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Solving The Problem of Multi-Stakeholder Construction Site Layout Using Metaheuristic Algorithms

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Abstract

Project management elements are widely recognized as critical success factors in the execution of construction projects. One of the primary challenges encountered in these projects is construction site layout planning (CSLP), which can significantly impact the achievement of project objectives. Optimizing CSLP can lead to substantial economic savings, reduced time, minimized risks, and fewer changes throughout the project. However, due to the complexity of these issues, they have often been underemphasized in project management practices. To address these challenges, the application of meta-heuristic algorithms is proposed. In this study, genetic algorithms, multi-objective particle swarm optimization, and firefly algorithms were utilized.Various factors influence the optimal location of the construction site, primarily to minimize costs. This research examines five critical factors in determining the optimal workshop placement, incorporating these into the objective function. The objective function is derived from the interaction of multiple stakeholders, modeled through agent-based modeling (ABM) within an integrated system. To better understand workshop placement optimization and its influencing factors, a case study was conducted using meta-heuristic algorithms.The results indicate that modeling complex multi-stakeholder interactions in an integrated system, although challenging, can significantly improve decision-making. The findings demonstrate that, under optimal decision-making conditions, this approach is 12.34% more efficient than traditional methods. Notably, the multi-objective particle swarm optimization algorithm produced the most favorable results in multi-component integrated models compared to other algorithms investigated in this study.

Keywords:
Construction site layout planning (CSLP)
Multi-stakeholder interaction model
Genetic algorithm(GA)
Particle Swarm Optimization(PSO)
Agent-based modeling (ABM)

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INTRODUCTION

The integration of contemporary management science and its advanced methodologies into current management practices has preserved the traditional culture governing construction projects. This persistence has left many critical workshop issues from recent decades unaddressed, despite the introduction of innovative manufacturing technologies in workshops. Mahmoodabadi et al. (2014) successfully addressed one of the key challenges facing construction workshops through the application of the harmony search algorithm, a cutting-edge optimization model. This development not only helps resolve longstanding workshop issues but also bridges the gap between modern scientific approaches and the evolving needs of the construction industry.

A significant barrier remains, however: the prevailing distrust between workshop managers and the scientific advancements in construction management. Overcoming this distrust across the nation’s workshops is essential for progress (Mahmoodabadi et al., 2014). Traditional static layout models and common workshop layout methods have failed to effectively integrate the three essential components: space, time, and equipment. In contrast, Mahmoodabadi et al. (2014) introduced a dynamic layout model that utilizes the harmony search algorithm, optimizing equipment placement based on time distribution schedules and the potential for repositioning over time. A key feature of this model is the logical and efficient adaptation of harmony vectors to the concept of dynamic layout. To assess the performance of this dynamic model, it was compared with prior models, specifically addressing the dynamic layout problem discussed in previous research by Afshar and colleagues. The outcomes demonstrated significant improvements when using the harmony search algorithm, as evidenced by the comparison with earlier models (Nasirzadeh et al., 2018).

The harmony search algorithm has been shown to effectively implement dynamic arrangements, as demonstrated by Ma and Xu (2015), Gang et al. (2015), and Li et al. (2015). Several factors, if not properly managed, can lead to project failure, including the lack of attention to feasibility studies before project initiation, adverse risks at both the beginning and end of the project, inadequate understanding of contract requirements, and insufficient expertise among project team members. Two key elements of risk management—correct team design and the roles of critical project individuals, as well as prior assessment of project feasibility—are essential for the success of crucial projects, particularly in the context of the nation (Shahebrahimi et al., 2022).

Ghadiri et al. (2022) developed safety objective functions aimed at total cost reduction by accounting for risks associated with hazardous sources and interaction flows between temporary facilities (Min et al., 2010). Meanwhile, Khodabandelu and Park (2021) examined the application of simulation and agent-based modeling (ABM) in construction. ABM has gained popularity in construction research due to its distinctive system modeling capabilities and the advancements in computational technology, resulting in a growing body of literature on this subject. Their study utilized a case study to validate the usefulness of ABM in addressing the interactions between construction site layout planning (CSLP), construction material logistics planning (CMLP), and site security planning (SP). The research contributes to the field by offering both theoretical and practical perspectives on ABM, with specific recommendations to enhance its application in real-world construction projects.

Choi et al. (2022) employed an automated decision-making model to select optimal dam noise designs in terms of health impact, productivity, and cost, using three objective functions in conjunction with mathematical calculations. Their methodology also aimed to improve the urban sound environment, ensuring construction companies' profitability and enhancing the viability of construction projects. Rezaee et al. (2021) focused on travel distance, a key parameter in optimizing CSLP, using fuzzy graph theory to minimize travel distance while considering behavioral uncertainty. Unmanned aerial vehicles (UAVs) and 3D reconstruction were used for site mapping and layout planning in petrochemical development, addressing safety challenges in large-scale lifting. Song et al. (2017) demonstrated that real-time 3D spatial information could significantly improve facility layout planning. The combined optimization of CSLP, CMLP, and SP through agent-based decentralized optimization was explored to examine the impact of multi-stakeholder interactions on site layout planning. Song et al. (2019) minimized costs in their study by incorporating five main components into the objective function. They emphasized the importance of proper coordination with CSLP policy for successful optimization.

Ding et al. (2021) proposed a management framework and ABM approach for evaluating urban demolition waste, addressing the growing issue of construction and demolition (C&D) waste. The study highlighted the importance of accurate waste quantification and stakeholder engagement in the management of C&D waste. Kaveh et al. (2018) underscored the importance of space, materials, machinery, and labor in the planning of large-scale engineering projects, such as dams and tunnels. Site layout planners (LaP) are tasked with designing layouts that integrate site surroundings and transportation requirements, a challenging task given the NP-hard nature of CSLP problems. While no universal solution exists for determining optimal layouts, several mathematical models have been developed to transform CSLP challenges into objective functions with decision variables and constraints.

