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Multi-objective dynamic layout problem for temporary construction facilities with unequal-area departments under fuzzy random environment

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An optimal layout problem for temporary construction facilities (TFLP) is very important in large-scale construction projects. This problem involves the planning of temporary construction facilities within the boundaries of the restricted sites so that materials transportation and rearrangement costs are minimized and distances between the various departments are optimized. As construction continues, however, the temporary facilities may need to be dynamically relocated several times to accommodate the various operational demands. Thus, this study proposes a new method for dynamic TFLP with unequal-area departments. To begin with, a multi-objective dynamic optimization layout model based on facilities coordinates is presented, in which the transportation costs between the facilities are described as fuzzy random variables and the temporary facilities, represented as rectangles or squares, are restricted to two-dimensional geometric constraints. Subsequently, the multi-objective position-based adaptive particle swarm optimization (p-based MOPSO) is developed to obtain feasible optimization solutions for the proposed problem. In order to evaluate the performance of the proposed method, the Jinping-I Hydropower construction project is used as a practical example. The results and further analyses of the model, algorithm evaluation and effectiveness proved that satisfactory solutions were able to be obtained.

1. Introduction

The layout problems for temporary construction facilities (TFLPs) are an important aspect of construction project efficiency and effectiveness. This study examines the layout and placement of the temporary construction facilities needed to support construction operations within the boundaries of a construction site [15]. These temporary construction facilities often include reinforcing steel shop, truck maintenance shop, integrated warehouse, office, labor residence, etc. Significant research has been done in the facilities layout problems (FLPs) area, especially in industrial engineering and manufacturing (IEM). Drira et al. [11] outlined a comprehensive FLP representation and noted that it was not possible to have a common or exact definition of FLPs because of the different characteristics of the workshops [27], whether it was a static or dynamic environment [29] and each project's different objectives [3]. In the same way, while a great deal of research has been conducted on TFLPs [6,54,53,15,14], this area requires further investigation. This study attempts to adjust the methods for FLPs in IEM to TFLPs in large-scale construction projects (i.e. dams, power plants) based on their unique characteristics, thus, presenting a new method for TFLPs based on facilities coordinates.

TFLP involves the arrangement of temporary construction facilities on the construction site so that they do not overlap while seeking to optimize other objectives. When a different facility layout is required in each period, the TFLP is a dynamic facility layout problem (DTFLP). This means that at the new-start period decision makers need to plan again to optimize the multiple objectives, such as the minimization of material handling and rearrangement costs or the maximization of space utilization. For an FLP in IEM, facility shapes and sizes have often been taken into consideration when planning facility layouts [53,49,38]. Previous TFLP research has tended to focus on multi-objective dynamic facility layout problems (MODTFLP), but in most TFLP research only equal-area facilities and equal-sized grids have been used for the facilities sites on the construction site. They were foundations for unequal-area TFLPs research, which seek to achieve optimal arrangements for

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unequal-area facilities within the sites. There has been little comprehensive research on multi-objective, dynamic and unequal-area TFLPs in large-scale construction projects. Thus, the proposed TFLP method in this study deals with unequal departmental facilities' layout planning in a dynamic environment, and to test its effectiveness, the optimization formula for an FLP in IEM is modified based on TFLPs' characteristics, such as planning temporary construction facilities based on their coordinates on the construction site.

In practice, TFLP planners often do not know the exact data affecting the layout in large-scale construction projects. Fuzzy logic, therefore, has been proposed to handle this imprecision or uncertainty [16,18,36]. Although previous studies have significantly improved FLPs with uncertainty, it is often difficult to simultaneously reflect the subjective and objective imprecision and complexity. Decision-making processes for the TFLP in large-scale construction projects often take place in a hybrid uncertain environment, so it is usually difficult to know precisely whether the environment is fuzzy or random. Therefore, fuzzy random variables have been applied to describe this twofold imprecision, as can be found in inventory problems [13,44], portfolio problems [1], civil engineering [35] and resource allocation [46]. These studies have shown the efficiency of fuzzy random variables in dealing with hybrid uncertain environments where fuzziness and randomness co-exist. Therefore, this study applies fuzzy random variables to deal with the twofold uncertainty for a TFLP in a large-scale construction project, which creates an unprecedented research field for TFLPs.

