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Tabu search-based multi-objective optimization of work package schemes to minimize project costs and carbon emissions

Yaning ZHANG[1][2], Yue TENG[3]*, Xiao LI[4]

[1] *Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong, China,*
[2] *The School of Management, Northwestern Polytechnical University, Xi'an, China,* E-mail address: ya-ning.zhang@connect.polyu.hk
[3] *Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong, China, Corresponding Author,* E-mail address: yue.teng@polyu.edu.hk
[4] *Department of Civil Engineering, The University of Hong Kong, Hong Kong, China,* E-mail address: shell.x.li@hku.hk

Abstract: Effective project planning is essential in construction project management for timely delivery and economic benefit realization. Work packages are pivotal in this planning, providing clear organization and progress tracking. However, existing methods for creating work package schemes often overlook environmental sustainability, specifically carbon emissions—a growing concern in construction. This study introduces a tabu search-based optimization method for work package schemes, aiming to reduce both project costs and carbon emissions. A cost-carbon model is devised, and a tabu search algorithm is developed to identify the Pareto frontier for total project cost and carbon emissions. A case study shows the tabu search outperforms existing heuristics, reducing carbon emissions by 6.19% with a marginal cost increase of 0.9%. The algorithm's adaptability and generalizability suggest it could significantly enhance economic and sustainable outcomes in construction project planning.

Keywords: tabu search, multi-objective optimization, carbon emissions, work package, project planning

1. INTRODUCTION

Construction projects are pivotal to the economic development of countries worldwide and are supported by advanced project management methodologies to ensure their success and benefits [1]. However, they are also major contributors to global carbon emissions [2]. The construction industry is also beginning to consider reducing carbon emissions and achieving sustainability for construction projects [3]. Including, but not limited to, the use of low-carbon building materials [4], optimizing building structure design [5], and employing advanced digital and information construction technology [6]. Project management traditionally focuses on quality, time, and cost, often overlooking emissions [3]. With increasing emphasis on carbon neutrality, project managers now face the challenge of balancing project costs with carbon emissions, adding a new dimension to the management of construction projects.

Project planning is vital in project management, providing a framework for guiding project execution and control. The project plan details the scope, objectives, deliverables, schedules, resources, and risk mitigation strategies to align with stakeholders' expectations and goals [7]. Within this framework, the Work Breakdown Structure (WBS) is a key tool, breaking down a project hierarchically into work packages [8], forming the project's "package scheme." Implementing projects using a work package scheme offers numerous benefits. These consist of explicitly delegating authority and responsibility to designated individuals or groups, simultaneously executing within the boundaries of available resources, enhancing precision in controlling schedules and costs throughout the project, and simplifying risk management [10], [11], [12]. A project involves multiple work package schemes, and creating different work package schemes involves a trade-off in project cost [12]. Existing research has shown that optimizing work package programs can effectively reduce project costs [12], [10]. However, there are still gaps in research regarding how the project's work package scheme affects project carbon emissions.

This study tackles the multi-objective optimization of construction work package schemes, aiming to minimize both costs and carbon emissions. A tabu search algorithm is developed for this purpose, with the following objectives: 1) Model the link between work package schemes and their carbon emissions. 2) Craft a tabu search algorithm to identify the Pareto optimal set for cost and emissions. 3) Assess how carbon emission levels influence project costs within this set. The rest of the atricle is structured as follows: Section 2 reviews literature on carbon emissions, work package creation, and multi-objective optimization in construction management. Section 3 defines the optimization problem of work package schemes. Section 4 details the tabu search algorithm. Section 5 tests the algorithm against a real construction project and compares it with existing heuristics to evaluate its performance and the cost-emissions trade-off. Section 6 concludes the research findings.

2. Literature Review

This study addresses carbon emissions in construction, work package formation, and multi-objective optimization in project management. It assesses current research on construction-related carbon emissions, identifies work packages' roles in emission reduction, and applies multi-objective optimization to balance cost and carbon emissions minimization.

