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A GIS supported Ant algorithm for the linear feature covering problem with distance constraints

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Abstract

This paper analyzes a linear feature covering problem (LFCP) with distance constraints, and characterizes the problem by a fuzzy multi-objective (MO) optimization model. An integrated approach combining an Ant algorithm (LFCP-Ant) and a Geographic Information System (GIS) has been devised to solve the LFCP problem in large scale. The efficacy of the proposed approach is demonstrated using a case study of locating new fire stations in Singapore. A GIS has been used to transform the continuous problem into a discrete one, which is then solved using the LFCP-Ant. This algorithm employs a two-phase local search to improve both search efficiency and precision.

Keywords: Ant algorithm; Linear feature covering problem; GIS; Two-phase local search

1. Introduction

A typical linear feature covering problem (Fig. 1) with distance constraints consists of m polylines (m is 5 in Fig. 1) and n points (shown as dots in Fig. 1 and termed as potential location. n is 8 in Fig. 1) located at a Cartesian plane. In such problems, polylines are considered as lines composed of one or more linear line segments. Given a critical distance R, a desired balance distance D, and an integer number p (p is 4 in Fig. 1), the locations of p (out of n) points (for p new facilities) are to be selected so that the total length of those polylines lying within distance R of at least one point is maximized. Also, the distance between each new point and its nearest point must also maximally approach the desired balance distance D. The aforementioned problem is a bi-objective optimization problem, i.e. a MO (Multi-Objective) optimization problem with two objectives. The problem simultaneously considers linear feature coverage maximization (termed as objective A) and distance balancing (termed as objective B). To facilitate the understanding of objective A, we may take the points as supply side while regard polylines as demand side. Without losing generality, we may suppose that the demands are uniformly generated from the polylines, hence maximizing the coverage of polylines is equivalent to satisfying the demands maximally. Besides objectives A and B, other objectives might also be considered, e.g. minimizing the maximum dis-

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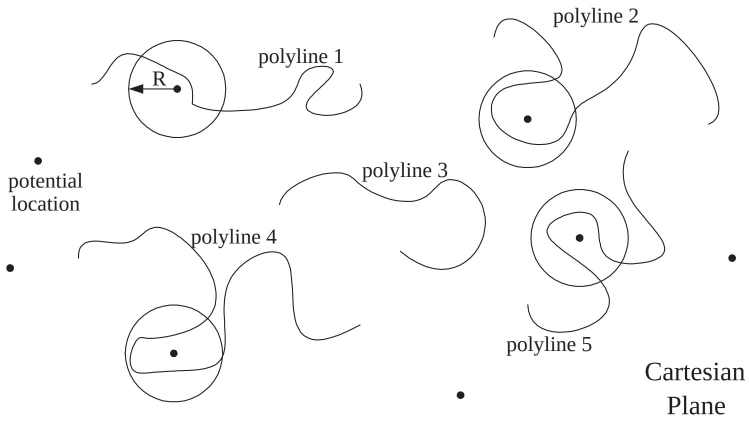

Fig. 1. Linear feature covering problem.

tance from a point to a linear feature. Nevertheless, such objectives are supplementary, and this paper addresses primarily the optimization problem with the aforementioned two objectives.

Problems of this kind occur in a variety of practical applications, especially in locating emergency and protection facilities. Locating new fire stations under plan is an archetypal representation of such a problem. Fire stations offer the personnel and equipment for protecting lives and belongings, and their location considerably influences their emergency response and fire protection abilities. While situating fire stations, the following two factors must be considered: (1) The stations should be capable of providing 'timely aid' when a road-accident or a mishap involving hazardous materials occurs; (2) There should be a reasonable distance between two fire stations [14], in order that any two fire stations may cooperate more easily and efficiently. Simply stated, all fire stations should be distributed "evenly" over the land, so as to be able to provide necessary protection to the largest possible area.

Location problems with distance constraints have been studied by researchers during the past several decades. Cooper and Drebes [4] presented a set covering approach involving a heuristic procedure to determine the minimum number of centers to cover all customers. However, this objective is significantly different from those dealt in our MO problem and hence the approach adopted in [4] is not relevant for the case discussed herein. Watson-Gandy [15] provided three heuristics and their variations to solve the m-partial cover problem (maximal covering problem) on a Cartesian plane. Their objective was to situate m centers so as to maximize the sum of the weights of those points lying within a critical distance (R) of at least one center. Even though this appears to be in line with objective A considered in this paper, Watson-Gandy [15] has not considered objective B (distance balancing) in their work. In some discrete location problems, distance constraints also do exist, e. g. the set covering problem and the maximal covering problem [5]. Such discrete problems are usually formulated as an Integer Linear Programming Problem (ILPP) and solved either by branch-and-bound approaches or Lagrangian relaxation heuristics. However, the demands in all these problems originate from nodes and hence the demand nodes can be easily recognized using a coordinate pair (x, y). It can be overtly judged if a demand node is covered by a supply facility (node). This is done by comparing the critical covering distance R with the Euclidean (network or user defined) distance between the two nodes. Nevertheless, in our case, we are dealing with polylines rather than points. The fire stations that are to be situated should serve accident locations uniformly distributed along particular routes and are not situated at points whose locations are known well in advance. This can hardly be expressed in a general mathematical equation and presents tremendous challenge in determining the percentage of polylines that have been covered. Simply put, it is hard to find a way to evaluate the objectives when the demand is originated from polylines. As will be discussed below, we solve this problem by discretizing the polylines into a series of connected cells. Although this makes it possible to model the whole problem in ILPP, the combinatorial complexity prohibits us to do so. This will be detailed later.

Badri et al. [1] stressed the need for a MO model in determining fire station locations. They employed a multiple criteria modeling approach via integer goal programming to evaluate potential sites in 31 subareas in the state of Dubai. Their model determines