In this study, a mathematical model is presented to deal with the MODTFLP with unequal area departments under a fuzzy random environment. In the model, transportation costs for transporting materials per unit distance are considered as fuzzy random variables. Since layout problems are known to be complex and are generally NP-hard [17], approximation approaches have often been used to obtain optimal feasible solutions. For example, GIS has been used for construction site layout [6]. Zouein and Tommelein solved a dynamic layout planning using a hybrid method [54], and El-Rayes and Said applied approximate dynamic programming to a dynamic site layout [14]. Over the past decades, many efficient meta-search heuristic techniques and evolutionary approaches have been developed to solve the TFLPs [12], such as genetic algorithms (GA) [9], ant algorithm (AA) [40,3], simulated annealing (SA) [8], and tabu search [7,33]. However, particle swarm optimization (PSO) has not yet been widely applied to solve TFLPs in large-scale construction projects. PSO is a population-based search method first developed by Kennedy and Eberhart [22]. Kennedy et al. [23] continued to confirm its excellent performance in solving NP-hard problems with fast speed and convergence. Thus, to obtain feasible solutions, the multi-objective position-based adaptive PSO algorithm (p-based MOPSO), which is a variant of the standard PSO and also a meta-search heuristic technique, is applied to solve the proposed mathematical model.

The structure of this study is as follows. A problem statement is presented in Section 2, and the modeling of the MODTFLP with unequal departmental areas under a fuzzy random environment is presented in Section 3. In Section 4, the p-based MOPSO for solving the MODTFLP is developed. In Section 5, the proposed model and algorithm are implemented in a TFLP for a large-scale hydropower station construction project and Section 6 concludes the study with some future research recommendations.

2. Key problem statement

A TFLP in a large-scale construction project seeks to find optimal sites for temporary facilities such as offices and warehouses within the construction site. The locations of those temporary facilities can have a significant impact upon transportation costs, productivity, safety and the environment [37]. Generally speaking, TFLPs are symmetric with site layout problems. Compared to a general FLP in the manufacturing industry, TFLPs in construction projects have two distinct characteristics, which make a long-standing facility layout model from the manufacturing industry impracticable: (1) Unequal-area temporary facilities need to be relocated at different periods of the construction project with multiple objectives. (2) Fuzzy random variables are applied to replace the deterministic transportation costs between the facilities. Fig. 1 shows a MODTFLP with unequal-area departments under a fuzzy random environment.

2.1. Description for a MODTFLP with unequal-area departments

TFLPs in large-scale construction projects are often needed over several time periods, which can be defined in weeks, months, or years depending on the material handling flows or job category differences. The estimated flow data remain constant and the job categories are almost the same at each period, so different temporary facilities are required at different places for the various operations over the entire planning horizon. Optimal dynamic planning solutions provide a global reference for project managers to ensure more effective operations and management. With the TFLP, the decision makers aim to obtain satisfactory objectives based on their requirements and preferences (i.e. cost minimization, pollution minimization, safety maximization). For example, project managers may propose that total cost and environmental aspects are the main objectives and they prefer to spend more than to damage the environment. In addition, the shape and size of temporary facilities in construction projects are often different. Project managers, therefore, need to accommodate unequal-area departments for facilities, such as water suppliers, fabricating plants, or warehouses. In this study, these variable-sized facilities are dealt with using rectangles or squares. When there are irregular-shaped facilities are confronted, squares can be used as shown in Fig. 2: (1) determine the longest diagonal in the irregular facility; (2) develop a circle with the longest diagonal as the diameter; (3) construct a square with the diameter of the circle.

2.2. Motivations for considering fuzzy random environment

Uncertainty is widely recognized to exist in MODTFLP as it is often shown in materials transportation process between facilities. Essentially, a facility layout plan is drawn up before the facilities are placed in the large-scale construction site. Therefore, the transportation costs of transporting materials between the facilities cannot be determined in advance, leading to the need to consider uncertainty. The uncertainties prompt the motivation for considering fuzzy random environment.

During a TFLP process for a large-scale project, it is very difficult for decision makers to estimate the precise transportation cost. However, because of this scarcity of precise statistical transportation cost data, it is appropriate to use fuzzy variables to model the decision makers' experience. When asked about the average unit cost for materials transportation, a decision maker is only able to provide a cost range, i.e. $(c_l,\ c_m,\ c_r)$. However, transportation costs are able to be adjusted from day to day or week by week, which indicates that the transportation cost is a variable in a period over more than a year because of fuel price fluctuations. Under these circumstances, there is a need to stress the uncertainty caused by this fuel price fluctuation, as it allows for a more comprehensive analysis of the TFLP transportation process uncertainties. In previous studies, probability theory has been applied to describe these kinds of uncertainties, in which the transportation cost approximately follows a normal distribution expressed