Section 1 establishes the dichotomy of construction projects: they drive economic growth but are also significant sources of carbon emissions [13]. Various mitigation strategies have been proposed, such as employing life cycle assessment (LCA) to quantify and reduce emissions. Integrating Building Information Modeling (BIM) with LCA can streamline embodied carbon assessments in prefabrication, as suggested by Xu et al. [6]. Teng et al. [14] examined inconsistencies in LCA databases and their impact on carbon emissions from construction materials. Structural design and material choices are pivotal in influencing emissions, with Zhang et al. [5] focusing on optimizing module design to reduce embodied carbon (EC). Chen et al. [4] proposed a framework for evaluating low-carbon concrete materials (LCCMs) to lessen environmental impacts. Furthermore, digital technologies are being harnessed to curtail emissions. Despite advancements in project control [3] and scheduling [15] to mitigate carbon emissions. *There is still a gap in research on using WBS to reduce carbon emissions in construction projects during the project planning stage.*

A WBS defines all tasks in a project hierarchy to meet objectives and manage work [16]. Work packages, the WBS's lowest level, are challenging to develop due to the complex decision-making required to group tasks, considering task duration, content, and task interdependencies [9]. Liu et al. [10] introduced an automated sizing technique based on modular construction data to optimize packages for cost savings. Li et al. [12] defined work package sizing challenges, offering heuristic solutions and problem lower bounds. *However, existing research still lacks consideration of the project's carbon emissions in forming work packages.*

In construction projects, the interconnection of elements means that focusing on one objective often impacts others. Multi-objective optimization (MOO) addresses this by optimizing multiple goals simultaneously [17]. MOO approaches fall into two categories: (1) When optimization goals have a clear functional or weighted relationship, they can be amalgamated into a single objective [18]. ((2) When the relationship between goals is uncertain, a range of trade-off solutions, known as the Pareto frontier, is sought [19].*The complexity of these relations underlines the need for an efficient MOO approach for work package optimization, aiming to find the Pareto optimal solutions for both project costs and emissions. Given that the latest work package optimization methods focus on single objectives, typically cost* [12]*, there's a clear incentive to extend these methods to encompass MOO.*

In summary, current research lacks a multi-objective optimization approach for work package schemes that balances project costs and carbon emissions. The proposed tabu search algorithm aims to bridge this gap.

3. Problem statement

This section will describe the work package scheme problem with minimizing project total cost and total carbon emissions [12]. Systematic and comprehensive definitions from a current study will be followed to calculate the project costs of work package schemes. This article will define the variable of *work package efficiency* to calculate the project carbon emissions of the work package schemes.

3.1. Formation of project work package schemes

A project can be represented by a directed acyclic graph $G(N, E)$, where the nodes $N = \{1, \dots, n\}$ represent the *tasks,* and arcs $E \subset N \times N$ represent zero-lag finish-start *precedence relations* between tasks. Each task $a \in N$ has a given *duration* $t_a \geq 0$ and given *work content* $x_a \geq 0$. The beginning and end of the project are dummy tasks, and their work content and duration are both 0. Fig. 1 shows the process of tasks being packaged into work packages. Two constraints are considered in this process: 1) inactive tasks, tasks with special requirements (e.g., risk control), and dummy tasks can only form a single-task work package. For example, tasks 1, 8, and 9 in Fig. 1. 2) The task precedence relations. Since there is a precedence relationship between tasks, there is also a precedence relationship between work packages formed by tasks. There are two main perspectives about precedence relations between work packages [12]. The first is *strict precedence-constrained work packages*. That means that if task a in work package W is a predecessor of task a' in work package W', then all tasks in W precede all tasks in W'. The second is *generalized precedence constrained work packages*. Under this perspective, the processing of work package W and W' may be partially overlapped even though one of the tasks in W is a predecessor of one of the tasks in W'. Since previous research paid more attention to the strict precedence constrained work packages [10], [12]. The generalized precedence-constrained work packages are considered in this article to supplement insights. Based on the above two constraints, the work package scheme formed in Fig. 1 can be recorded as $\{\{1\}, \{2,3,4\}, \{5,6\}, \{7\}, \{8\}, \{9\}\}$.

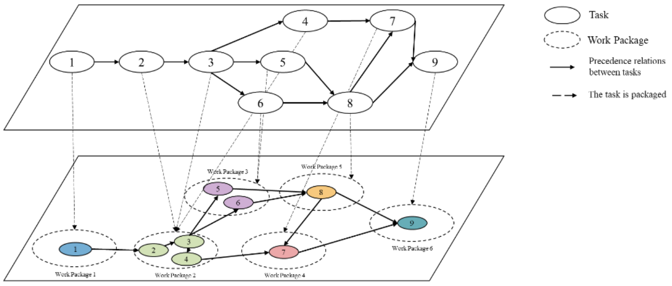


Fig.1 Project tasks are packaged into work packages

3.2. The project costs of work package schemes

The project costs corresponding to the work package schemes have been comprehensively defined in a previous study [12]. These definitions are also used in this article to facilitate comparison of algorithms and results. The project's total cost is equal to the sum of the costs of all work packages formed. The cost of a work package is a function of fixed costs ω, the work content of the work package x_w and the completion time C_W of the work package. That is,

$$TC = \omega(p + m - 2) + \sum_{k=1}^{p} F(x_{W_k}) + \xi \sum_{k=1}^{p} G(x_{W_k}, C_{W_k}) + \sum_{k=1}^{m} F(x_{R_k}) + \xi \sum_{k=1}^{m} G(x_{R_k}, C_{R_k}) \quad (1)$$

TC is the sum of the costs of the total work packages in the project. The cost of a work package consists of three parts: fixed cost ω, work content cost function $F(x_W)$, and cash flow cost function $G(x_W, C_W)$. The meaning of the symbols in the formula is as follows: ω: Fixed costs for one work package. Each work package bears a fixed cos ω, which represents the expenses related to administration and maintenance. Crucially, this cost remains unaffected by the specific contents of the work package; x_{W_k}: Workload of work package, $x_{W_k} = \sum_{a \in W_k} x_a$; C_{W_k}: The completion time of work package. It is equal to the latest task completion time in the work package; p: The number of work packages formed by active tasks; m: The number of work packages formed by inactive tasks; $F(x)$: $F(x)$ is a cost composite function related to the content of the work package, which consists of three functions: Cost and schedule estimation $f(x)$, The cost associated with tracking and managing the progress of the work package is expressed as a function $g(x)$, and The economies of scale, derived from repetition and similarity of tasks within a work package, are expressed as a function $h(x)$. $F(x) = f(x) + g(x) + h(x)$. ξ: A cost of per unit of work content; $G(x_W, C_w)$: The total discounted cash flow cost with discount rate α, $G(x_W, C_w) = \xi x_W(1 - e^{-\alpha C_W})$.

3.3. The project carbon emissions of work package schemes

Unlike project costs, the current studies still lack a generalized definition of the relationship between project carbon emissions and work package schemes. This article calculates the project carbon emissions based on generalized work package work content and time. Calculation details are as follows. The total carbon emissions of the project are the sum of the carbon emissions of each work package E_{W_k}, that is $TE = \sum_{k=1}^{p+m} E_{W_k}$. The carbon emissions of each work package are the carbon emissions per unit of work content of the work package e_{W_k} multiplied by the work content of the work package x_{W_k}, $E_{W_k} = x_{W_k} \times e_{W_k}$. The key to the problem now is to determine per unit of work content of the work package e_{W_k}. This article introduces *work package efficiency* r_{W_k} to calculate e_{W_k}. Work package efficiency comes from the production rate in supply chain management (that is, the number of products produced per unit time). Work package efficiency is the work content completed by the work package within a unit time. is a quadratic function of [20], that is,

$$e_{W_k} = a \cdot r_{W_k}{}^2 - b \cdot r_{W_k} + c = a \cdot \left(\frac{x_{W_k}}{t^*_{W_k}}\right)^2 - b \cdot \frac{x_{W_k}}{t^*_{W_k}} + c \qquad (2)$$

a, b, c are the coefficients of the function. To calculate actual work package efficiency, $t^*_{W_k}$ is the actual time any task in the work package is executing, not the Makespan. As shown in Fig. 2, time gaps (t_2 to t_3) may arise because predecessor tasks may exist in other work packages. The actual execution time of a work package $t^*_{W_k}$ is the work package makespan minus all time gaps. In summary, the total carbon emissions of the project are calculated as shown in Eq. (3).

$$TE = \sum_{k=1}^{p+m}\left(a \cdot \frac{x^3_{W_k}}{t^*_{W_k}} - b \cdot \frac{x^2_{W_k}}{t^*_{W_k}} + c \cdot x_{W_k}\right) \qquad (3)$$

4. Tabu search algorithm for finding Pareto frontier

Optimizing the work package schemes is a complex optimization problem [12]. This problem is further complicated by multi-objective optimization, which considers project costs and carbon emissions. Metaheuristic algorithms have become effective in solving complex optimization problems due to their high efficiency. This article proposes a tabu search algorithm to optimize work package solutions and identify the Pareto frontier of project costs and carbon emissions. Tabu search is a neighborhood-based metaheuristic widely utilized in project planning and scheduling. This section provides the details of the tabu search algorithm, including the encoding of the work package scheme, neighborhood actions, tabu list, and iterative process.