Hammad et al. (2016) created a mixed integer programming model to minimize CSLP costs between any pair of facilities, addressing interactions in large-scale construction projects. Fang et al. (2018) emphasized the roles of safety managers (SaM) and logistics planners (LoP) in overseeing occupational health and safety measures and ensuring material supply channel logistics planning. Collaborating with other stakeholders, the CSLP system must balance construction costs, project duration, quality, and environmental impact. RazaviAlavi and AbouRizk (2017) developed a centralized model for material procurement and site layout optimization, while Xu et al. (2016) proposed a decentralized bi-level model to optimize CSLP and SP through the interactions between the LaP and material suppliers. Although previous research acknowledged the importance of stakeholder interactions in CSLP, limited attention has been given to the multi-stakeholder dynamics. Zhou et al. (2017) addressed this gap by integrating agent-based modeling (ABM) and two-level programming to optimize multi-stakeholder interactions. Their research introduced a two-level multi-stakeholder model for CSLP-CMLP/SP system optimization, which accounts for the interactions between LaP, LoP, and SaM. This model provided a structure for examining the effects of multi-stakeholder interactions on site layout design, aiming to balance the objectives of each stakeholder.

The remainder of this paper is structured as follows: Section 2 details the CSLP-CMLP/SP model and the contributions made in this research. Section 3 presents a case study, where a two-level mathematical model is formulated and an interactive solution method is designed to find an optimal integrated solution. In Section 4, the case study results are reviewed through comparative tables, and future research directions and recommendations are discussed in Section 5.

CSLP-CMLP/SP MODE

This research was conducted utilizing relevant library resources, academic papers, and expert interviews. Information collection tools were developed by creating a questionnaire informed by expert perspectives and existing challenges in construction projects. The questionnaire was distributed both electronically via contractor, manager, and client websites and in hard copy format. The model used in this study was developed by Song et al. (2019). The questionnaire consisted of 10 questions, which were answered by 42 experts and managers. The purpose of distributing the questionnaire was to identify the stakeholderS and check it in this research, Lop, Lap and SaM were selected.

It presents an agent-based, decentralized bi-level mathematical model that incorporates the decisions of three key stakeholders to analyze multi-stakeholder interactions in construction site layout planning (CSLP). A genetic algorithm (GA)-based optimization approach was employed to solve the model, producing integrated solutions for CSLP, construction material logistics planning (CMLP), and site security planning (SP). These solutions were then compared with outcomes from particle swarm optimization (PSO).

In this model, stakeholders are represented as individual agents with distinct decision-making processes and objective functions, and the bi-level model addresses the interdependencies between the layout planner (LaP) and the other two stakeholders—the logistics planner (LoP) and the safety manager (SaM). To facilitate multi-stakeholder interactions, each agent's decisions are iteratively updated to achieve an optimal, integrated solution with minimal stakeholder conflicts during the construction phase.

Song et al. also introduced the tri-PSO framework based on interaction modeling concepts. Initially, LoP employs PSO to solve the CSLP optimization problem, generating a CSLP decision. This decision is passed to LoP and SaM via an integrated system (ISO). Subsequently, PSO is applied to solve the CMLP and SP optimization problems, with the decisions from CMLP and SP being integrated into a feasible solution. This solution is then relayed back to LaP for evaluation. If the objectives are met, ISO incorporates the relevant CSLP, CMLP, and SP decisions into a final integrated solution, which is then applied for overall project control.To illustrate the problem-solving framework, a conceptual model for the tri-PSO is provided in Fig 1.

CASE STUDY

The integrated CSLP-CMLP/SP model addresses multi-stakeholder interactions in site layout design, supply chain logistics, and security planning through a practical case study involving the construction of a dam base—a critical component for ensuring the structural integrity of large-scale infrastructure projects. The case study builds upon previous research by Song et al. (2018), which focuses on a specific section of a construction contract (depicted in Fig. 2). The integrated CSLP-CMLP/SP system is utilized to manage and resolve site layout (CSLP), material logistics planning (CMLP), and security planning (SP) challenges concurrently, ensuring the project's successful completion within the specified time frame. For confidentiality reasons, project names and details of engaged bidders remain undisclosed. The primary scope of the project involves constructing dam blocks and auxiliary structures.

The interrelated CSLP, CMLP, and SP subsystems work collaboratively to ensure the successful execution of the project. Specifically:

- **CSLP Subsystem:** This subsystem manages site layout by organizing on-site routes and temporary facilities.
- **CMLP Subsystem:** This subsystem facilitates the transportation of materials from suppliers to construction sites.
- **SP Subsystem:** This subsystem ensures health and safety standards throughout the project.

These subsystems are tightly interconnected, as demonstrated in earlier research (Song et al., 2018). The study integrates shared physical security measures between the CSLP and SP subsystems. Since both the CMLP and SP subsystems influence CSLP decision-making, understanding the degree of this influence is vital for the layout planner (LaP) and overall project management. To optimize the integrated CSLP-CMLP/SP system, the model generates solutions for the CSLP, CMLP, and SP subsystems, facilitating a comprehensive and effective project management strategy.

One critical component of this work is the availability and accuracy of data, which is essential for developing a viable solution. Collecting precise data for the model's constant parameters and solution approach is crucial to achieving this goal.

Model Parameter Settings

To arrive at an optimal integrated solution, the following data must be provided by the LaP, LoP, and SaM stakeholders:

Candidate Location Matrix: This matrix (denoted as 1, 2, ..., L) was used in previous research as a basis for identifying suitable locations within the project site.

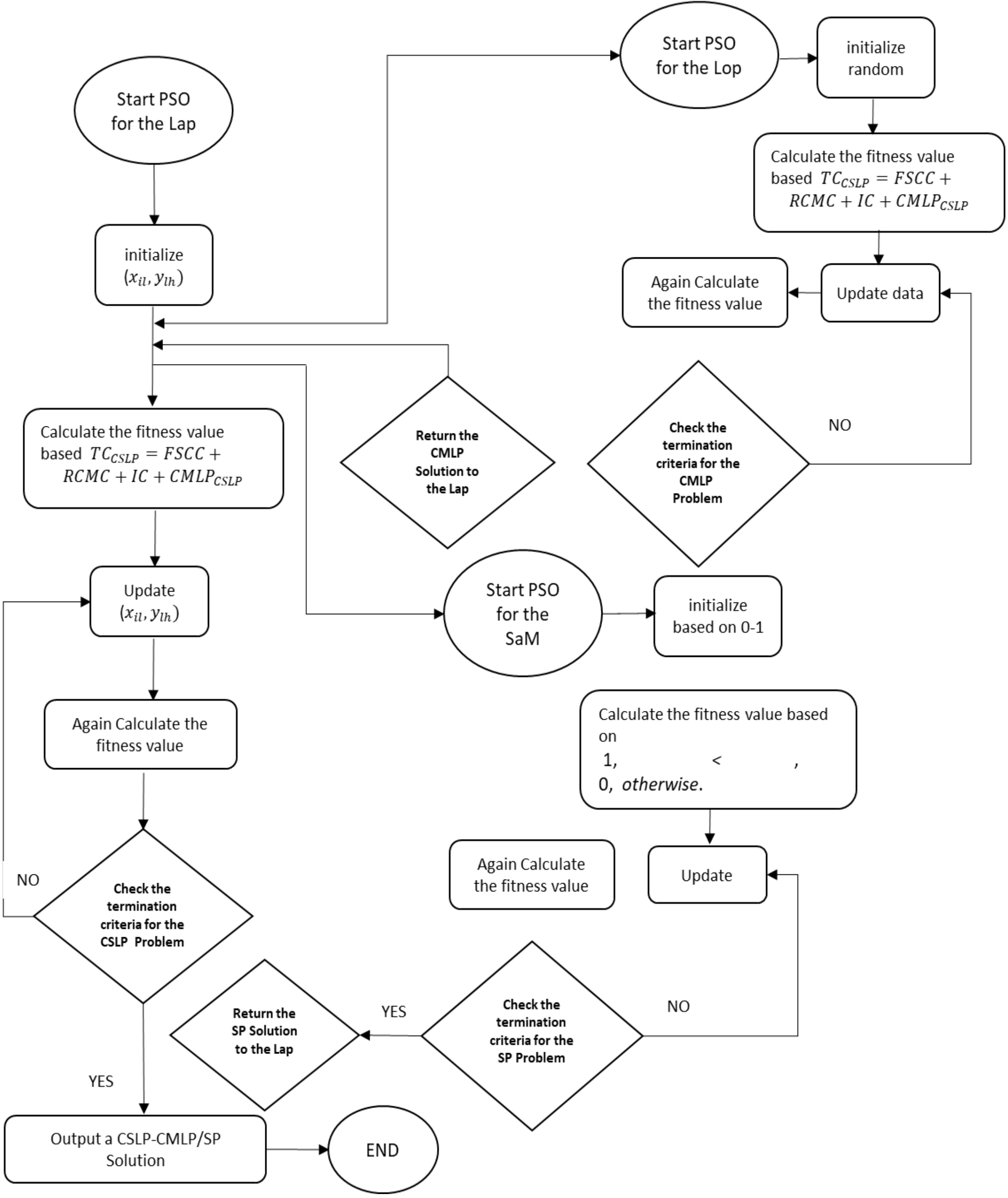


Fig. 1. Conceptual tri-PSO flow chart

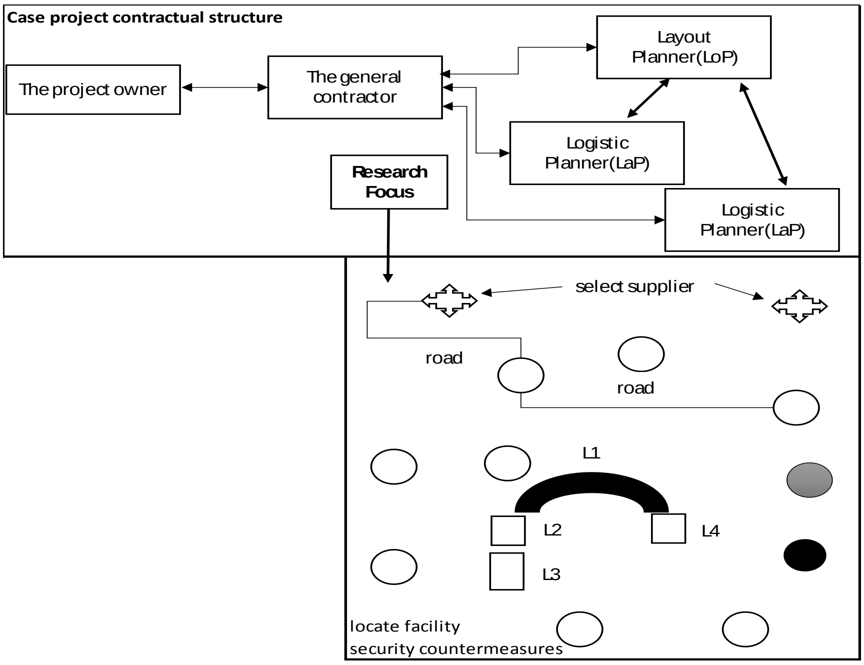


Fig. 2. Case project conceptual structure

Parameter Settings for the Model-Solving Approach

The tri-PSO (Particle Swarm Optimization) algorithm was developed to solve the bi-level CSLP-CMLP/SP model. The parameter values used for the Logistics Planner (LoP), Layout Planner (LaP), and Safety Manager (SaM) were pre-set based on previously validated studies. These parameter settings include:

Population Size (Pop-size): 200, denoting the number of particles in the swarm.

Generation Number (GN): 200, defining the number of iterations for the algorithm.

Inertia Weight (ω): A range of [0.2, 1.2], controlling the balance between exploration and exploitation by influencing the particle's momentum.

Coefficient Values ($c_1 = 2, c_2 = 2$): Representing the cognitive (c_1) and social (c_2) learning factors that guide particles toward personal best and global best solutions.

Random Numbers ($Rand_1$, $Rand_2$, $Rand_{a\beta}$): Values within the range [0, 1], introducing stochastic behavior to ensure diversity and prevent premature convergence.

This combination of parameters was shown to yield optimal solutions for the integrated CSLP and CMLP problems based on results from previous optimizations. However, additional sensitivity analyses are required to further assess the robustness of this parameter combination. These analyses should focus on evaluating:

Performance in Relation to Stakeholder Objectives: Examining how well the algorithm meets the goals of each stakeholder.

Average Computation Time: Assessing the efficiency of the algorithm in practical applications.

Convergence Speed: Determining the rate at which the algorithm approaches an optimal solution.

These analyses will provide further insights into the algorithm's adaptability and effectiveness under varying conditions.

DISCUSSION

To find the optimal solution for the relevant stakeholders in the construction site layout planning (CSLP), construction material logistics planning (CMLP), and site security planning (SP), the combined CSLP-CMLP/SP and tri-PSO model's parameters were adjusted. The Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) models were run 50 times to assess their performance. Results from these iterations revealed that the selected parameter combinations demonstrated low performance variance, indicating the efficacy and stability of the model. Tables 1 and 2 present partial results from the 50 runs using the PSO and GA algorithms, offering actionable solutions for each stakeholder.

The decision variables and objective function solutions varied among the different stakeholders, as illustrated in Tables 1 and 2. For instance, the second column represents site layout plans, which are decision options for the Layout Planner (LaP), while the fourth and sixth columns correspond to decision alternatives for the Logistics Planner (LoP) and Safety Manager (SaM), respectively. The optimal solutions were derived from 50 tri-PSO and GA runs. For example, solution 6, which has the lowest fitness value, was developed using Eva Lucien's fitness functions to identify the most suitable integrated solution for the CSLP-CMLP/SP system.

Figures 3 and 4 (a) illustrate how the optimal solution was broken down into components, such as a site layout that reflects facility location decisions, a design plan that integrates supply channel details (including supplier and order values, inventory and production quantities, and transportation networks), and a security map. In this case, genetic algorithm solution 6 was selected to guide the LaP, considering the inputs from the LoP and SaM. The objective values achieved for the LoP were 25.036×10825.036 \times 10^825.036×108 CNY, the LaP's profits were 0.997×1080.997 \times 10^80.997×108 CNY, and the SaM's risk was minimized at 19.02%.

Despite some assumptions regarding supply channels, which limited the applicability of the LoP and SaM solutions, the case study results successfully highlighted the critical relationships among site layout design, material supply channel planning, and security planning tasks. Tables 1 and 2 reveal that changes in the CMLP or SP decisions and their corresponding objective function values led to changes in the CSLP decisions and objectives. This demonstrates how CSLP decisions are simultaneously influenced by CMLP and SP activities and underscores the importance of understanding multi-stakeholder interactions in site layout planning.

To minimize conflicts during the construction phase, CMLP and SP requirements were integrated into the CSLP design and planning stages. Even though LoP and SaM make decisions based on CSLP outcomes, optimal CSLP solutions often require compromises to accommodate material supply and security demands. For example, decisions related to CMLP production quantities and SP's anti-security measures are influenced by the size and location of temporary processing centers.

The study further explores performance improvements and confirms the viability of the proposed CSLP-CMLP/SP model. From a systems engineering perspective, various studies have addressed construction site layout planning and other optimization challenges. The proposed CSLP-CMLP/SP system advances CSLP by modeling the impact of multi-stakeholder interactions on feasible site layout plans from a high-level coordination and control perspective. The integration of CMLP and SP optimizations as hard constraints in the CSLP-CMLP/SP model captures the effects of multi-stakeholder interactions, even if this results in a compromise in the overall site layout’s optimality. Potential conflicts between CSLP-CMLP and CSLP-SP decisions can be efficiently managed by selecting sub-optimal solutions for one or more stakeholders. Additionally, disputes or legal issues between LaP, LoP, and SaM can often be avoided by addressing potential CSLP-CMLP and CSLP-SP conflicts during the planning phase.

In conclusion, the CSLP-CMLP/SP model represents a significant advancement in understanding and managing the complex interdependencies between various stakeholders in construction site layout planning. The tri-PSO approach, in particular, provides a stable and effective method for optimizing multi-stakeholder interactions and decision-making processes, ultimately contributing to the successful execution of large-scale construction projects.

Table 1: Fifty solutions for the CSLP-CMLP/SP model.(Data based on the base article) (Song et al., 2019)

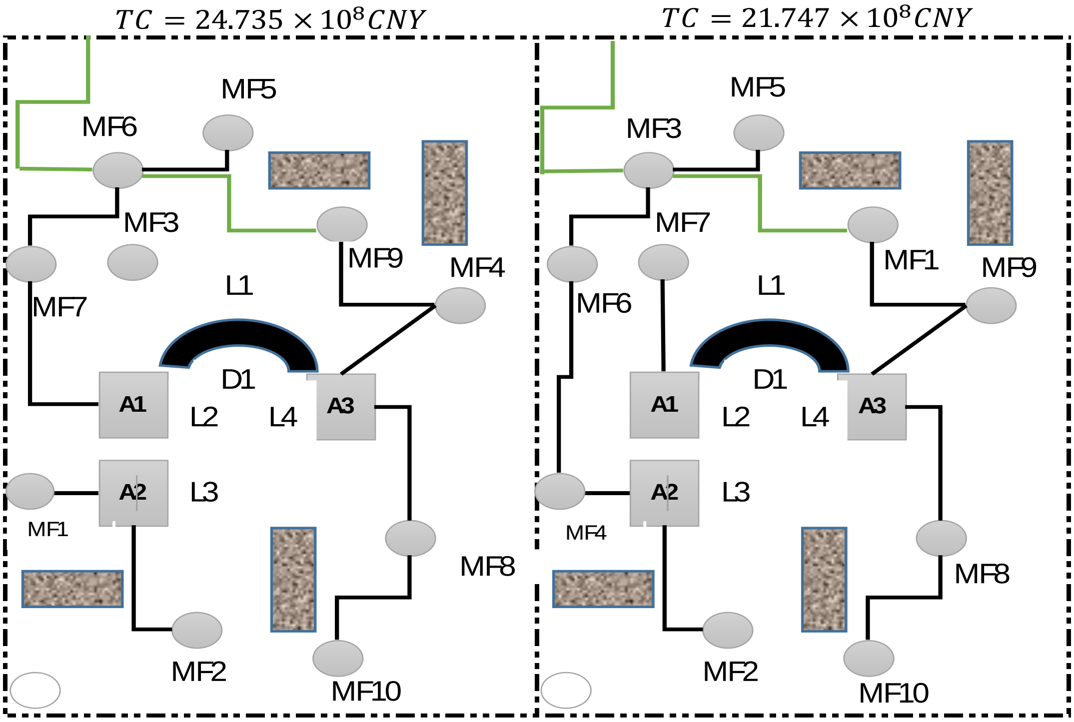
Solution no.	CSLP solutions		CMLP solutions		SP solutions	
	Site layout plan	*TCCSLP* (*CNY*)	Supply channel	*TFCMLP* (*CNY*)	Security plan	*TRSP* (%)
1	*Site_Layout_1*	26.533 * 10^8	*Supply_Channel_1*	0.815 * 10^8	*Security_Plan_1*	17.05
2	*Site_Layout_2*	26.937 * 10^8	*Supply_Channel_2*	0.873 * 10^8	*Security_Plan_2*	20.33
3	*Site_Layout_3*	25.335 * 10^8	*Supply_Channel_3*	0.755 * 10^8	*Security_Plan_3*	18.75
4	*Site_Layout_4*	27.89 * 10^8	*Supply_Channel_4*	0.903 * 10^8	*Security_Plan_4*	19.35
5	*Site_Layout_5*	25.755 * 10^8	*Supply_Channel_5*	1.014 * 10^8	*Security_Plan_5*	23.45
6[a]	*Site _Layout _ 6*[a]	24.735 * 10^8 [a]	*Supply _Channel _ 6*[a]	0.956 * 10^8 [a]	*Security _Plan _ 6*[a]	17.75[a]
7	*Site_Layout_7*	24.997 * 10^8	*Supply_Channel_7*	0.895 * 10^8	*Security_Plan_7*	24.53
…	…	…	…	…	…	…
46	*Site_Layout_46*	28.557 * 10^8	*Supply_Channel_46*	0.897 * 10^8	*Security_Plan_46*	25.95
47	*Site_Layout_47*	28.975 * 10^8	*Supply_Channel_47*	0.795 * 10^8	*Security_Plan_47*	26.37
48	*Site_Layout_48*	26.855 * 10^8	*Supply_Channel_48*	0.813 * 10^8	*Security_Plan_48*	23.75
49	*Site_Layout_49*	27.951 * 10^8	*Supply_Channel_49*	0.955 * 10^8	*Security_Plan_49*	20.31
50	*Site_Layout_50*	25.755 * 10^8	*Supply_Channel_50*	1.037 * 10^8	*Security_Plan_50*	25.35

a Represents the best solution and the underlined is the worst solution.

Table 2: The results of table 1 are based on the information of this paper in the genetic algorithm (GA)

Solution no.	CSLP solutions		CMLP solutions		SP solutions	
	Site layout plan	TC_{CSLP} (*CNY*)	Supply channel	TF_{CMLP} (*CNY*)	Security plan	TR_{SP} (%)
1	*Site_Layout_1*	25.873 * 10^8	*Supply_Channel_1*	1.012 * 10^8	*Security_Plan_1*	22.17
2	*Site_Layout_2*	26.236 * 10^8	*Supply_Channel_2*	0.894 * 10^8	*Security_Plan_2*	21.09
3	*Site_Layout_3*	28.436 * 10^8	*Supply_Channel_3*	0.896 * 10^8	*Security_Plan_3*	23.17
4	*Site_Layout_4*	25.234 * 10^8	*Supply_Channel_4*	0.923 * 10^8	*Security_Plan_4*	19.76
5	*Site_Layout_5*	25.756 * 10^8	*Supply_Channel_5*	1.003 * 10^8	*Security_Plan_5*	22.56
6	*Site_Layout_ 6*	27.871* 10^8	*Supply_Channel_ 6*	0.872 * 10^8	*Security_Plan_ 6*	18.31
7	*Site_Layout_7*	27.098 * 10^8	*Supply_Channel_7*	0.976 * 10^8	*Security_Plan_7*	19.78
8	*Site_Layout_8*	26.120 * 10^8	*Supply_Channel_8*	1.023 * 10^8	*Security_Plan_8*	24.32
9	*Site_Layout_9*	25.876 * 10^8	*Supply_Channel_9*	0.876 * 10^8	*Security_Plan_9*	20.44
10	*Site_Layout_10*	25.139 * 10^8	*Supply_Channel_10*	0.987 * 10^8	*Security_Plan_10*	19.87
11[b]	*Site _Layout _11*[b]	25.036 * 10^8 [b]	*Supply _Channel _ 11*[b]	0.997 * 10^8 [b]	*Security _Plan _ 11*[b]	19.02 [b]
…	…	…	…	…	…	…
32	*Site_Layout_46*	27.913 * 10^8	*Supply_Channel_46*	0.975 * 10^8	*Security_Plan_46*	24.8
33	*Site_Layout_47*	29.234 * 10^8	*Supply_Channel_47*	0.868 * 10^8	*Security_Plan_47*	25.43
34	*Site_Layout_48*	28.432 * 10^8	*Supply_Channel_48*	0.789 * 10^8	*Security_Plan_48*	24.92
…	…	…	…	…	…	…
48	*Site_Layout_48*	25.107 * 10^8	*Supply_Channel_48*	0.899 * 10^8	*Security_Plan_48*	22.09
49	*Site_Layout_49*	27.112 * 10^8	*Supply_Channel_49*	0.899 * 10^8	*Security_Plan_49*	20.76
50	*Site_Layout_50*	26.106 * 10^8	*Supply_Channel_50*	1.038 * 10^8	*Security_Plan_50*	25.21

b Represents the best solution and the underlined is the worst solution.

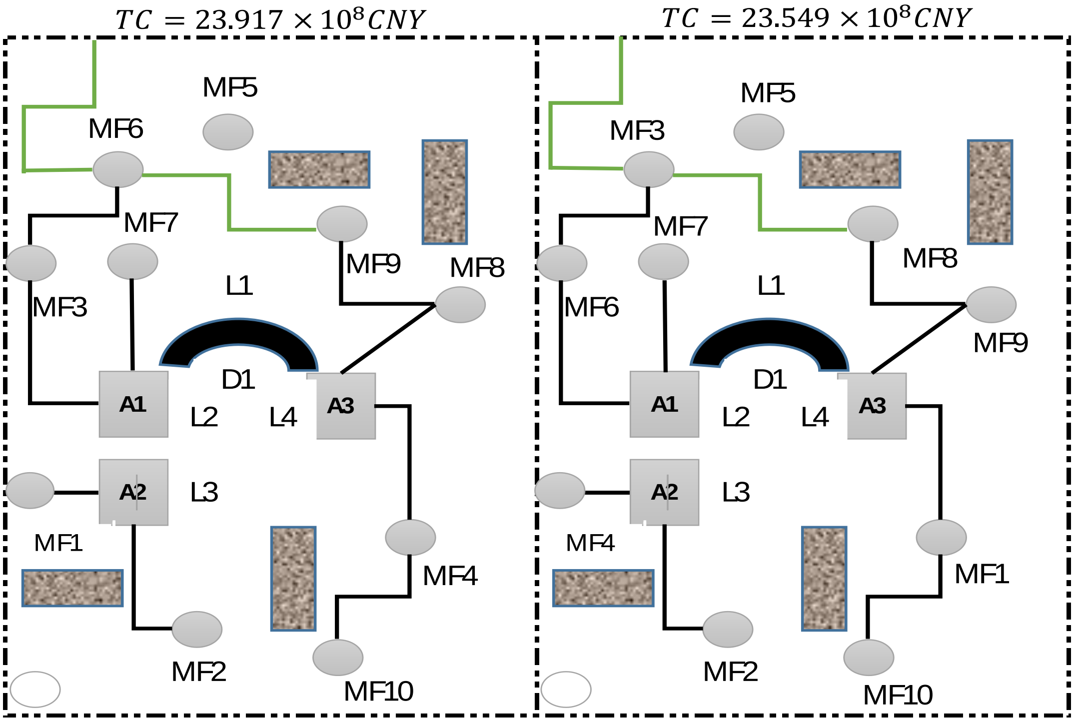


$TC = 24.735 \times 10^8 CNY$

$TC = 21.747 \times 10^8 CNY$

(a) The site layout plan from a multi-stakeholder perspective

(b) The site layout plan from a singular planner perspective



$TC = 23.917 \times 10^8 CNY$

$TC = 23.549 \times 10^8 CNY$

(c) The site layout plan from a bi-stakeholder perspective

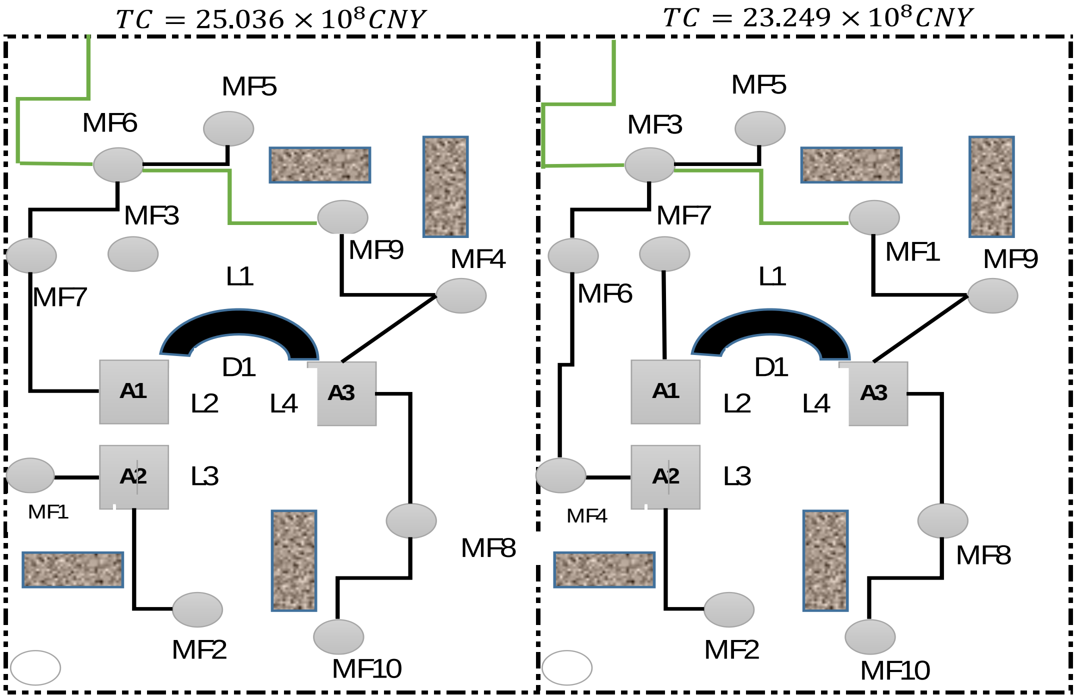
(b) The site layout plan from a bi-stakeholder perspective

