Automation in Construction 85 (2018) 241–248

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Mathematical programming models for construction site layout problems

Wen Yi[a], Hung-Lin Chi[b], Shuaian Wang[c,*]

[a] School of Engineering and Advanced Technology, College of Sciences, Massey University, Auckland, New Zealand
[b] Department of Building and Real Estate, Faculty of Construction and Environment, The Hong Kong Polytechnic University, Hung Hom, Hong Kong
[c] Department of Logistics and Maritime Studies, Faculty of Business, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

ARTICLE INFO

Keywords:
Construction site layout
Construction management
Mathematical programming
Bi-objective optimization

ABSTRACT

We address the construction site layout problem that determines the locations of temporary facilities. Mathematical programming models for the site layout problem are proposed, which can be solved by state-of-the-art solvers to optimality. A number of safety, health and environmental concerns, such as falling objects, dusts, and noise, are incorporated in the extensions of the mathematical models. We demonstrate, using numerical experiments, the superiority of our proposed mathematical programming model over existing heuristics in terms of solution optimality and the wide applicability in terms of handling practical considerations. Based on the results of conducted experiments, the proposed method achieved a 3–19% improvement on optimality over those of the existing heuristics methods. The contribution of this research work includes the advanced development of a mathematical programming model incorporating extended concerns and solving site layout problems within reasonable time.

1. Introduction

Construction site layout is a planning activity that determines the locations of temporary facilities (TFs) to improve construction efficiency. TFs include warehouses, fabrication shops, maintenance shops, batch plants, administration offices, tool trailers, staging areas, maintenance areas, labor residence facilities, and tower cranes. The types of TFs required vary for projects of different sizes, locations, and other characteristics. The layout of TFs affects the construction time (e.g., for construction sites of limited space), costs (e.g., for large sites with a large amount of material transported between different TFs), safety (e.g., there must be some clearance around a tower crane), and environment (e.g., it is better not to position a noisy workshop close to an office for health and safety reasons). A main objective of the TF layout is to minimize travel times, to remove unnecessary movement of resources, and to reduce the frequency of handling of materials. A well-designed site layout saves considerable nonproductive time that is caused by inefficient coordination of the resources employed, especially for large projects where traveling between facilities can be considerably time consuming. Deriving the best construction site layout is a difficult problem because there are many possible alternatives and it is impractical to evaluation all of the alternatives. In the conventional approach, site layout planning is done based on the experience of planners. The level of accuracy that can be achieved varies among different projects and lacks of stabilities. Site managers and related contractors still need to make further adjustments based on the actual information acquired from sites. The planning activities and qualities of plans seriously rely on experience and accuracy of site information. To improve the current circumstance, the development of computational approaches to guarantee the objective optimality and reliability is necessary.

1.1. Literature review

Because of the practical importance and the computational complexity of TF layout problems, a large number of attempts for them have been made by researchers. The TF layout problem can be classified in different dimensions: (i) discrete vs. continuous construction site layout, (ii) static vs. dynamic site layout, and (iii) layout construction vs. layout improvement. (i) Discrete layout (or called 'facility to location assignment' by Osman et al. [15]) means there are a finite number of candidate locations in a construction site and each TF needs to be assigned to one of the candidate locations. Continuous layout (or called 'facility to site assignment' by Osman et al. [15]) refers to the situation where TFs can be placed at any empty space of a construction site. The continuous empty space is sometimes discretized in solution algorithms for continuous layout problems. (ii) Static layout problems assume that all the TFs are set up and removed at the same time; as a result, a TF cannot overlap spatially with permanent facilities or other TFs. Dynamic layout problems account for the time dimension of the

* Corresponding author.
E-mail address: hans.wang@polyu.edu.hk (S. Wang).

http://dx.doi.org/10.1016/j.autcon.2017.10.031
Received 25 May 2017; Received in revised form 7 September 2017; Accepted 28 October 2017

construction of the permanent facilities, and hence, after completing their tasks, some TFs will be removed to make room for new TFs to be set up. (iii) Layout construction is to design the layout of TFs from scratch, whereas layout improvement deals with conducting some but not fundamental changes to an initial layout, which is likely to be designed by site managers based on experience.

A large variety of heuristic and meta-heuristic algorithms have been developed to generate solutions for construction site layout problems. We present the stream of studies on discrete site layout in this paragraph and the stream of works on continuous site layout in the next paragraph. Yeh [22] studied a static discrete site layout problem with the objective of minimizing the sum of construction costs of TFs at candidate locations and interactive costs between TFs. An annealed neural network method was developed and tested over two case studies with 12 TFs and 12 candidate locations. Li and Love [7] formulated a static discrete site layout model that minimizes total traveling distance of site personnel between facilities. They proposed a genetic algorithm to solve an example with 11 TFs and 11 candidate locations. Li and Love [8] extended the above study to an unequal-area facility layout problem, where some candidate locations are too small to accommodate large TFs. Unlike the above studies which require deterministic cost parameters in the models, Lam et al. [6] applied fuzzy reasoning to calculate the closeness relation of TFs in the objective function to account for the uncertainty of the parameters, and proposed an ant colony optimization (ACO) algorithm to solve the problem. This research was extended in Lam et al. [5], which proposed a max-min ant system algorithm. Unlike the above static site layout problems, Xu and Li [20] proposed a multi-objective particle swarm optimization algorithm for a dynamic site layout problem with two objectives: one is minimizing the total transportation costs and the other is maximizing the distances between high-risk facilities.

