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A cutting plane algorithm for the site layout planning problem with travel barriers

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ABSTRACT

Site layout planning is an imperative procedure that may significantly impact the productivity and the efficiency of logistical operations undertaken on a construction site. This paper considers the site layout planning problem (SLPP) which entails the allocation of temporary facilities on a construction site in the presence of travel barriers such that the total transportation cost between facilities is minimised. In order to account for travel barriers, the SLPP is typically solved under the assumption that the available region for facility layout can be discretised. In this paper, we propose a general Mixed Integer Programming (MIP) model to represent the SLPP, accounting for the presence of barriers, and we show how space-discretised formulations can be derived from this model. In particular, we propose a novel MIP model, which permits facilities to cover multiple locations. This is then benchmarked against a commonly adopted MIP model in the literature. We also highlight a systematic procedure to convert the continuous feasible space in SLPP to a set of discretised locations based on the concept of d-visibility, enabling us to approximate the barrier distance function embedded in the objective function. In particular, we focus on presenting a simple space discretisation approach for converting the continuous SLP into a discrete problem for which the discrete SLP models would be applicable. Space-discretised MIP formulations are highly combinatorial and we introduce a cutting plane algorithm to improve their tractability. Specifically, we propose a novel exact location-decomposition algorithm which works from a relaxed MIP formulation and iteratively generates feasibility cuts to converge to an optimal solution. Both space-discretised MIP models and the decomposition algorithm are tested on a large group of instances to analyse their effectiveness in solving the SLPP. Computational results indicate that the proposed location-decomposition algorithm improves on the pure MIP approach and provides a competitive framework to solve realistic SLPP instances.

1. Introduction

In engineering construction and management, the site layout planning problem (SLPP) is a well-studied layout problem which requires finding an appropriate physical arrangement of temporary facilities operating on construction sites [15,21,26,47,51]. The physical layout of the facilities should respect design constraints, i.e. site boundaries and non-overlapping restrictions, and a layout is said to be *feasible* if all design constraints are satisfied. The total transportation cost, measured in terms of distance-weighted travel frequencies among facilities, is commonly used as a criterion for assessing the suitability of the construction site layout [50]. This is because the construction process of various types of projects, including infrastructure, buildings and heavy civil works, is one that entails many logistical and building activities, requiring the envelopment of different types of facilities throughout the construction period. These activities often involve the transportation of construction material from one facility to another. Hence the layout of the construction site may have a considerable impact on the efficiency of such integral operations. The SLPP can be then stated as follows: *given a construction site and a set of permanent and temporary facilities with a priori known dimensions, find a feasible arrangement of the temporary facilities on the available space of the construction site such that the total transport cost among all facilities is minimised.*

The decision process for locating facilities in the SLPP problem is commonly formalised using the Euclidean plane, adopting either a continuous or a discrete space approach [27]. The solution to the SLPP is a block layout showing the dimensions along with the relative positions of the facilities within a given area [7]. In relation to similar problems presented in the operational research field, the SLPP falls in the general category of layout-location problems,

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having a close association with the facility layout problem where the aim is to allocate departments, workshops, facilities etc. to locations [39].

Adopting an efficient on-site layout of temporary facilities serves the purpose of improving the overall work organization aspect on a construction site in several ways. In construction, especially for expansive construction sites where large equipment is utilised for transporting the material between facilities, it is expected that a site layout configuration which reduces frequency-weighted travel distances would have a significant impact on the operating costs, measured in terms of material movement between facilities [16,34]. Productivity is improved when an adequate construction site plan is put into use [36], as it is expected that a more coordinated material flow will result between the temporary facilities, leading to a reduction in the overall costs expended on material handling equipment, and a better use of such systems. In the area of manufacturing, facility layout and its effect on the total material costs inflicted by its underlying structure has been assessed to reach levels of up to 50% of the total operating costs [44]. Improvement to the layout of facilities can also lead to reductions of 10% - 30% in the total material handling costs expended [37]. In terms of safety, it has been acknowledged that a well planned construction site helps in reducing the number of accidents and injuries occurring to workers [12,32]. Other aspects that are also affected include the safety of people in the vicinity of the construction site, along with the environmental and social influences caused by the adopted site layout [2].