4.1. Encoding of the work package scheme

Encoding a solution to an optimization problem involves representing the solution in a systematic and simplified format that an algorithm can easily process, such as binary strings, numbers, or symbols. This enables the algorithm to efficiently navigate through potential solutions to find the best one based on the optimization criteria. A sequence of integers is used to encode the work package scheme, and the length of the sequence is the number of tasks in the project . Each position in the sequence represents each task in the project. The value in each position represents the work package number to which the task is assigned. All tasks in the project can form up to work packages. The first work package is recorded as 0, so the set of work package numbers is a set of integers .

4.2. Neighborhood actions

In tabu search, a *neighborhood action* refers to slight modifications or changes to a current solution to generate a neighboring solution, which is a slightly altered variant of the original. Neighborhood actions play a crucial role in systematically exploring the solution space to find an optimal or improved solution by transitioning from one potential answer to another while avoiding cycles and local optima. The proposed tabu search algorithm incorporates three neighborhood actions: (1) task transfer, (2) task exchange, and (3) task independence.

(1) Action 1: Task transfer

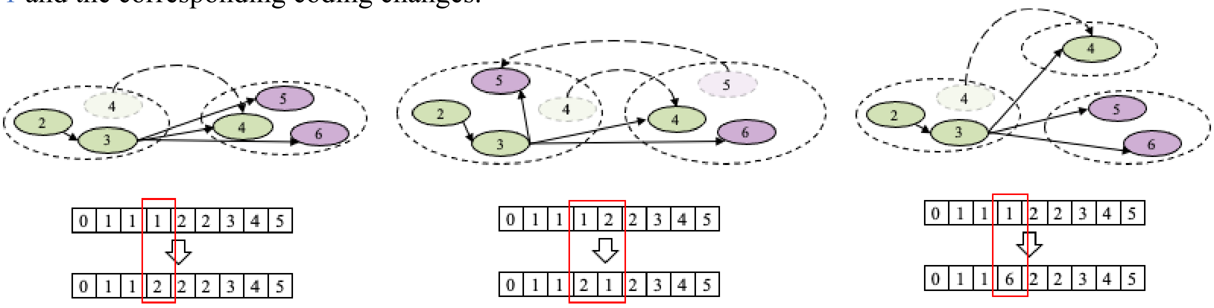
Task transfer refers to transferring an active task from the current work package to another. The new work package to which the task is transferred cannot be the same as the inactive task's work package. Fig. 2 (a) illustrates the process of task transfer of task 4 in Fig. 1 and the corresponding coding changes.

(2) Action 2: Task exchange

Task exchange is when any two active tasks located in different work packages exchange the work packages in which they are located. Fig. 2 (b) illustrates the process of task exchange of task 4 and task 5 in Fig. 1, along with the corresponding coding changes.

(3) Action 3: Task independence

Task independence refers to the separation of an active task from the original work package to create a new work package. The execution of task independence requires two prerequisites: (1) The original work package containing the task must have at least two tasks. Otherwise, the task independence will not generate a new solution; (2) The number of work packages in the current solution is less than the maximum. Otherwise, new work packages cannot be added, and the neighborhood action will become action 1 task transfer. Fig. 2 (c) illustrates the process of task independence for task 4 in Fig. 1 and the corresponding coding changes.



(a) Task transfer (b) Task exchange (c) Task independence

Fig. 2 Neighborhood actions

4.3. Tabu list

The tabu list in tabu search is a short-term memory structure that records recently visited solutions or actions, marking them as “tabu” to prevent the algorithm from revisiting them. Its role is to help the algorithm avoid cycling back to previous solutions, thereby promoting the exploration of new areas in the solution space and potentially escaping local optima. The tabu list of the proposed tabu search algorithm records the searched solutions. Recording solutions simplify the tabu mechanism because checking against a list of complete solutions is often more straightforward than evaluating a complex sequence of individual actions or partial solution attributes.

4.4. Iterative process

The following describes the multi-objective tabu search algorithm adapted for minimizing carbon emissions and cost. It uses a tabu list to avoid cycling and its systematic exploration of the solution space to update an approximated Pareto frontier incrementally.

Step 1 Initialization: The algorithm begins by initializing its parameters, which include an empty tabu list, an empty set for the Pareto frontier, and the iteration counter with a value of 0. **Step 2 Initial solution generation**: An initial solution is generated randomly. This solution is evaluated to determine its associated carbon emissions and cost, which are then used to update the Pareto frontier, reflecting the trade-offs between the objectives. **Step 3 Neighbor solution generation**: A set of neighboring solutions is produced in each iteration through predefined actions that slightly modify the current solution. These actions are subject to the condition that their solutions have not been marked tabu, preventing the algorithm from revisiting recent solutions. **Step 4 Evaluation and selection**: A neighbor is considered superior if any solution in the Pareto frontier does not dominate it. Considering that cost is still the objective that project stakeholders are more concerned about, the search direction is to reduce costs. The solution with the lowest cost among the neighbors is selected for the next iteration. **Step 5 Updating the current solution and tabu list**: If the best neighbor is identified, the current solution is updated to this new solution, and the solution is added to the tabu list. After the tabu list reaches the preset length, it is updated by “first in, first out (FIFO),” keeping the length of the tabu list constant. **Step 6 Pareto frontier update**: The Pareto frontier is incrementally updated with non-dominated solutions throughout the iterations. **Step 7 Convergence**: The algorithm proceeds through the predetermined number of iterations. The Pareto frontier, which contains the final set of non-dominated solutions, is obtained during the iteration process.

5. Case project experiment

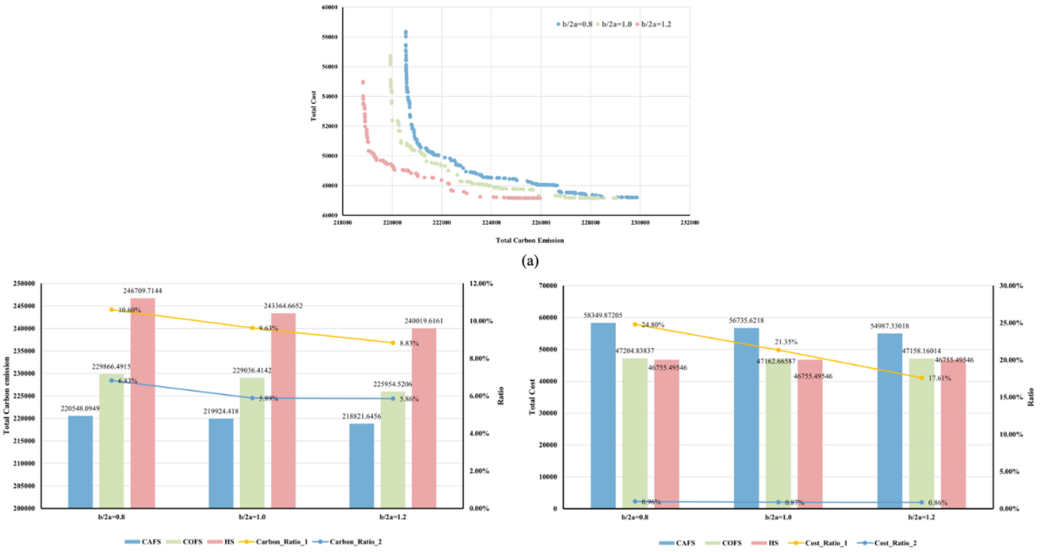
5.1. Data preparation

The initial task information for the project, including task durations, task work content, and precedence relations between tasks, is obtained from a construction project in Shenzhen, China. This is a modular construction project consisting of five towers, each 28-29 stories, comprising a total of 6028 modules. The entire construction process, from module production to installation, is adapted into the original work package scheme, which consists of 289 tasks[i]. The proposed tabu search algorithm aims to optimize the work package schemes to identify the Pareto frontier of the total project cost and total carbon emissions. The parameters of the problem model also need to be set. In the total cost function, to facilitate the comparison of the performance of different algorithms, the parameter settings in previous research are also used in this article. Details can be found in [12]. I In the total carbon emission function, a, b, and c need to be set in advance. Obviously, the project has the lowest carbon emissions when the work package efficiency is equal to $b/2a$. To comprehensively evaluate the performance of the proposed models and algorithms in different project scenarios, $b/2a$ is set to 1.0, 0.8, and 1.2, respectively, to represent scenarios under different progress modes.