In the stream of literature on continuous construction site layout, Mawdesley et al. [10] applied a genetic algorithm to a problem setting in which the inter-facility distance (minimum and maximum distance between two TFs) is account for. Zouein et al. [24] further took into account the orientations of TFs. In addition to factors considered in the above two studies, Osman et al. [15] developed a computer-aided design (CAD) platform to visually observe the layout; another characteristic of Osman et al. [15] is that it minimizes the "relative proximity weight" instead of transportation costs as the values of transportation costs are difficult to obtain. Elbeltagi et al. [3] and Sanad et al. [17] have also investigated continuous site layout problems using genetic algorithm. In the two studies, Elbeltagi et al. [3] addressed the dynamic site layout problem and Sanad et al. [17] took into account many safety and environment considerations, such as safety zones around construction areas, noisy workshops and facilities that emit gases, and effect of harmful TFs on other facilities. Zhou et al. [23] integrated genetic algorithm and simulation to address continuous construction site layout for tunnels. Ning et al. [13] proposed a max-min ant system algorithm to address the continuous construction site layout problem with two objectives: safety/environment concerns and total transportation cost of flows between the facilities. The models and algorithms were integrated into a decision-making system in Ning et al. [14]. To find Pareto-optimal solutions for site layout, Ning and Lam [12] presented a modified Pareto-based ant colony optimization algorithm and Yahya and Saka [21] developed a multi-objective artificial bee colony algorithm. As opposed to the above studies which have taken into account solely quantitative factors, Ning et al. [11] applied the intuitionistic fuzzy set theory to account for qualitative factors in construction site layout.

There are few studies that have applied mathematical optimization to construction site layout problems. Easa and Hossain [2] developed a mathematical optimization model for a static continuous site layout problem. The model was solved using LINGO software for an instance of four TFs. By contrast, we take advantage of state-of-the-art mixed-integer programming techniques and solve larger problems much more efficiently. Said and El-Rayes [16] designed an approximate dynamic programming method for a dynamic continuous site layout problem. Approximate dynamic programming, by nature, is a heuristic and cannot guarantee optimal solutions, in contrast to our exact mixed-integer programming approach. Wong et al. [19] used integer programming to solve site layout problems to minimize transport costs. Our model distinguishes from theirs in three aspects: first, we consider many more realistic factors; second, they applied a big-M method to linearize constraints, whereas our linearization approach does not require the big-M; third, we consider two objectives and propose methods to obtain the exact Pareto-frontier for the two objectives. Hammad et al. [4] applied mathematical programming technique for site layout to minimize noise pollution and transport costs. Their model is inherently nonconvex and solvers cannot guarantee global optimality. Furthermore, they proposed an epsilon-constraint method to identify an approximate Pareto-frontier for the two objectives, while our study takes advantage of the discrete nature of the decision variables and proposes cutting planes to obtain the exact Pareto-frontier.

1.2. Objectives and contributions

The objective of this paper is to develop mathematical models for TF layout problems that can be solved by state-of-the-art solvers to optimality. The contribution of the paper is two-fold. First, for a long time, the construction management community has considered it unrealistic to use mathematical programming to address layout problems due to their large set of feasible solutions. However, in the last 30 years, the spectacular advances in computational power and in integer optimization methods have made it possible to address problems that were once thought to be intractable in practical settings [1]. Hence, in contrast to most of the existing literature, which tries to develop heuristic or meta-heuristic approaches, we take advantage of the latest development of mathematical programming techniques in developing mathematical models to solve the problems to optimality within reasonable time. Second, we demonstrate how mathematical models can be applied to handle many practical considerations, especially those that can hardly be dealt with by heuristic methods.

The remainder of this paper is organized as follows. Section 2 presents a mathematical programming model for a basic static discrete construction site layout problem. Section 3 demonstrates how mathematical programming can be applied to handle a large variety of practical considerations. Section 4 reports the results of numerical experiments that are used to validate the effectiveness of the proposed models. Conclusions are presented in Section 5. The symbols used in the paper are listed in Table 1.

2. Mathematical programming model for construction site layout

In this section, we present a mathematical programming model for a basic static discrete construction site layout problem. Then we investigate the computational complexity of the problem and finally we propose techniques to transform the mathematical programming model into an integer linear programming formulation.

2.1. A nonlinear optimization model

A static discrete construction site-level layout problem is concerned with assigning a number of predetermined TFs to a number of predetermined locations. The number of predetermined places is equal to or greater than the number of predetermined TFs. We assume that each of the predetermined places is capable of accommodating any of the TFs, i.e., we consider an equal-area facility layout problem. To minimize the transportation costs between TFs, the problem can be formulated as a nonlinear optimization model: