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Layout optimization of looped networks by constrained ant colony optimisation algorithm

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ABSTRACT

A constrained version of ant colony optimisation algorithm (ACOA) is proposed in this paper for layout optimization of looped water distribution networks. A novel formulation is used to represent the layout optimization problem of pipe networks in the proper form required for the application of the ant algorithm. The proposed formulation is based on the engineering concept of reliability in which the number of independent paths from the source node to each of the network nodes is considered as a measure of reliability. In the proposed formulation, the ants are constrained to choose from the options provided by a constraining procedure so that only looped layouts are constructed by the ant leading to huge reduction of search space size compared to the original search space. Three different constraining procedures are used leading to three different algorithms. The proposed methods are used to find the optimal layout of three benchmark examples from the literature and the results are presented and compared to the results of the conventional ant colony optimization algorithm. The results show the efficiency and effectiveness of the proposed method for optimal layout determination of looped networks.

1. Introduction

Reliability is commonly considered as a necessary characteristic for most distribution networks such as water, gas, electricity networks. This is normally achieved by constructing the networks such that each consumption node is supported by more than one path from the source/sources. While this feature is currently considered only for main electricity and gas networks due to the costs involved, the water distribution networks are all designed to enjoy this characteristic irrespective of the size of the network. The reliability of the networks and in particular the water distribution network is often observed by engineers via considering a looped layout for the networks.

Due to high costs associated with the construction of these networks, much research over the recent years has been dedicated to the development of techniques to minimize the capital costs of such infrastructures. As the joint consideration of network layout and component design is extremely complex, especially in large scale networks, optimization problem of these networks and in particular the water distribution networks is often split into two distinct problems of optimal layout and optimal component design of these networks. The solution of the layout problem defines the way the network components, such as pipe in the water and gas distribution networks, are connected together to form the network while the component size design determines the size of these components defined by their diameters. While saving caused by layout geometry optimization of networks is usually more than that obtained via component size optimal design, much researches has been developed around optimizing sizing assuming a predetermined geographical layout of the systems [1,5,8,10,11,15–17,19,28]. The volume of the work carried out on the problem of optimizing the layout of these networks and more importantly on the joint layout and component size determination is rather limited. Therefore, engineers have to develop the layout through experience and sheer intuition.

Some limited works have addressed the problem of layout geometry optimization of branched networks using different methods of optimization. Walters and Lohbeck [26] proposed two genetic algorithms (GAs) using binary and integer coding for layout determination of tree-like networks and compared their storage and computation time requirements with that of Dynamic Programming (DP). Davidson and Goulter [13] proposed an evolution programming method for layout optimization of rectilinear branched networks. They replaced crossover and mutation of the GA with two operators, labeled recombination and perturbation, to guaranty the feasibility of the children produced. Walters and

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Smith [27] combined graph theory with the conventional crossover and mutation operators of the GA to ensure that infeasible solutions are avoided in the reproduction stage. Geem et al. [20] proposed a heuristic algorithm, namely, harmony search, mimicking the improvisation of music players for the optimal design of branched networks. Afshar and Marino [2] hybridized ant algorithm with a Tree Growing Algorithm (TGA) for layout optimization of tree networks in which the TGA was used to restrict the search space to feasible tree layouts during the search process.

The problem of layout optimization for looped water distribution networks has received even less attention mostly because of its complexity [23] while the component sizing of the looped networks are much more dependent on the layout aspect of the problem. In other words, the potential saving by the layout optimization of looped pipe networks is much more than that which can be achieved by optimal component sizing.

This paper proposes a constrained version of ant colony optimization algorithm (CACOA) for layout optimization of looped pipe networks. The proposed formulation is based on the engineering concept of reliability in which the number of independent paths from the source node to each of the network nodes is considered as a measure of reliability. In the proposed formulation, the ants are constrained to choose from a Tabu list provided to the ants at each decision point of the problem so that only looped layout is constructed by the ants. The Tabu list is formed using a constraining procedure leading to huge reduction of search space size compared to the original search space. Three different constraining procedures are used leading to three different algorithms. Performance of the proposed formulations are tested against three benchmark examples from the literature for different level of reliabilities and the results are presented and compared with those of conventional ant colony optimization algorithm (ACOA). It is shown that for the examples considered, the proposed constrained ant colony optimization algorithm shows superior performance compared to the conventional ACOA.

