



A tri-objective ant colony optimization based model for planning safe construction site layout

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ABSTRACT

Realizing safety improvements in construction site layout planning (CSLP) is vitally important to construction project safety management. Unlike previous studies in which the safety objective is built without detailed risk factors analysis, this study transforms CSLP into a multi-objective optimization (MOO) problem with designing two safety objective functions due to facility safety relationships (potential risks arising from interaction flows) and geographic safety relationship (potential risks arising from hazardous sources) from the holistic interpretation of interaction relationship connecting temporary facilities. Besides, a supplementary cost reduction objective function was also derived as cost is a critical barrier against safety improvement. Subsequently, a tri-objective ant colony optimization based model was developed to solve MOO problem. Finally, a case study is used to verify the proposed model. The study enriches safety implications by considering onsite safety issues from interaction relationship and enhances site safety of CSLP in the pre-construction stage.

1. Introduction

Construction site layout planning (CSLP) is a critical activity that should, ideally, be given full consideration to early in the pre-construction stage of construction projects. Various researchers have discussed the significance of “design for safety” and argued that most accidents or serious risks can be avoided by incorporating more safety considerations into planning schemes [1–4]. It is significantly beneficial and vital to improve construction site safety through better site layout in safety planning, and thus the considerable attention paid to safety planning in the pre-construction stage is critical to improving project safety performance efficiently [5].

CSLP is commonly treated as an optimization problem, and site safety can be realized by designing different objective functions based on safety requirements or considerations (hereafter called “safety objective function”), such as minimizing accidents by optimizing safe locations for tower cranes [6–8], controlling hazardous materials onsite [9, 10], reducing intersections between heavily traveled routes [11], defining the safety zones in term of necessary regulations [12], and reducing the noise pollution onsite [13, 14]. With a specific safety objective function, the generated site layout plan can only fulfil the partial safety requirement mentioned above. In previous researches,

limited attention has been paid to designing safety objective functions with full risk factor evaluation involved in the function design. Developing safe construction site layout plans under the partial safety objective function without adequate and further risk factors analysis will result in layout with more risk tendency. Thus, this study was conducted with the objective of designing safety objective functions with full consideration of onsite safety after holistic risk factors analysis associated with site layout.

To find an optimal site layout with defined safety objective functions, CSLP tends to be modeled as a quadratic assignment problem [15, 16]. This problem is commonly solved by genetic algorithm [17–23], ant colony optimization (ACO) algorithm [24–26], artificial bee colony optimization [27], particle swarm optimization (PSO) algorithm [28, 29], harmony search algorithm [30], cutting plane algorithm [31], and simulated annealing algorithm [32]. Among these algorithms, multi-objective optimization with two conflicting or congruent objective functions is solved by determining the dominant relationship between solutions [33, 34] or constructing a weighted sum of all objectives [35–37]. As regards algorithms relying on finding dominance relations between solutions, Yahya and Saka [27] applied enhanced artificial bee algorithm with levy flights to generate site layout plans fulfilling the requirements of safety and cost simultaneously. Xu and Li [38]

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developed a multi-objective PSO algorithm to solve the dynamic construction site layout problem considering the total cost of site layout planning, and the possibility of safety and environmental accidents. Ning and Lam [39] proposed a Pareto-based ACO algorithm to find cost and safety tradeoff solutions for an unequal-area site layout problem. As regards the weighted sum method in multi-objective optimization, Singh and Singh [16] developed an improved heuristic approach that employs the weighted sum method to combine multiple objectives (workflow, closeness rating, material handling time, and hazardous movement) into a single objective to generate alternative layouts. Ning et al. [36] used the max-min ant system to handle site layout problems by summarizing the objective functions of safety and cost. The well-known drawback of the latter method is the predetermined weighting coefficients of each objective, as the weighting coefficients do not necessarily correspond directly to the relative importance of the objectives or allow tradeoffs between the objectives to be expressed [40]. The significant advantages of Pareto optimization compared with the weighted sum method are its provision of site managers with several reference solutions and its reflecting of their preference [38]. Therefore, the preferred optimization principle of Pareto optimization theory [34], determining the dominance relation between solutions, is adopted in this paper.

In order to ameliorate the discrepancies discussed above, i.e., the significant limitation of current safety objective functions and deficiency of the weighted sum method in solving multi-objective optimization problems, a tri-objective ACO-based safety model was developed in this study to help construction site planners determine safe site layout plans with more detailed risk factors analysis in the pre-construction stage. More specifically, the layout plans in this study will be significantly enhanced arrangements of the temporary facilities on the construction site considering more safety factors. Finally, the proposed model is applied in the case study to verify its applicability and effectiveness. The findings from the case study is aimed to give constructive suggestions on designing a safe construction site layout plan in a more scientific and reasonable manner.

2. Safety considerations in previous CSLP

In 1997, Anumba and Bishop [41] stated the importance of safety consideration in construction site layout as follows: "... in many cases, site and project managers tend to focus on considerations such as optimizing productivity without adequately taking into account the health and safety implications. This is despite the fact that there is major scope for preventing, or minimizing, the effects of many construction site accidents through appropriate site layout design and organization".

CSLP is a multi-objective decision-making problem, in which optimal site layouts or the best site layout are generated by different algorithms and technologies. During the optimization process, site layout plans are improved continuously considering conflicting or congruent objective functions with the constraints of site condition and resources. In order to design a safety site layout plan, some safety considerations can be realized in the objective functions or by assigning facilities in the preset safety zone.

Ning and Lam [39] designed a safety objective function that minimizes the representative score of safety/environment concerns, which may arise when the two facilities are close to each other, and may affect site workers by increasing the likelihood of accidents, noise, uncomfortable temperature, and pollution. El-Rayes and Khalafallah [11] targeted the safety issue from falling accidents caused by tower cranes, dangerous or hazardous materials, and intersections between heavily travel routes. Abune'meh et al. [9] derived a safe site layout by minimizing the summarization of hazard levels received from hazardous sources such as fires, explosions, thermal flux, and blast waves. In addition to objective functions pertaining to safety issues in optimizing construction site layouts, some safety site spaces or safe distances have also been used as additional site constraints to improve site safety

performance and efficiency [42, 43]. A safety zone is an unoccupied and available additional space that is used to accommodate temporary facilities defined by specific rules, regulations, and standards, i.e., the facility space is equal to the sum of the actual dimensions of the facility and the relevant safety zone. In this study, available safe spaces are identified during the assignment of facilities to avoid accidents occurring around potential hazardous sources [12, 44]. To reduce the probability of exposing facilities to potential danger, the safety distance between pairs of facilities is also determined [45, 46].

In previous studies, both the safety objective functions and site space constraints described and recognized the danger to temporary facilities arising from being around hazardous sources. The optimal site layout assigns temporary facilities far away or maintains a necessary distance from the hazardous sources/facilities, such as tower cranes, material hoists, and fuel storage areas. This kind of potential risk coming from being around hazardous sources is related to location. If the location is fixed, regardless of the kind of facilities assigned to the location, their risk arising from the surrounding hazardous sources is constant. In other words, the potential risks considered in previous site layout safety optimization problems were merely dependent on the facilities' positioning. According to El-Rayes and Khalafallah [11], frequent movement of resources (materials, personnel, and equipment) leads to more conflicts or collisions between resources, which can potentially trigger accidents. The transportation of resources between facilities is not related to the facilities' positioning but is highly related to the resources' transportation determined by job demand between the facilities. In order to design a construction site layout with comprehensive risk factors analysis, the movement of resources between the facilities should be considered. In the following section, objective functions are built based on further discussion of risk factor analysis.

3. Optimization objective functions

Reasonable temporary facilities' assignment within a construction site is significantly influenced by the interaction relationship and the distance between the facilities with fulfilment of pre-defined objective functions. As discussed in the previous section, there is insufficient risk factor analysis conducted considering the interaction relationship between the facilities when developing a safety CSLP. It is vital to make good facilities displacement in the construction site for high safety performance in terms of their mutual safety impact on each other. Thus, with interaction relationship analysis to find more risk factor, the tri-objective functions for safety improvements and cost reduction are established.

3.1. Interaction relationship analysis

In a construction site, the facilities participated have interaction relationship with each other. Assume that there are m site facilities that need to be assigned to n free locations ($n \geq m$), a network consisting of facilities and the interaction relationship between them can be depicted as shown in Fig. 1.

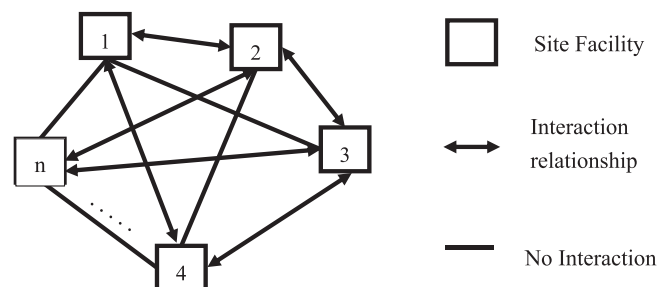


Fig. 1. A network of site facilities.

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