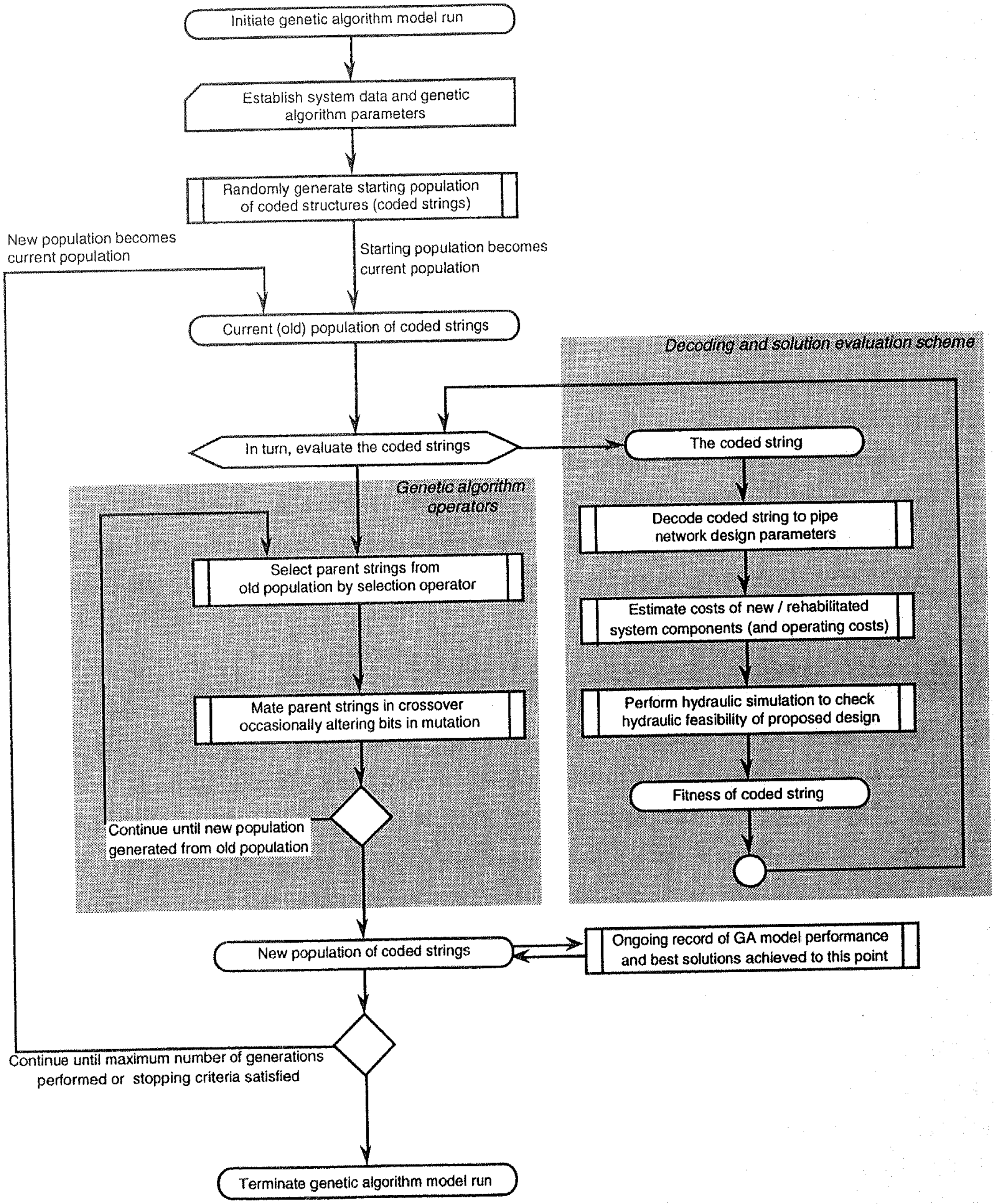

Figure 1.1 Flow chart for the proposed genetic algorithm model

The GA model operates with a population of coded solutions at any time. The initial population of coded strings is usually randomly generated. GA operators generate new populations using the code and fitness information of coded solutions in the old population. GA operators such as proportionate (roulette-wheel) selection, one-point crossover and random bit-wise mutations are employed by the traditional GA. The GA operators and GA parameters such as population size, probability of crossover and of mutation are selected to control and guide the GA search. Simpson, Dandy and Murphy (1994) presented a detailed procedure for applying the traditional GA approach to optimise a relatively simple hypothetical pipe network design which is referred to as the two-reservoir Gessler network.

1.8 The Two-Reservoir Gessler Network

The two-reservoir Gessler network (Gessler, 1985) is the case study chosen to investigate the application of the GA model to pipe network optimisation. The 14-pipe Gessler network introduced in Chapter 5 is a looped, gravity-fed distribution system. The Gessler network expansions require the sizing of five new pipes and the upgrade (cleaning, duplication or 'do nothing') of three existing pipes. The network expansions are required to satisfy three demand patterns, including a peak loading condition and two emergency loading conditions.

It was feasible to perform an exhaustive enumeration of every possible pipe network design solution (about 4 million) for the Gessler problem. The exhaustive enumeration identified the two global optimum solutions and other characteristics of the solution space such as relative proportions of feasible and infeasible solutions, critical nodes in the system and critical demand patterns. Gessler (1985) used a partial enumeration of a pruned search space of about 900 combinations to optimise the problem.