Consensus on the hardness of layout problems is that they are NP- hard [10,23,51]; this explains the great number of studies in the literature in which non-exact solution techniques have been proposed. Many of the studies reviewed on facility layout problems therefore tend to propose heuristic or meta-heuristic approaches for solving the problem [19, 29, 28, 40]. In the SLPP, considerable attention has been directed at the applications of various solution techniques. This includes the deployment of: 1) exact methods such as Linear Programming [52], Mixed Integer Programming (MIP) [11,46] and Mixed Integer Non-Linear Programming (MINLP) [16]; 2) Heuristics, mostly developed originally for facility layout planning and which have been suggested as appropriate for the SLPP, such as entire layout algorithms [17], solution improvement algorithms [31], partial improvement algorithms [41] and priority facility selection [43]; 3). Meta-heuristics such as genetic algorithms [24], ant colony optimisation [33], particle swarm optimisation [49] and bee colony algorithm [48].

In this paper, we focus on the application of exact approaches for the SLPP. Currently, exact methods adopted in the SLPP literature are able to solve for cases involving only 4 facilities [11]. The maximum number of facilities for which the SLPP has been solved is 16 facilities, though this is achieved through use of meta-heuristics [1]. To the best of our knowledge, no exact approach capable of solving large instances of the SLPP has yet been proposed.

A distinctive element of construction sites that plays an important role in the determination of the distance measure adopted between facilities is the presence of work area zones, known as building footprints, where most construction activities take place. These regions are barriers that impose an obstacle to travel, as mobility across these regions by on-land material handling equipment is normally prohibited. Studies on the SLPP tend to neglect the impacts that the barriers can have on the distance measure adopted in the formulations. The construction site layout planning problem considered in this paper therefore concerns the arrangement of temporary facilities around such barriers, labelled as permanent facilities, such that the distance metric adopted between the temporary facilities accounts for the presence of the barriers.

In this paper, we propose a general MIP formulation for the SLPP accounting for travel barriers, and we show how integer-linear space-discretised formulations can be derived from this model. In particular, two space-discretised SLP models are benchmarked. The first is commonly adopted in the literature and requires facilities to cover at most a single discretised location. In this model, the underlying space discretisation structure implicitly prevents overlap with barriers. The second is a novel model which permits facilities to cover multiple discretised locations and which explicitly accounts for the presence of barriers through non-overlap constraints. We then introduce an exact cutting plane algorithm for the space-discretised SLPP. The proposed solution method works from a relaxed MIP formulation and iteratively adds cutting planes to achieve feasibility. We show that this decomposition algorithm improves on a pure MIP approach and is able to solve the problem on realistic sized instances in reasonable time. Further, we quantify the trade-off between computational performance and model accuracy induced by the space-discretisation procedure. The importance of our work is thus in the formation of a method to optimally solve reasonable-sized site layout planning problems within a realistic time frame, all the while incorporating the additional restrictions imposed by the presence of travel barriers.

The contributions of this paper can be summarised as follows: 1) we propose a general MIP model to represent the SLPP while accounting for travel barriers in the design and in the objective function; 2) we introduce a systematic space-discretisation approach for the SLPP and we propose a method to approximate travel distance in the presence of travel barriers using the concept of *d*-visibility; 3) we present a novel multi-cover discretised SLP model which is benchmarked against the common MIP formulation used in the literature to solve the SLPP; 4) we improve on the existing exact approaches in the literature by presenting an exact cutting plane algorithm which is able to solve large scale instances of the SLPP to optimality, hence enhancing tractability; and 5) we conduct numerical experiments to quantify the impact of the proposed space discretisation scheme on the solution quality of the space-discretised MIPs.

To describe the contributions of this work, the structure of this paper is organised as follows: In Section 2, we formally define the SLPP and introduce a general MIP model to represent it. In Section 3, we present a space-discretisation approach, based on the concept of *d*-visibility, which provides a network representation of the SLPP. In Section 4, two MIP models for solving the discrete SLPP are presented. In Section 5, we introduce a cutting plane algorithm to solve the space-discretised SLPP. In Section 6, we perform numerical experiments to contrast the proposed SLP models and quantify the impacts of the space discretisation scheme on the solution quality. Section 7 summarises the findings of the paper and discusses possible extensions of this work.

2. Problem definition and general formulation for slp

In this section we provide a description of the feasible region available for locating temporary facilities within a construction site in the presence of barriers, along with a formal definition of the SLPP and a general MIP representation.

First the notation is given as follows: let F denote the set of temporary facilities to be positioned on the construction site. We do not consider positioning permanent facilities in the SLPP since they are presumed to have a priori defined locations. We also assume that all facilities can be represented as rectangles. Other shapes, possibly non-convex, can be handled by fitting a minimum bounding rectangle. For each temporary facility $i \in F$, let W_i and H_i denote the input width and length of the facility in the SLP model, respectively. Adopting rectangular shapes for facilities enables the definition of constraints to control requirements such as non-overlap between facilities and facility positioning within