Senario 1

Senario 2

▨ denote obstacles

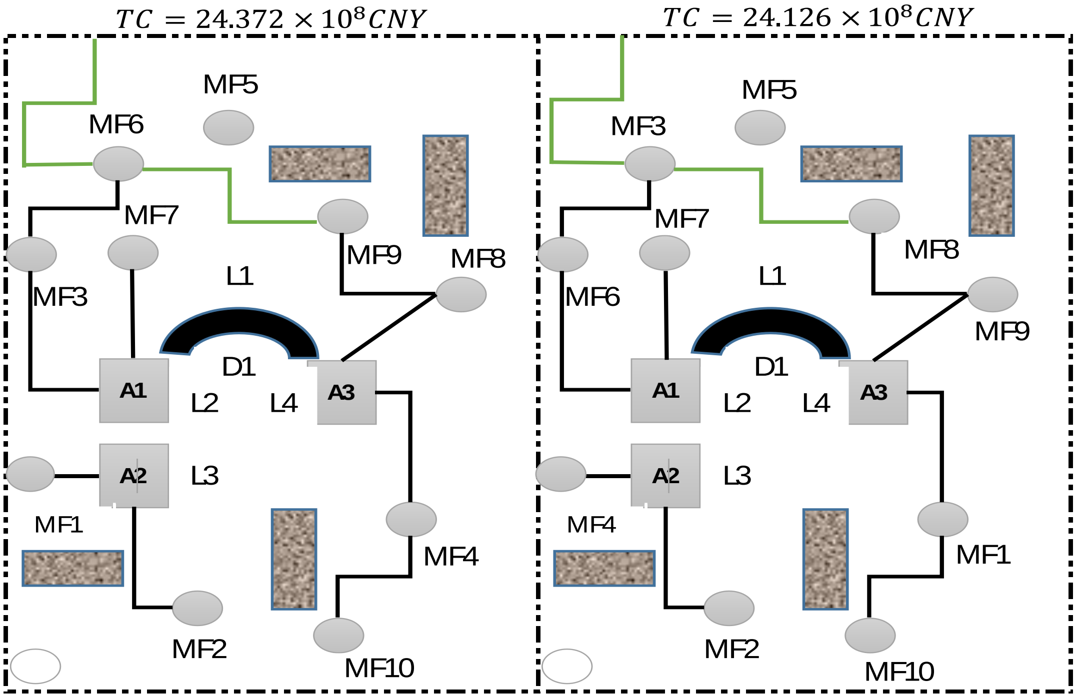
Fig. 3. CSLP solutions by PSO algorithm



$TC = 25.036 \times 10^8 CNY$ $TC = 23.249 \times 10^8 CNY$

(a) The site layout plan from a multi-stakeholder perspective

(b) The site layout plan from a singular planner perspective



$TC = 24.372 \times 10^8 CNY$ $TC = 24.126 \times 10^8 CNY$

(c) The site layout plan from a bi-stakeholder perspective

Senario 1

(b) The site layout plan from a bi-stakeholder perspective

Senario 2

▨ denote obstacles

Fig. 4. CSLP solutions by genetic algorithm(GA)

To better align with practical situations and develop feasible approaches, most previous research on construction site layout planning (CSLP) has focused on the perspective of a single layout planner or project manager. However, recent findings underscore the need to integrate CSLP with other pre-planning tasks through centralized and decentralized approaches when examining the interactions between multiple stakeholders. Motivated by agent-based modeling (ABM) and modified deccan optimization, recent studies have incorporated multi-stakeholder interactions to demonstrate the benefits of the proposed CSLP-CMLP/SP model in addressing practical challenges faced by Layout Planners (LaP), Logistics Planners (LoP), and Safety Managers (SaM).

In this research, computational analyses were conducted to evaluate site layout planning from three perspectives: a single planner, two stakeholders, and multiple stakeholders. The first step involved modifying the integrated CSLP-CMLP/SP model to focus on the single planner's perspective to obtain an optimal solution for comparison purposes. To achieve this, the two hard constraints representing the CMLP and SP problems were removed, meaning that the influence of LoP and SaM activities was no longer considered. The reduced version of the tri-PSO and GA algorithms was then used to generate the decision variables and corresponding objective functions, employing the same parameter combinations as in the full model. The layout plan resulting from this adjustment is graphically depicted in Figures 3 and 4 (b), while Tables 3 and 4 present the LaP's objective function values across various scenarios for both algorithms.

Next, the CSLP problems were evaluated from a bi-stakeholder perspective by integrating CSLP with either CMLP or SP, mirroring the research focus on multi-stakeholder interactions. Two comparison scenarios were developed to assess the extent of influence that CMLP and SP have on CSLP decisions in practical settings. In the first scenario, the CMLP optimization model constraint was retained, while the SP optimization constraint was removed. This allowed for an analysis of how the CMLP affected CSLP decision-making. In the second scenario, the SP optimization model constraint was retained, and the CMLP optimization model constraint was removed to evaluate how the SP influenced CSLP decisions.

The findings from these comparative scenarios revealed the distinct impacts that CMLP and SP have on CSLP decisions. In practical site layout planning, these influences underscore the importance of understanding the interdependencies between logistics planning, security measures, and site layout design. The comparison scenarios provided valuable insights into the extent to which each stakeholder's activities shape the overall planning process, further reinforcing the significance of multi-stakeholder interactions for the successful execution of construction projects.

Table 3: Results for the different planner perspectives. (Data based on the base article) (Song et al., 2019)

Objectives	Perspectives			
	Singular perspective	Bi-stakeholder perspective		Multi-stakeholder perspective
		Scenario 1	Scenario 2	
$TCCSLP$	$21.747 * 10^8 CNY$	$23.917 * 10^8 CNY$	$23.549 * 10^8 CNY$	$24.735 * 10^8 CNY$
Variations to CSLP from a multi-stakeholder perspective	+12.08%	+3.31%	+4.79%	–

CNY is the basic currency unit of the People's Republic of China.

Table 4: Results for the different planner perspectives. (The information of this paper in the genetic algorithm(GA))

Objectives	Perspectives			
	Singular perspective	Bi-stakeholder perspective		Multi-stakeholder perspective
		Scenario 1	Scenario 2	
TCCSLP	23.249 $*10^8$ *CNY*	24.372 $*10^8$ *CNY*	24.126 $*10^8$ *CNY*	25.036 $*10^8$ *CNY*
Variations to CSLP from a multi-stakeholder perspective	+7.14%	+2.65%	+3.63%	–

CNY is the basic currency unit of the People's Republic of China.

The model performed less effectively than the single-planner perspective in terms of results when only the Construction Material Logistics Planning (CMLP) or Site Security Planning (SP) were considered as beneficiaries within the two-stakeholder optimization framework. Despite these suboptimal results, they are considered more applicable to real-world scenarios because they better reflect the complexity of multi-stakeholder interactions. The site layout plans that considered the CMLP and SP constraints are illustrated in Figures 3 and 4 (c) and (d), respectively. Tables 3 and 4 display the results for Scenario 1, which integrates the CSLP-CMLP optimization problem, and Scenario 2, which focuses on the CSLP-SP optimization problem, for the Layout Planner’s (LaP) objective function values.

The generated site layout plans varied across scenarios, and the objective function values from the multi-stakeholder perspective were 2.65% higher than the bi-stakeholder perspective for Scenario ۳،۶۳% ,۱ higher for Scenario 2, and 7.14% higher than the single-planner perspective. These results, derived using the genetic algorithm, showed similar trends when compared with those obtained using the PSO model. Several conclusions can be drawn from this analysis:

Compromise in Optimality: The site layout plan's optimality was compromised due to the failure of involved stakeholders (e.g., LoP, SaM) to achieve individually optimal solutions. This was evident from the variation in CSLP decisions and corresponding objective functions across different scenarios. Increased CSLP Costs: As the number of stakeholders increased, CSLP costs rose accordingly, indicating that the LaP had to make more compromises to address the diverse demands of the stakeholders. Varying Influence of Stakeholders: The bi-stakeholder results from Scenario 1 (CSLP-CMLP) and Scenario 2 (CSLP-SP) showed that the influence of LoP and SaM on LaP differed, suggesting that further investigation is necessary to focus on the most crucial factors when attempting to solve CSLP and other pre-planning tasks simultaneously.

The results from the genetic algorithm, presented in Tables 2 and 4 and Figures 3 and 4, underscore that modeling complex multi-stakeholder interactions in an integrated system can yield more optimal outcomes—by 12.34%—compared to traditional methods, provided correct decision-making processes are employed.

The comparative analysis of the site layout plans generated from single- and bi-stakeholder viewpoints versus those from the multi-stakeholder perspective revealed that the latter was superior. While the objective function values from the multi-stakeholder approach were slightly inferior to those of a single-planner scenario, they were more aligned with the realities of practical projects that involve interdependent stakeholders. The case study began with the hypothesis that conflicts arising during the construction stage could be mitigated if interdependencies were proactively addressed in the planning stage. Failure to resolve these conflicts during planning would likely result in an overly optimistic site layout plan.

The proposed CSLP-CMLP/SP model emphasizes the need for correlating, coordinating, and managing high-level pre-planning tasks to preemptively resolve conflicts before the construction phase begins. However, an increase in the number of stakeholders was associated with a rise in computational complexity, highlighting the need for further research. Future studies should focus on determining the optimal number of stakeholders to involve in multi-stakeholder interaction research without significantly increasing computational complexity while still benefiting from the integration of stakeholder inputs.

CONCLUSION

Construction Site Layout Planning (CSLP) represents one of the most critical challenges in project management, requiring optimal solutions that align with best practices in managing project stakeholders. Stakeholder management is a key component of project management knowledge, and this study focuses on understanding and optimizing the interactions between stakeholders and CSLP to achieve better outcomes. The primary objective of the study was to use meta-heuristic algorithms to optimize the interactions between various stakeholders involved in CSLP and compare the results. In this study, individual stakeholders were modeled as distinct factors within a layout optimization framework, each with specific optimization goals: layout cost, profit, and safety level. The Layout Planner (LaP) was the primary decision-maker, responsible for selecting candidate facility locations and designing the on-site transport network to minimize CSLP costs. The Logistics Planner (LoP) focused on optimizing the material supply channel to maximize profits, while the Safety Manager (SaM) developed a safety and health security plan to minimize the risk of facility attacks. These stakeholder decisions were combined into a bi-level mathematical model, featuring one upper-level decision-maker (LaP) and two lower-level decision-makers (LoP and SaM). Multi-stakeholder dependency models were also analyzed, examining the interaction between CSLP-CMLP and CSLP-SP subsystems. The effects of these multi-stakeholder interactions were then compared with findings from previous studies. Due to the complexity of the model, meta-heuristic Genetic Algorithm (GA) methods were examined and compared with results from earlier studies utilizing random data. Notably, under identical conditions, Particle Swarm Optimization (PSO) produced more optimal results than GA. The study verified the efficiency of the proposed agent-based decentralized model in accounting for multi-stakeholder interaction effects. The model successfully optimized LaP's total layout costs, LoP's profits, and SaM's safety levels concurrently, providing an integrated, practical solution. The findings underscore the importance of focusing on critical project success factors and optimizing interactions to enhance project effectiveness. The results also demonstrated the benefits of integrating multiple stakeholders to arrive at the most advantageous solutions for single stakeholders and dual-beneficiary optimization systems. In particular, for significant projects, combining inputs from a few critical stakeholders can contribute to project success. This research highlights the effectiveness of different algorithms for solving CSLP-related challenges, yielding noteworthy results. Future research could expand the study by introducing additional stakeholders beyond CSLP, CMLP, and SP to examine multi-stakeholder interactions in other executive projects. Furthermore, a cooperative system could be developed to manage pre-planning tasks, using the decentralized bi-level model as an application. A filtration mechanism could also be designed to identify the optimal number of stakeholders based on their degree of influence. While increasing the number of stakeholders may improve practicality, it also introduces additional complexity, making the problem more challenging to solve. In conclusion, this study contributes valuable insights into the role of multi-stakeholder interactions in construction site layout planning, providing a robust framework for optimizing project outcomes through decentralized decision-making models. The proposed approach paves the way for more effective pre-planning and stakeholder management strategies in complex construction projects.

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