Hyperparameters in tabu search, such as the neighborhood size, the length of the tabu list, and the termination condition, influence the algorithm’s balance between exploration and exploitation in the search space. Proper tuning of these hyperparameters is crucial for determining the efficiency and effectiveness of the search. It significantly impacts the algorithm’s ability to escape local optima and find near-optimal solutions within a reasonable computational time. Based on previous research and empirical testing, the hyperparameter values are finally determined. The size of the neighborhood, the length of the tabu list, and the maximum generations are 289, 289, and 10000, respectively.

5.2. Experiment results and analysis

The Pareto frontier of the total project cost and total carbon emissions, obtained by the proposed tabu search algorithm in the three modes, is shown in Fig. 3 (a). Furthermore, state-of-the-art heuristics [12] are used to obtain a work package scheme with near-minimum cost. This scheme is referred to as “HS”. It is compared with the work package schemes on the Pareto frontier that have the lowest carbon emissions and the lowest cost to evaluate the performance of the tabu search algorithms. The work package scheme with the lowest carbon emissions is referred to as the “Carbon emission friendly scheme (CAFS).” The work package scheme with the lowest cost is referred to as the “Cost friendly scheme (COFS).” The comparison results are shown in Fig. 3 (b)(c).



(a)

(b)

(c)

(a) The Pareto frontier;(b) The total carbon emission and decrease ratio of CAFS, COFS, and HS under three modes;(c) The total costs and increase ratio of CAFS, COFS, and HS under three modes
Fig. 3 Comparative results of CAFS, COFS, and HS. “Carbon_ratio_1” is the ratio of carbon emissions decreased by CAFS compared to HS. “Carbon_ratio_2” is the ratio of carbon emissions decreased by CAFS compared to HS. “Cost_ratio_1” is the ratio of cost increased by COFS compared to HS.

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[i] The WBS is provided in https://github.com/Paperwor/Tabu_search_MOO.

"Cost_ratio_2" is the ratio of cost increased by COFS compared to HS.

The comparative experimental results in Fig. 3 (b)(c) fully illustrate the effectiveness of the proposed tabu search algorithm, which is specifically reflected in the following three aspects: (1) Compared with HS, multi-objective optimization with additional consideration of the total carbon emissions of the project effectively reduces carbon emissions. In the obtained Pareto frontier, CAFS can reduce the project's total carbon emissions by approximately 9.69% on average. Even COFS can reduce carbon emissions by approximately 6.19% on average. (2) Compared with HS, the proposed algorithm reduces carbon emissions while also considering the project cost. Especially in COFS, the project's total carbon emissions are reduced by approximately 6.19% on average, while the project cost is only increased by approximately 0.9% on average. The proposed multi-objective optimization algorithm achieves significant carbon emission reduction at a minimal cost. (3) The proposed algorithm achieves very close carbon emission optimization performance under three different modes: standard, delay, and rush. This finding proves that the algorithm can effectively reduce carbon emissions for different values of and , reflecting the outstanding generalization of the algorithm.

Furthermore, the experimental results also demonstrate the phenomenon of a marginal increase in cost during the process of reducing carbon emissions. From COFS to CAFS, Although the average carbon emission decrease ratio increases from 6.19% to 9.69%, the average cost increase ratio increases from 0.9% to 21.25%. As the project's total carbon emission reduction increases, more additional costs need to be paid.

6. Conclusion

Construction project planning serves as a strategic guide for timely, on-budget, and specification-compliant project completion. Work packages divide the project into manageable segments, enabling detailed planning, resource allocation, and project monitoring. This research introduces a multi-objective optimization model for balancing "project total cost" with "project total carbon emissions" in work package schemes. A tabu search algorithm is proposed to navigate the Pareto frontier between cost and emissions, employing task transfer, exchange, and independence as strategies for solution exploration, with cost minimization guiding the search. A case study validates the algorithm's effectiveness, showing the Pareto optimal "Cost-friendly scheme" reduces carbon emissions by 6.19% for a small cost uptick of 0.9% compared to leading heuristics. The algorithm's adaptability to standard, delay, and rush work modes reveals its potential to enhance the economic and environmental sustainability of construction projects.

Future research opportunities arise from this article's preliminary examination of the relationship between work package attributes, such as content and duration, and their associated carbon emissions. A more granular analysis is warranted to deepen the understanding of this correlation. Additionally, while this study focused on work packages with simplified precedence constraints, further exploration is needed into optimizing carbon emissions in work packages governed by stringent precedence constraints.

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