First, a small-scale GA is applied by hand to the Gessler problem. A small population size (only 10 members) is used for a close examination of the operations of the GA search. Then, full-scale GA model runs are performed with realistic population sizes for the application to the Gessler problem. The GA runs were allowed a maximum of 10,000 new solution evaluations (for example, about 100 generations of a population of 100 coded string members). The least cost solutions determined by the GA may be compared with the best solutions identified by the exhaustive enumeration. The traditional GA is found to be effective, but it becomes apparent that some modifications may improve performance.

1.9 Modifications to the Traditional GA

Many researchers have found it necessary to experiment with variations of the traditional GA, introducing innovative coding schemes, alternative fitness evaluation schemes and advanced GA operators to tailor the GA to a specific problem. Although, there is considerable freedom to express and formulate the GA search, it would be unwise to depart too far from the theoretical foundations of the GA search established by Holland (1975).

Variations of the traditional GA are applied to the search for the known optimal solutions to the Gessler network expansions problem in Chapter 6. The performance of specific elements of the GA formulation is observed, including various penalty functions and fitness functions and alternative coding representations, parent selection methods, crossover and mutation mechanisms. The experiments suggest the operators, coding and evaluation schemes likely to lead to improved performance in the search of the solution space to the pipe network optimisation problem. An improved GA formulation for the application to pipe network optimisation begins to emerge as a result of the study of the Gessler problem in Chapter 6.

1.10 Multiple Gessler Problems

The exhaustive enumeration of the relatively small Gessler problem (14-pipe network) in Chapter 5 positively identifies the lowest cost solutions. The effectiveness of various forms of the GA is measured in Chapter 6 by the ability to find these solutions. Larger water system design optimisation problems with many decision variables are required for further development and testing of the GA application. As problems increase in size and complexity, it soon becomes impossible to perform an exhaustive enumeration.

In Chapter 7, a larger pipe network optimisation problem with known global optimum solutions is devised by considering the simultaneous optimisation of two Gessler problems. The coded string solutions are separated into two component substrings for evaluation, representing two solutions to independent Gessler problems. Even larger solution spaces are manufactured by considering the simultaneous optimisation of three and five Gessler problems. The improved GA, incorporating many of the recommendations of Chapter 6 is applied to these problems. In addition, an elitist concept (DeJong, 1975; Goldberg, 1989) is introduced to the GA model. A population of the best solutions obtained in earlier generations are maintained in a parallel elite population and elite mates are occasionally crossed with members of the working population.

1.11 The New York City Water Supply Tunnels

In Chapter 8, the GA model is applied to the optimisation of the expansions of the New York City tunnels network. The classic New York tunnels problem was first introduced and optimised by Schaake and Lai (1969). Since then, the New York tunnels network has become a benchmark for researchers of pipe network optimisation techniques.

The five least cost feasible designs and three low cost infeasible designs identified by the GA are presented. The designs are compared with the designs obtained by traditional optimisation methods such as linear programming, nonlinear programming and enumeration techniques. There are estimated to be 1.93 x 10^{25} possible (discrete tunnel size) solutions to the New York tunnels problem.

The performance of the traditional three-operator GA and the new GA developed in Chapters 6 and 7 and various intermediate GA formulations are compared for the application to the New York tunnels problem. Dandy, Simpson and Murphy (1996a) presented an improved GA approach for the application to the New York tunnels problem (the GA used decision variable substrings of Gray codes, fitness scaling and decision-variable-wise creeping mutations, but not the elitist concept).

1.12 The Fort Collins - Loveland System Expansion Plan

Ultimately, the objective of this research is to develop the GA model for pipe network optimisation as a practical design tool. A final case study is intended to demonstrate the usefulness of the GA approach in a realistic design situation. In Chapter 9, the GA model is applied to the optimisation of aspects of the expansion plan for the Fort Collins - Loveland water transmission and distribution system.

The system provides water to an area of about 60 square miles between the cities of Fort Collins and Loveland in Colorado, U.S.A. The system will require expansions to meet anticipated increased agricultural and municipal water needs. A Master Plan prepared recently by a local engineering consultant predicted future water demands and outlined a proposed system expansion plan for 2015. The Master Plan design was determined using design guidelines, experience and a hydraulic simulation model.

The GA optimises the diameters of new and duplicate pipes and pressure reducing valve (PRV) pressure settings. The Fort Collins - Loveland water system is a complex system of source and booster pump stations, storage tanks, about 330 pipes (of which 49 are proposed new or duplicate pipes) and 13 major PRVs which isolate the system into 5 major pressure zones.

The water is supplied from several alternative sources of supply. The GA model helps to identify the preferred water sources by considering increasing the supply (up to allowable limits) from the connections to adjacent city systems. The Fort Collins - Loveland system expansion plan presents the GA model with many real problems facing optimisation models for pipe network design. The design generated by the GA model is compared to the original Master Plan design.

The GA model is reconstructed for the Fort Collins - Loveland system expansion problem to link with a commercial hydraulic simulation package. The simulation model is employed to confidently test the hydraulic feasibility of proposed expansions to the complex system of multiple pressure zones.