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A multi-objective bi-level location planning problem for stone industrial parks

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ABSTRACT

This paper focuses on a stone industrial park location problem with a hierarchical structure consisting of a local government and several stone enterprises under a random environment. In contrast to previous studies, conflicts between the local authority and the stone enterprises are considered. The local government, being the leader in the hierarchy, aims to minimize both total pollution emissions and total development and operating costs. The stone enterprises, as the followers in the hierarchy, only aim to minimize total costs. In addition, unit production cost and unit transportation cost are considered random variables. This complicated multi-objective bi-level optimization problem poses several challenges, including randomness, two-level decision making, conflicting objectives, and difficulty in searching for the optimal solutions. Various approaches are employed to tackle these challenges. In order to make the model trackable, expected value operator is used to deal with the random variables in the objective functions and a chance constraint-checking method is employed to deal with such variables in the constraints. The problem is solved using a bi-level interactive method based on a satisfactory solution and Adaptive Chaotic Particle Swarm Optimization (ACPSO). Finally, a case study is conducted to demonstrate the practicality and efficiency of the proposed model and solution algorithm. The performance of the proposed bi-level model and ACPSO algorithm was highlighted by comparing to a single-level model and basic PSO and GA algorithms.

1. Introduction

Stone industry generates significant amount of waste water and dust in the process of stone quarrying, transportation and production, causing serious environmental damage. Excessive exploitation and uncontrolled stone processing result not only in significant vegetation decrease, but also in substantial pollution of the water and air in stone-rich areas [2,15]. The annual amount of waste generated includes one million tonnes of solid waste as well as 700,000 tonnes of slurry waste. Dumping this waste in open areas has consequently created several environmental problems and has negatively influenced agricultural production, local inhabitants and groundwater [1]. Furthermore, stone enterprises are often managed individually, resulting in high maintenance costs and inefficiencies. A possible solution to control pollution and reduce cost is to build stone industrial parks, which provides a central location for stone enterprises and, hence, reduces costs and pollution by taking advantage of economies of scale.

In recent years, the expansion of production scales in mining has further led to an increased need for efficient stone industrial park planning. Choosing appropriate locations for the industrial parks, however, is a complex decision, as potential park locations often have different geographical conditions, production environments and distances from the mines.

The optimization literature abounds with different methods for dealing with location problems [3,13,16,12,7,5]. These models, however, mainly assume a single decision maker. There is little research considering conflict of objectives among multi-layers of decision-making entities. Different from the typical location problems, two levels of decision makers with conflicting interests are considered in this paper. As the planning leader, the local government considers the park's location based mainly on the mine section distributions and the regional environment so as to minimize total pollution emissions, as well as maximizing operation efficiencies for the entering stone enterprises. On the contrary, as the occupiers of the parks, each stone enterprise chooses a specific park to lower total costs. These two levels of decision makers act in their own best interests, which are inevitably in conflict. Therefore, the location problem for stone industrial parks is modeled as a bi-level programming problem in this paper.

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In addition, almost all the studies aforementioned assume deterministic parameters. However, many parameters in real-world problems (e.g., transportation costs) cannot be accurately predicted due to the complexity of the planning systems. Hence, decision makers inevitably encounter uncertain parameters when making a decision in practice. To account for the shortcomings of the existing literature, we construct a multi-objective bi-level location planning model, in which unit production cost and unit transportation cost are considered random parameters. The proposed model, therefore, captures both cost uncertainties and multiple decision makers with conflicting interests.

It is very difficult to obtain *exact* solutions for a complicated model with bi-level objectives and uncertain parameters. An improved Particle Swarm Optimization algorithm is proposed to search for *satisfactory* solutions. Particle Swarm Optimization (PSO) is one of the evolutionary algorithms developed in the last few decades for solving optimization problems. Researchers over the years have developed various PSO algorithms for bi-level multi-objective problems. For example, Deb and Sinha [34] proposed a viable algorithm based on Evolutionary Multi-objective Optimization (EMO) principles, which was further improved by Sinha and Deb [35]. Deb and Sinha [36] designed an efficient and accurate solution methodology using a hybrid Evolutionary-Local-Search Algorithm. Gao et al. [37] dealt with Fuzzy-Linear Multiple-Objective Bilevel (FLMOB) decision problems using a λ-cut and goal-programming-based algorithm. Zhang et al. [33] solved a high dimensional bi-level multi-objective programming problem using a hybrid particle swarm optimization algorithm with crossover operator. Xu et al. [40] dealt with a multi-objective bi-level traffic assignment problem under fuzzy random environment and proposed a PSO algorithm with fuzzy random simulation-based constraint checking procedure. While these studies have significantly improved evolutionary algorithms for multi-objective bi-level optimization, they cannot be directly applied to the model proposed in this paper. The main reason is that they are incapable of dealing with the optimization tasks of multiple decision makers at the lower level. Moreover, the communication between the upper-level and lower-level decision makers is not reflected in these models [23]. As discussed earlier, the location selection problem for stone industrial parks involves an upper-level decision maker and multiple lower-level decision makers with conflicting objectives. Hence the locations selected depend in part on the degree of cross-level cooperation or interaction, even though there is only incomplete and vague information. Considering the fuzziness of human judgment, the decision makers of the two levels have fuzzy goals for their objective functions [9,25,8]. A useful tool to deal with this situation is to employ an interactive method based on satisfactory solutions [21,17–19]. In this paper, an improved PSO algorithm is developed to transform the bi-level problem into a single-level programming model that can be utilized to search for satisfactory solutions. Results and comparison analysis with a case study are presented afterwards to demonstrate the effectiveness and efficiency of the optimization method.

The remainder of this paper is structured as follows: in Section 2, an introduction to the multi-objective bi-level stone industrial park location planning problem is presented along with the motivation for employing random variables. An expected multi-objective bi-level programming model with chance constraints is established in Section 3. Next, a solution method is proposed in Section 4 based on a bi-level interactive method and a particle swarm optimization algorithm. In Section 5, a case study is presented to show the validity and efficiency of the proposed models. Concluding remarks and a discussion on further areas of research are presented in Section 6.

2. Key problem statement

Stone is very important to many production activities, has a high production value and plays an increasingly important role in the improvement of the local economies. The stone industry, however, is a pollution-intensive industry, resulting from activities including quarrying, transportation and production [15]. Pollution reduction is a major goal for local governments. In China, most stone mining and processing is done in relatively primitive family workshops which have small production scales, dispersed production sites, and serious production and transportation pollution. Controlling for these factors may result in the ability to mitigate the negative effects of pollution and improve the economic benefits of the stone industry. Stone industrial park construction, which centrally manages the stone enterprises, has proved to be an effective method.

The specific choice of stone industrial park geographic location leads to different construction costs, which influences the stone enterprises' profits and pollution emissions. At the regional level, the problem local government faces is choosing park locations in order to reduce both pollution emissions and operating costs. Hence, for the local government, minimizing total pollution emissions and operating costs are the two main objectives. The local government must seek to achieve its goals through an optimal selection process. It should be noted that the cost and pollution levels mentioned above strongly depend on the individual stone enterprises as it is improbable for the local government to allocate the stone enterprises to an industrial park. When more than one park is constructed, each stone enterprise can freely choose a park to enter, directly affecting total park pollution and costs. Furthermore, the stone enterprises' objectives are not completely aligned with the objectives of local government as they most often seek to minimizing their own costs while ignoring the resulting pollution. With conflicting interests, the local government must be cognizant of the decisions of the stone enterprises while making his location selection decisions. In a word, the two stakeholders (i.e., local government and stone enterprises) aim to maximize their own conflicting interests, resulting in a bi-level programming problem.

The decision process is further complicated as it has to be conducted under a random environment. In stone industrial park location problems, existing data on production and transportation costs are often vague or inaccurate, therefore, it is often inappropriate to describe these problem parameters as known variables. Production costs often vary over time due to capacity changes, wage changes, varying utility prices, technology improvement and economies of scale. Transportation costs also vary over time due to different weather conditions, vehicle performances and loading capacities. Since park location decisions are long-term strategic decisions and need to be completed far in advance of production activities, it is not possible to accurately predict future production costs and transportation costs. Hence, it is appropriate to model these parameters as stochastic variables and their distributions can be estimated using historical data. Stochastic variables have been widely applied in many areas of scholarly research, and have been used to model uncertain environments in many existing studies [4,6,48,10,20]. In particular, production and transportation costs have been considered random variables in many papers for their inherent uncertainties [28–32]. The complete framework of the bi-level decision-making with conflicting interests is illustrated in Fig. 1. The figure demonstrates that the industrial park location problem studied in this paper has a variety of challenges. Table 1 summarizes the major challenges and the corresponding strategies adopted in this paper.

3. Modeling

In this section, a bi-level programming model is constructed for the stone industrial park location problem considering random production and transportation costs. The mathematical description for the problem is given as follows.