2. Reliability of pipe networks

The reliability of the pipe networks is often enforced by considering fixed looped or tree layout for the networks to be designed [1,8,28]. It is well known that optimal component sizing of a pipe network under single loading with any optimization algorithm would lead to a branched network if no reliability constraint is enforced on the problem [12,25]. No global definition of reliability exists in the literature. The researchers have used different definitions for reliability of a network and used various methods for its computation. Some definitions, however, in particular mathematical and engineering-based definitions, seem to be widely accepted in the community. Bazovoski [7] proposed the mathematical definition for the reliability of a pipe network, as the probability that a network can deliver the desired flow at all consumption nodes under required head in normal or abnormal conditions. This definition has been used by several researchers and used to determine the reliability of pipe network [6,9,18,22,24]. Calculation of the mathematical reliability, however, is extremely time consuming. Moreover, the mathematical concept of reliability is not simply understood by practicing engineers in the industry who are supposed to be the actual users of such algorithms.

The minimum number of the independent paths from each consumption node to source node or nodes in a pipe network is used for measuring the engineering concept of reliability. Therefore tree networks have reliability level 1 and looped networks have reliability greater than or equal 2. This definition of the reliability is well-understood by engineers and may be easily integrated into existing pipe network optimization algorithms for layout optimization. In pipe network optimization problems, the reliability constraint can be easily implemented by assuming a looped layout for the network while defining a lower bound different from zero for the pipe diameters. In layout optimization, however, the lower bound of the pipe diameters should be equal to zero enabling the optimization algorithm to remove the pipes from the network if required. Setting the lower diameter to zero without any proper measure to enforce the reliability may result in a branched network as mentioned before. This is the basic difference between a component sizing and a layout optimization problem from a computational point of view. Otherwise, identical procedures and algorithms currently available for optimal component sizing can be used for layout optimization if this computational issue is somehow removed.

3. Layout optimization of looped networks using conventional ACOA

Ant colony optimization (ACO), developed by Dorigo et al. [14], is a discrete combinatorial optimization algorithm based on the collective behavior of ants in their search for food. Over a period of time, a colony of ants is able to find the shortest route from their nest to a food source. The swarm intelligence of the ant colony is achieved via an indirect form of communication that involves the ants depositing and following a chemical substance, called a pheromone, on the paths as they travel. Over time, shorter and, therefore, more favorable paths are strengthened with higher amount of pheromone, as they need less time to be traversed, hence becoming the dominant path for the colony.

To apply ACO to a combinatorial optimization problem, it is required that the underlying problem is represented as a graph. For this, assume a graph consisting of n decision points (d_i; $i = 1, 2, \ldots, n$) where each decision point is connected to its adjacent decision point via set of edges. Assume that l_{ij}; $j = 1, 2, \ldots, NE_i$ represent the set of edges available at decision point I where NE_i represents the total number of edges available at the decision point. A solution termed a path in ACO is represented by a set of edges constructed by the selection of an edge at each decision point of the problem. The ACO algorithm operates by iteratively generating a population of solutions where each solution is representative of the path that a single ant has traveled.

In conventional ACOA for the solution of the layout problem, each link of the base graph is considered as the decision point of the problem. The number of decision points n are, therefore, equal to the number of links in the base graph. The available options or edges l_{ij}; $j = 1, 2, \ldots, NE_i$ at each decision point i of the problem would, therefore, be the same as zero or one, where the zero option corresponds to the ‘no link’ option. In this formulation, a typical layout optimization problem shown in Fig. 1(a) can be represented by the graph shown in Fig. 1(b). In this formulation, as seen from Fig. 1(b), the two available options at each decision point, denoted by numbers, are independent from the decisions made at the previous decision point and, therefore, the decisions can be made independently at all decision points of the problem. The order in which the decisions are made is immaterial in this representation of the layout optimization problem. The basic steps of the conventional ACOA for the problem under consideration may be defined as follows [4]:

1. The total number of ants, m, is chosen and the amounts of pheromone trail on all edges l_{ij} are initialized to some proper value.
2. Starting from an arbitrary or pre-selected decision point i, ant k is required to build a solution by selecting an edge from available edges using the following transition rule: