Bundling Strategies for Routine Expressway Maintenance Projects with Similarity Thresholds

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Abstract: This study explored the bundling of routine expressway maintenance projects by utilizing project similarity to achieve economies of scale. Although existing studies have introduced methods for measuring similarity, limited theoretical research has addressed the issue of the optimal bundling scale across different project types. To fill this gap, this study developed a bundling decision-making model based on combinatorial optimization theory and designed a greedy algorithm for its solution. By introducing a similarity threshold, bundling schemes with varying levels of similarity were generated, and evaluation indicators are proposed to assess their effectiveness. A case study of 41 expressway maintenance segments under the jurisdiction of the Provincial Expressway Group Company was conducted to validate the model. The results indicate that different similarity thresholds lead to significantly distinct bundling schemes, requiring a comprehensive consideration of management needs, market competition, and contract execution capacity. The findings suggest that an optimal scheme should strike a balance between economies of scale and management coordination, with expert adjustments made when necessary. This study adds to the body of knowledge by introducing a novel quantitative framework and solution approach for project bundling decisions, providing valuable implications for improving resource allocation efficiency and economic performance. **DOI: 10.1061/JCEMD4.COENG-18202**. *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, https://creativecommons.org/licenses/by/4.0/.*

Author keywords: Project bundling; Routine expressway maintenance; Combinatorial optimization; Similarity threshold; Decision-making model.

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Introduction

Project bundling in highway management has received increasing scholarly attention, particularly regarding its economic benefits. Recent studies classified these benefits into three major categories: economies of scale, competitive economies, and bundling economies.

1. Economies of scale. As project size expands, both single- and multiproject contracts tend to exhibit scale effects, leading to reductions in unit costs (Qiao et al. 2018, 2019b; Xiong et al. 2017). A larger contract size lowers the proportion of fixed costs to total costs, stimulates greater market competition, and ultimately drives down bid prices (Damnjanovic et al. 2008). In addition, bundling improves procurement efficiency by enlarging the scale and scope of purchasing, which helps reduce common expenses such as bidding, supervision and management costs (Estache and Iimi 2025). Empirical evidence suggests that bundling can achieve project cost savings of up to 20% (Shrestha et al. 2022).
2. Competitive economies. Although scale expansion can generate benefits, excessively large bundled contracts may deter smaller contractors from participating, thereby reducing the number of bidders and potentially increasing bid prices. Hence, contract size must be carefully determined—not too large, in order to maintain competition, and not too small, to preserve economies of scale (Qiao et al. 2018, 2019d, 2021; Shrestha et al. 2022; Xiong et al. 2017). Xiong et al. (2017) identified the optimal contract size for different project types based on historical data analysis: approximately 1,858 m^2 (20,000 ft^2) for bridge projects and 16–32 lane-km (10–20 lane-mi) for pavement projects. Qiao et al. (2019b) developed a probabilistic model to explore the relationship between project size and market competition, and found that contracts bundling two to four projects tend to attract the largest pool of bidders.
3. Bundling economies. Beyond scale and competition, bundling provides contractors with greater flexibility to allocate resources such as materials, equipment, and labor across multiple projects. This enhances the management efficiency, reduces the risk of project delays, minimizes traffic disruptions, and lowers traffic maintenance costs. Qiao et al. (2019c) constructed regression models to quantify traffic maintenance costs across different project types and found that bundling significantly reduced the costs of bridges, pavements, roadside safety facilities, and miscellaneous projects. Other studies have extended bundling research further by integrating organizational arrangements into bundling strategies. For example, bilevel optimization models have been developed to jointly consider bundling strategies and construction scheduling, thereby reducing agency management and user costs (Miralinaghi et al. 2022; Saneii et al. 2023).

Overall, the literature demonstrates that the economic benefits of project bundling are multifaceted, but highly contingent on the design of appropriate bundling strategies. Although economies of scale, competitive dynamics, and resource synergies can yield

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substantial efficiency gains, poorly designed bundling schemes may undermine these benefits. Thus, determining the optimal bundling strategies remains an important research gap. Bundling strategies must address two fundamental questions: (1) Which projects should be bundled together?; and (2) What is the optimal scale of projects to be included in a single contract?

With respect to the first question, Assaf and Assaad (2023) highlighted project similarity as one of the core and most critical decision factors in implementing bundling strategies, suggesting that a high degree of project relatedness is a necessary precondition for bundling. Existing approaches to measuring project similarity generally can be categorized into three groups: case-based reasoning methods (Hyung et al. 2019; Li et al. 2020; Niu et al. 2020; Wang 2012), ontology-based methods (Bi et al. 2021; Li et al. 2022; Torkanfar and Azar 2020; Chen 2018), and bill-of-quantities–based methods (Do et al. 2023; Qiao et al. 2019c). These approaches have been applied in construction cost estimation (Hyung et al. 2019; Li et al. 2020; Niu et al. 2020; Chen 2018; Wang 2012), project bundling (Do et al. 2023; Qiao et al. 2019c), and other domains of project management (Bi et al. 2021; Li et al. 2022; Torkanfar and Azar 2020). Qiao et al. (2019a) proposed a method for calculating project similarity based on the composition of bill items, arguing that projects with a higher proportion of common items were more similar. They also developed a model to calculate the average similarity among multiple projects, providing theoretical guidance for bundling decisions.

However, Do et al. (2023) pointed out that relying solely on the proportion of common bill items might overlook semantic similarities. For example, hot-mix asphalt paving of different thicknesses may be recorded as separate bill items owing to differences in the dimensions and unit prices, although their work content is essentially the same. To address this limitation, Do et al. (2023) advanced the model by integrating natural language processing and introducing a cost-weighted term frequency-inverse document frequency (CW-TF-IDF) method to more precisely assess project similarity. Quantitative comparative results further confirmed that the CW-TF-IDF method markedly enhances project clustering performance compared with the most recent state-of-the-art techniques.

The aforementioned quantitative similarity method primarily focuses on project content, reflecting asset types and maintenance categories. However, when designing project bundling schemes, it is equally important to consider geographical proximity (Assaf and Assaad 2024; Qiao et al. 2019a; Ridderstedt and Nilsson 2023; Shrestha et al. 2022; Xiong et al. 2017), as well as road classification, technical condition, and traffic volume, which capture the essential attributes of maintenance projects (Assaf and Assaad 2024; Qiao et al. 2019a). Generally, geographically adjacent and physically connected projects are better positioned to share resources such as equipment, personnel, and traffic management systems, thereby reducing coordination and transportation costs. Likewise, similarity in project attributes enhances the homogeneity of bundled projects and contributes to economies of scale. Accordingly, this study employed an integrated similarity index that combines four dimensions—geographical proximity, route connectivity, basic project information, and maintenance content—to guide the bundling analysis.

Although previous studies have proposed methods for measuring project similarity, existing research still cannot precisely address the fundamental questions of bundling: which projects should be grouped together, and at what level of similarity are projects appropriate for bundling? To bridge this gap, this study introduces the concept of a similarity threshold that serves as a decision criterion for determining whether projects are sufficiently similar to be bundled into a single contract. On this basis, a second issue must also be considered: bundled projects not only are expected to share technical or structural similarities, but must also achieve a balance between economies of scale and economies of competition.

Regarding the second question, Xiong et al. (2017) analyzed historical data and identified the optimal contract sizes for bridge and pavement projects. However, these findings are influenced by regional price levels and project types, making them context-specific and not universally applicable. For example, the optimal bundling scale for routine maintenance and rehabilitative maintenance projects in different regions inevitably will vary owing to differences in local price levels as well as project characteristics and scope. Therefore, the determination of the optimal bundling scale must be tailored to the project attributes and the economic context of the study area. In China, the long-cycle, area-based maintenance model has been adopted for expressway routine maintenance, aiming to achieve economies of scale by bundling routine maintenance projects. However, current practices typically rely on administrative boundaries or management units as the basis for bundling, and no quantitative methodology has yet been developed to systematically determine optimal bundling schemes.

In this study, a bundling strategy for routine expressway maintenance projects was developed by integrating similarity measurement and optimal scale considerations. The paper first introduces a decision-making model designed for maintenance project bundling, together with the corresponding solution algorithm and evaluation criteria. The proposed methodology was applied to a real-world case involving 41 routine maintenance projects managed by Provincial Expressway Group Company (PEGC), generating practical bundling solutions. Subsequently, the results of the case analysis are presented and discussed. Finally, the study concludes with key findings and provides recommendations for future research.

Research Methodology

In the management of routine expressway maintenance, projects often are bundled for tendering to optimize the allocation of maintenance resources and achieve economies of scale. The core of this problem lies in selecting from a finite set of projects, and those with the highest degree of similarity will be bundled into a single contract (Assaf and Assaad 2023). In other words, the average similarity of projects within each contract should be maximized to better integrate resources, improve efficiency, and reduce costs. In addition, to realize scale benefits while maintaining a healthy level of market competition, contract size should not be excessively large or small (Qiao et al. 2019a). Therefore, the bundling problem for routine expressway maintenance projects can be formally described as identifying, from a finite project set, all feasible combinations that satisfy the contract-size constraints while maximizing the objective function, i.e., the average similarity of projects within each contract. This formulation places the problem within the combinatorial optimization domain.

Combinatorial Optimization Model for Project Bundling

Problem Description and Variable Definition

Given a set of routine expressway maintenance projects, each project is characterized by a specific scale and a defined degree of similarity with other projects. The research objective is to partition these projects into a number of contract bundles (subsets) such that

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1. intracontract synergy is maximized: the average similarity of projects within the same contract is as high as possible; and
2. economies of scale and market competition are balanced: the scale of each contract is subject to certain constraints.

The variables required for the formulation of this combinatorial optimization model, along with their definitions, are summarized in the "Notation" section.

Model Formulation

In project bundling decision-making, projects with high similarity should be grouped into the same contract; that is, the objective is to maximize the sum of the average similarities of all contracts (Assaf and Assaad 2023). Accordingly, the decision variable is the project-partitioning scheme, which is the determination of a set of contract bundles. The objective function can be expressed as

$$\text{maximize}_C \sum_{c_p \in C} AS_{c_p} \tag{1}$$

The average similarity of projects (AS_{c_p}) within a contract is calculated using Eq. (2). The permissible range of the number of projects ($|c_p|$) included in each contract is given by Eq. (3). Because similarity is defined as a pairwise measure between two projects, the average similarity within a contract is meaningful only when the number of projects ($|c_p|$) is at least two. When a contract contains fewer than two projects (i.e., only a single project), its average similarity is defined as zero

$$AS_{c_p \in C} = \begin{cases} \dfrac{\sum_{i<j \in c_p} \text{Sim}(i,j)}{C^2_{|c_p|}}, & |c_p| \geq 2 \\ 0, & |c_p| < 2 \end{cases} \tag{2}$$

$$|c_p| \in \{1, 2, 3, \ldots, n\} \tag{3}$$

where $C^2_{|c_p|}$ = number of project pairs within the contract, which can be calculated using

$$C^2_{|c_p|} = \frac{|c_p|(|c_p| - 1)}{2} \tag{4}$$

For any given contract, to achieve economies of scale and maintain a competitive bidding environment, the total project scale included in each contract must lie within a prescribed range, where $l_{\min}$ is the minimum and $l_{\max}$ is the maximum allowable scale. This constraint can be expressed as

$$l_{\min} \leq \sum_{i \in c_p} l_i \leq l_{\max}, \quad \forall c_p \in C \tag{5}$$

In addition, all projects must be selected, that is, no project can be left unassigned. Moreover, different contracts must be mutually exclusive, meaning that each project can appear in only one contract, and no overlap between the two contracts is permitted. These requirements are formulated respectively as

$$\bigcup_{p=1}^{k} c_p = P \tag{6}$$

$$c_p \cap c_q = \emptyset, \quad \forall p \neq q \tag{7}$$

Solution Algorithm for the Project Bundling Problem

Algorithm Overview

The project bundling problem investigated in this study can be described as partitioning a set of n projects into any number of nonempty subsets (contracts). Essentially, this problem belongs to the category of set partitioning problems, which have been proven to be nondeterministic polynomial (NP-hard) (Garey and Johnson 2009; Yu et al. 2013; Qu 2022). The number of possible partitioning schemes in the project bundling problem corresponds to the Bell number in combinatorics, denoted B_n. For example, for a set of $n = 3$ projects, there are five feasible partitioning schemes. In general, B_n can be formally defined as

$$B_n = \sum_{k=0}^{n} S(n,k) \tag{8}$$

where $S(n,k)$ denotes the Stirling number of the second kind (Graham et al. 2017), that is, the number of ways to partition a set of n elements into k nonempty subsets. The general term for the Bell number can be expressed as (Zhang et al. 2020)

$$S(n,k) = \frac{1}{k!} \sum_{i=0}^{k-1} (-1)^i C^i_k (k-i)^n \tag{9}$$

In the project bundling problem, the number of contracts can range from one (all projects bundled into a single contract) to n (no bundling). Combining Eqs. (8) and (9), it is evident that when the number of projects becomes large, exhaustive enumeration or exact methods suffer from the curse of dimensionality, making them impractical for solving bundling problems. This study adopted a greedy algorithm—an efficient approximation method for combinatorial optimization—rather than metaheuristic techniques such as genetic algorithms, simulated annealing, or particle swarm optimization. Although metaheuristics exhibit strong global search capabilities, their high computational demands, extensive parameter tuning, and stochastic nature reduce transparency and interpretability. Given the discrete, multiconstrained nature of the maintenance project bundling problem, such algorithms would significantly increase model complexity. In contrast, the greedy approach provides transparent, stable, and computationally efficient solutions, making it well suited for practical, time-sensitive decision-making in highway maintenance management.

Greedy Algorithm

The greedy algorithm is an approach that selects the locally optimal solution at each decision stage to obtain or approximate the global optimum (Cormen et al. 2009). Owing to its high computational efficiency, intuitive implementation and interpretability, it has been widely applied to various optimization problems. The core idea of the greedy algorithm is to decompose a complex problem into a series of smaller subproblems and make the optimal choice at each stage based on local information, thereby gradually constructing a feasible overall solution. Although the greedy algorithm typically does not guarantee a global optimum because it focuses only on the best choice at each stage, it is simple, easy to implement, and capable of producing near-optimal solutions within a reasonable computational time. Moreover, its solution accuracy is relatively high; the approximation ratio to the theoretical optimum can reach a provable bound, and even in the worst case, the greedy algorithm achieves at least 63% of the global optimal value (Wang et al. 2025).

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Applied to the project bundling problem in this study, the greedy strategy essentially represents a stepwise decision-making process: projects with high similarity are bundled first, and other projects subsequently are merged within acceptable limits to gradually construct contracts and form feasible bundling schemes. Compared with other heuristic methods, the greedy algorithm does not require complex parameter tuning. At each step, it selects the project that maximizes the contract's average similarity, while simultaneously checking the contract size constraints. This ensures a more straightforward decision-making process that aligns with practical management logic.

However, a limitation of the greedy algorithm is that prioritizing locally optimal bundling decisions at each stage may overlook their impact on subsequent contracts. That is, projects with the highest similarity are bundled first, thereby restricting the availability of high-similarity projects for subsequent contracts. Furthermore, excessive emphasis on satisfying contract size constraints may sacrifice the average similarity within contracts, ultimately influencing the overall bundling outcome.

To mitigate this limitation, a similarity threshold θ was introduced during the constraint validation stage. A contract is accepted only if its average similarity value exceeds a predefined threshold. By adjusting this threshold, different bundling schemes can be generated, enabling decision makers to evaluate the advantages and disadvantages of various alternatives based on project-specific conditions. This enhances the scientific rigor and practical rationality of bundling decisions.

Evaluation Indicators of Bundling Schemes

To investigate the characteristics of bundling schemes under different similarity thresholds θ, we define several evaluation indicators, including the total number of contracts k_r, intercontract dissimilarity CYD_r, intracontract consistency YZD_r, average scale cost elasticity EL_r, proportion of cross-company contracts KUA_r, and the proportion of contracts not meeting scale constraints NSC_r. The indicator for the proportion of cross-company contracts is designed based on the management model of Chinese expressways. A highway management authority typically oversees multiple subsidiary companies, each responsible for managing several road segments (Table 1). Such divisions are assigned administratively rather than organically.

Intercontract dissimilarity is defined as the average similarity among all contracts within a bundling scheme. This measure reflects whether the contracts in the bundling scheme maintain sufficient differentiation. The similarity between the two contracts can be calculated using Eq. (10), and the intercontract dissimilarity of the bundling scheme can be obtained using Eq. (11)

$$AS_{c_p,c_q} = \frac{\sum_{i \in c_p}\sum_{j \in c_q}\mathrm{Sim}(i,j)}{|c_p| \times |c_q|} \tag{10}$$

$$CYD_r = \frac{\sum_{p<q} AS_{c_p,c_q}}{k_r(k_r-1)/2} \tag{11}$$

where AS_{c_p,c_q} = similarity between contracts p and q; $|c_p|$ = number of road segments contained in contract p; $\mathrm{Sim}(i,j)$ = aggregated similarity between road segments i and j; CYD_r = intercontract dissimilarity of a bundling scheme; and k_r = total number of contracts in bundling scheme r.

Intracontract consistency is defined as the average of the mean similarity values within all contracts in a bundling scheme. This indicator reflects the overall coordination of the scheme and can be calculated using

$$YZD_r = \frac{\sum_{p=1}^{k_r} AS_{c_p}}{k_{r,|c_p|\geq 2}} \tag{12}$$

where YZD_r = intracontract consistency of bundling scheme r; and $k_{r,|c_p|\geq 2}$ = number of contracts containing at least two road segments in bundling scheme r.

Average scale cost elasticity is defined as the mean of the scale cost elasticities across all contracts in a bundling scheme. This measure reflects the overall economies of scale achieved by the

Table 1. Basic information of highways under jurisdiction of PEGC

Subsidiary number	Segment number	Mileage (km)
1	1	80.739
	2	82.279
	3	118.404
	4	178.484
	5	203.483
2	6	37.808
	7	44.662
	8	21.303
	9	58.400
3	10	196.037
	11	223.891
4	12	209.837
	13	26.029
	14	1.902
	15	13.091
	16	14.318
	17	23.614
5	18	40.380
	19	147.293
	20	88.289
6	21	199.682
	22	17.631
	23	1.302
7	24	180.912
8	25	83.304
	26	71.976
	27	24.194
9	28	62.078
	29	102.044
10	30	32.362
	31	108.637
11	32	127.023
12	33	86.369
	34	35.687
13	35	120.278
14	36	99.207
15	37	86.393
16	38	16.964
	39	55.252
17	40	52.499
	41	13.45

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scheme. The average scale cost elasticity for a given bundling scheme can be calculated using

$$EL_r = \frac{\sum_{p=1}^{k_r} EL_{c_p}}{k_r} \tag{13}$$

where EL_r = average scale cost elasticity of the bundling scheme r; and EL_{cp} = scale cost elasticity of contract p. The scale cost elasticity (EL) represents the percentage change in routine maintenance cost resulting from a 1% change in project scale. When $EL < 1$, a 1% increase in project scale leads to less than a 1% increase in maintenance cost, indicating the presence of economies of scale. When $EL > 1$, it suggests diseconomies of scale, because the maintenance cost increases more than proportionally with project size. Therefore, $EL = 1$ denotes the critical point between economies and diseconomies of scale.

The proportion of cross-company contracts is defined as the ratio of the number of contracts involving cross-company management to the total number of contracts within the bundling scheme. This indicator reflects the bundling scheme's managerial complexity. This can be calculated using

$$KUA_r = \frac{n_{kua}}{k_r} \times 100\% \tag{14}$$

where KUA_r = proportion of cross-company contracts in bundling scheme r; and n_{kua} = number of contracts involving cross-company management.

The proportion of contracts violating scale constraints is defined as the ratio of the number of contracts that do not satisfy scale constraints to the total number of contracts within a bundling scheme. This can be calculated using

$$NSC_r = \frac{n_{nsc}}{k_r} \times 100\% \tag{15}$$

where NSC_r = proportion of contracts violating scale constraints; and n_{nsc} = number of contracts that fail to meet the scale constraints.

Case Study

Overview of the Case Project

PEGC manages 3,837 km of expressways across the province through 17 subsidiaries responsible for the outsourced maintenance of 41 segments. These segments were assigned to different subsidiaries over time as the network expanded, mainly based on the physical connectivity of road segments. The basic information is provided in Table 1. This study conducted a bundling decision analysis for the 41 expressway segments under PEGC's jurisdiction.

To represent the geographical distribution of the 41 road segments, the longitude and latitude coordinates of the toll stations (or service areas) were used as the spatial indicators of each segment.

The average coordinate value was adopted for a road segment with multiple toll stations or service areas. The spatial distribution of the 41 road segments is shown in Fig. 1. Furthermore, the distribution is visualized based on the geometric centroid coordinates (longitude and latitude) of all road segments in Fig. 2, in which each point represents a road segment, and road segments managed by the same subsidiary company are marked with identical symbols.

The similarity among the 41 expressway segments was quantified using a weighted integrated similarity index that incorporates

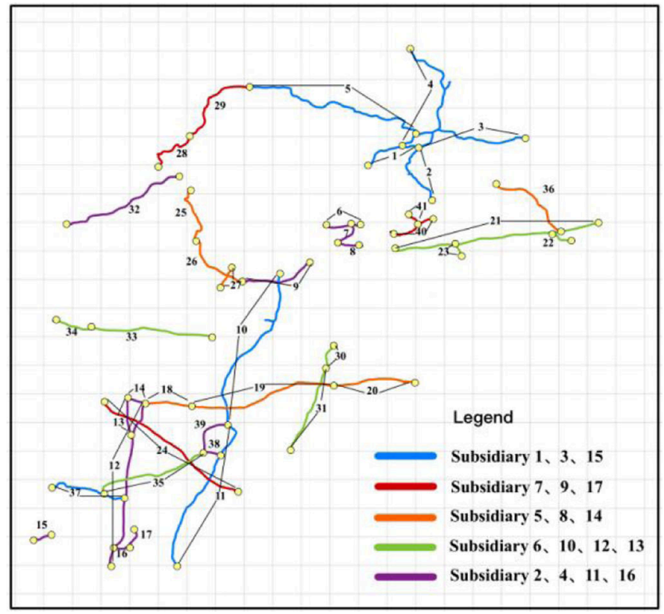

Fig. 1. Spatial distribution of highway segments under the jurisdiction of PEGC.

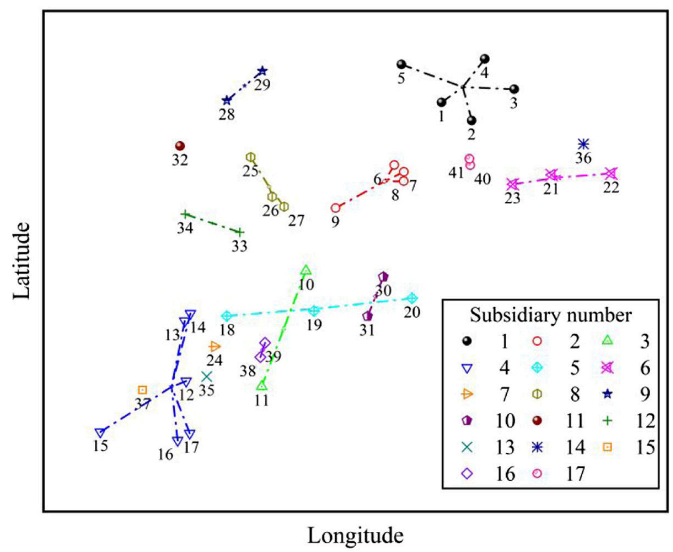

Fig. 2. Geometric center coordinate distribution of road segment.

four key dimensions: geographical proximity, segment connectivity, basic project information, and maintenance content. Geographical proximity was determined using the geometric centroid coordinates of each segment to construct spatial feature vectors. Segment connectivity was represented by a binary (0–1) vector indicating whether two segments are physically linked within the expressway network. Basic project information was characterized by variables relevant to routine expressway maintenance, including the proportions of bridges and tunnels, the annual average daily traffic (AADT), and the maintenance quality index (MQI). These low-dimensional numerical features were analyzed using the Minkowski distance to measure similarity. Maintenance content similarity was calculated from the bill of quantities (BoQ) using the CW-TF-IDF–based cosine similarity method proposed by Do et al. (2023). Because the present study primarily focused on the influence of similarity thresholds on project bundling outcomes,

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Table 2. Integrated similarity data of top 50 pairs of road segments

Rank	Segment pair	Sim(i, j)
1	38–39	0.9321
2	16–17	0.9137
3	40–41	0.8908
4	33–34	0.8870
5	2–3	0.8864
6	26–27	0.8861
7	30–31	0.8805
8	3–4	0.8785
9	7–8	0.8774
10	13–14	0.8699
11	6–7	0.8674
12	19–20	0.8547
13	28–29	0.8526
14	1–2	0.8512
15	21–23	0.8450
16	25–26	0.8428
17	21–22	0.8307
18	1–3	0.8270
19	10–11	0.8075
20	1–4	0.8033
21	11–24	0.7989
22	18–19	0.7944
23	4–5	0.7943
24	12–16	0.7652
25	12–13	0.7620
26	10–19	0.7546
27	19–31	0.7507
28	35–37	0.7251
29	6–8	0.7145
30	6–9	0.7123
31	1–5	0.7094
32	14–18	0.7070
33	12–37	0.6944
34	2–4	0.6752
35	14–16	0.6737
36	12–35	0.6661
37	11–38	0.6642
38	9–10	0.6634
39	24–35	0.6623
40	12–24	0.6562
41	8–9	0.6528
42	11–39	0.6474
43	13–15	0.6444
44	13–24	0.6434
45	10–39	0.6416
46	25–27	0.6366
47	2–5	0.6298
48	5–29	0.6287
49	14–17	0.6276
50	35–38	0.6253

only a concise summary of the composite similarity computation is presented here. In total, 820 pairs of similarity values were generated, ranked in descending order; the top 50 pairs listed in Table 2.

Based on the PEGC's historical expenditure data and following the approach of Xiong et al. (2017), the relationship between the scale cost elasticity EL and road segment length L was established [Eq. (16)]. Scale cost elasticity decreases with increasing route length [Eq. (16)]. Setting $EL = 1$ gives $L = 154$ km, the threshold between economies and diseconomies of scale; thus, 150 km was adopted as the minimum contract bundling scale. Analysis of the first derivative of Eq. (16) indicates that beyond $L = 290$ km, the curve flattens, suggesting that economies of scale have stabilized. Therefore, 290 km was considered to be the upper limit for the bundling contract scale

$$EL = 4.03 - 0.6014 \times \ln L \qquad (16)$$

Case Project Modeling

The bundling problem of routine maintenance projects under PEGC's jurisdiction can be described as follows. Given 41 expressway routine maintenance segments, denoted as the set $P = \{1, 2, \ldots, 41\}$, each segment has a defined length and a set of integrated similarity values with other segments. These constitute a length set $L = \{l_1, l_2, l_3, \ldots, l_{41}\}$ and a segment-pair similarity set (sorted in descending order) $S = \{\mathrm{Sim}(i,j)_1, \mathrm{Sim}(i,j)_2, \mathrm{Sim}(i,j)_3, \ldots, \mathrm{Sim}(i,j)_{820}\}$. The decision objective was to partition the 41 segments into nonempty, mutually disjoint contracts, forming a contract set $C = \{c_1, c_2, c_3, \ldots, c_k\}$, such that the sum of the average similarities across all k contracts was maximized while satisfying certain constraints. To examine the effects of different similarity thresholds on bundling schemes, this study defined the similarity threshold following the approach of Torkanfar and Azar (2020). The threshold was assigned a value of 0 and values between 0.5 and 0.8 in increments of 0.05, resulting in the set $\theta = \{0, 0.5, 0.55, 0.6, 0.65, 0.7, 0.75, 0.8\}$. These thresholds defined the minimum similarity level required for projects to be bundled into the same contract, and generated a series of alternative bundling schemes. The schemes ranged from loose bundling at lower threshold levels, which leads to larger contracts, to strict bundling at higher threshold levels, which leads to smaller contracts.

The objective function and constraints of the bundling problem are formulated as Eqs. (1)–(7). For any contract containing at least two candidate projects, the average similarity must exceed a given threshold θ for projects to be bundled into the same contract, and this requirement is expressed by Eq. (17). Accordingly, eight alternative bundling schemes were generated for comparative evaluation

$$AS_{c_p} \geq \theta, \quad \forall\ c_p \in C(|c_p| \geq 2) \qquad (17)$$

Greedy Algorithm Solution Procedure

To illustrate the decision-making process more intuitively, a flowchart depicting the solution procedure for the expressway routine maintenance project bundling problem based on the greedy algorithm is presented in Fig. 3.

Results and Discussion

Results and Analysis of Bundling Schemes

The bundling schemes obtained under different similarity thresholds were visualized by plotting the distribution of highway segments in each scheme, as well as bar–line charts illustrating the total contract scale and average similarity within contracts (Figs. 4 and 5).

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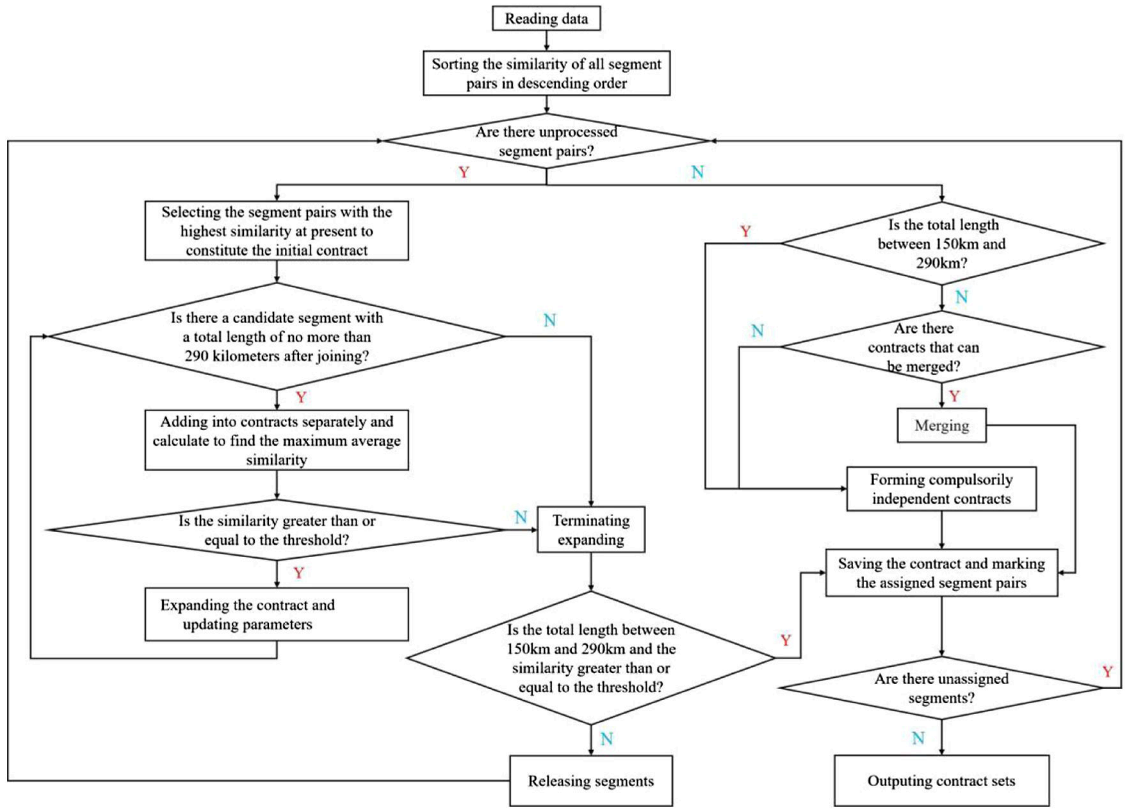

Fig. 3. Flowchart of greedy algorithm solution.

Fig. 4 illustrates the spatial distribution of road segments within the contracts under different similarity thresholds. Segments belonging to the same contract are represented by identical symbols and are connected by dashed lines. When the similarity threshold was low, the spatial distribution of segments within contracts was relatively dispersed, indicating that under low-threshold conditions, bundling schemes tend to form large-scale, cross-regional contracts. As the similarity threshold increased, the segments within contracts gradually became more concentrated, reflecting a stronger tendency to group into highly similar segments. However, the number of contracts consisting of a single segment also increased. This trend demonstrates the spatial evolution of different bundling schemes: low thresholds favor large-scale, cross-regional contracts, whereas high thresholds result in more-compact contracts, enhancing intracontract coordination but reducing the overall economies of scale.

Fig. 5 presents the variation in the total contract scale and average intracontract similarity under different similarity thresholds using a combined bar-line chart. When θ was set to 0, 0.5, 0.65, and 0.7, 13 contracts met the scale constraint; when θ was 0.55, 0.6, and 0.8, 12 contracts met the constraint; and when θ was 0.75, 11 contracts met the constraint. This indicates that the distribution of scale-compliant contracts remains relatively balanced across different similarity thresholds. However, the total number of contracts increased from 13 at $\theta = 0$ to 27 at $\theta = 0.8$, reflecting the influence of stricter similarity requirements on contract fragmentation.

At $\theta = 0.5$ and 0.65, 10 contracts simultaneously satisfied both the scale and similarity constraints, and three additional single-segment contracts met the scale condition. This outcome arose because the greedy algorithm must satisfy both the scale and similarity thresholds during optimization. For segments that are relatively long or have low similarity with others, further merging would either exceed the scale limit or reduce the average similarity. Consequently, the algorithm tends to assign these as independent contracts. Similarly, at $\theta = 0.7$ and 0.75, nine and eight contracts, respectively, met both constraints, accompanied by five single-segment contracts that met only the scale constraint. The emergence of such single-segment contracts reflects segments with distinct characteristics, such as limited geographical proximity or connectivity, or specialized maintenance requirements, that hinder effective bundling. In these cases, managerial judgment is essential to determine whether these segments should remain independent or be manually integrated into other bundles.

Evaluation of Bundling Schemes

The results of the six evaluation indicators for bundling schemes, as defined in the section "Evaluation Indicators of Bundling Schemes," are summarized in Table 3. To provide a more intuitive understanding of the impact of similarity thresholds on bundling outcomes, the evaluation indicators of different schemes under various thresholds were visualized. Fig. 6(a) presents the two indicators, k_r and EL_r, which characterize scale properties, and Fig. 6(b) shows the remaining four indicators. By comparing the evaluation values across schemes, the analysis offers practical insights for determining the similarity threshold and selecting the most suitable scheme for the PEGC's actual bundling applications.

Table 3 and Fig. 6 indicate the following:

1. Variation in the total number of contracts (k_r): The number of contracts increased significantly with higher similarity thresholds. This indicates that under low-threshold conditions, the similarity requirements among segments are relatively relaxed, allowing more segments to be merged into larger contracts. By contrast, higher thresholds impose stricter similarity requirements, permitting only highly similar segments to be grouped together, which leads to more but smaller contracts. Therefore,

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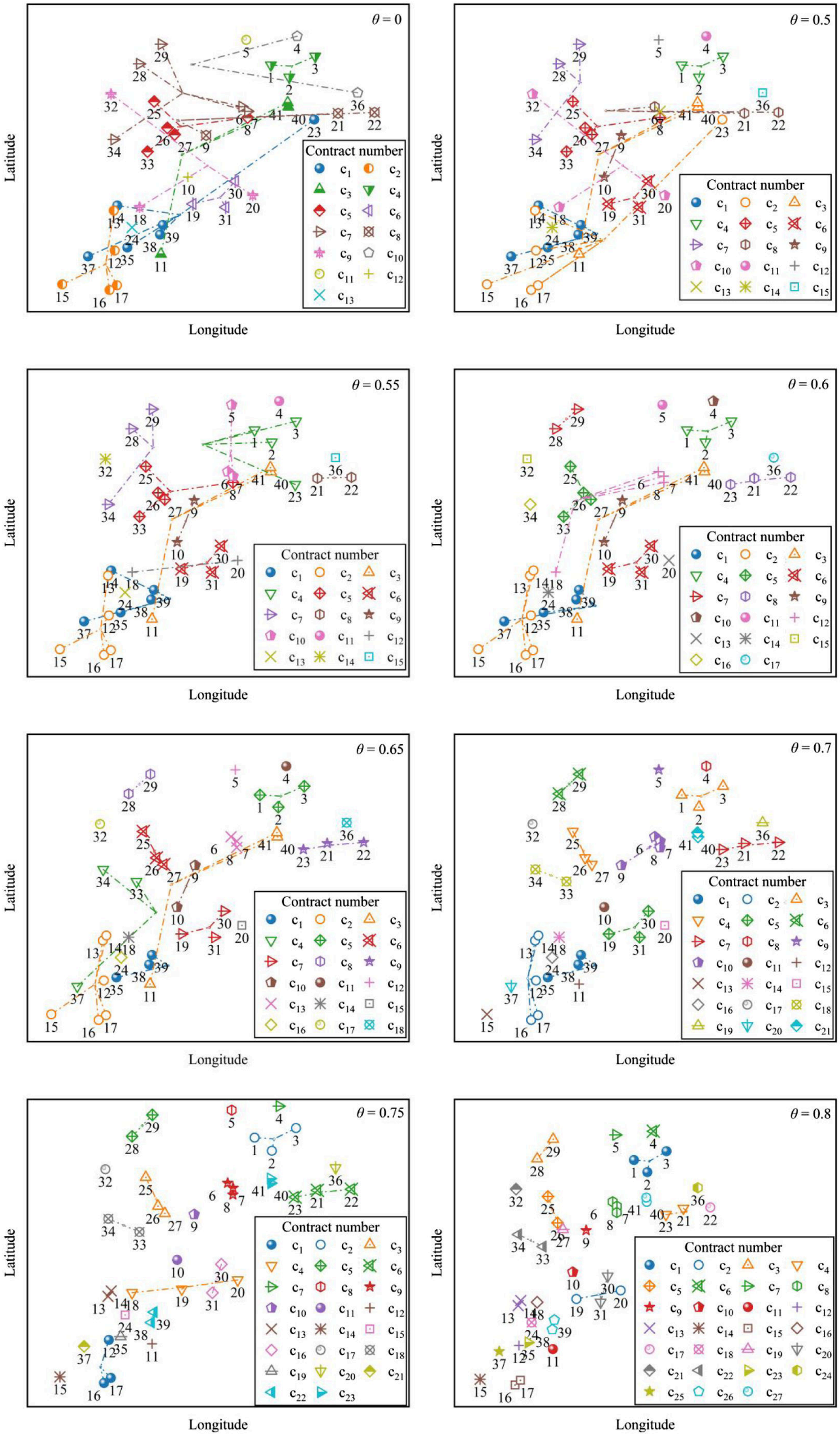

Fig. 4. Distribution of road segments with different bundling schemes.

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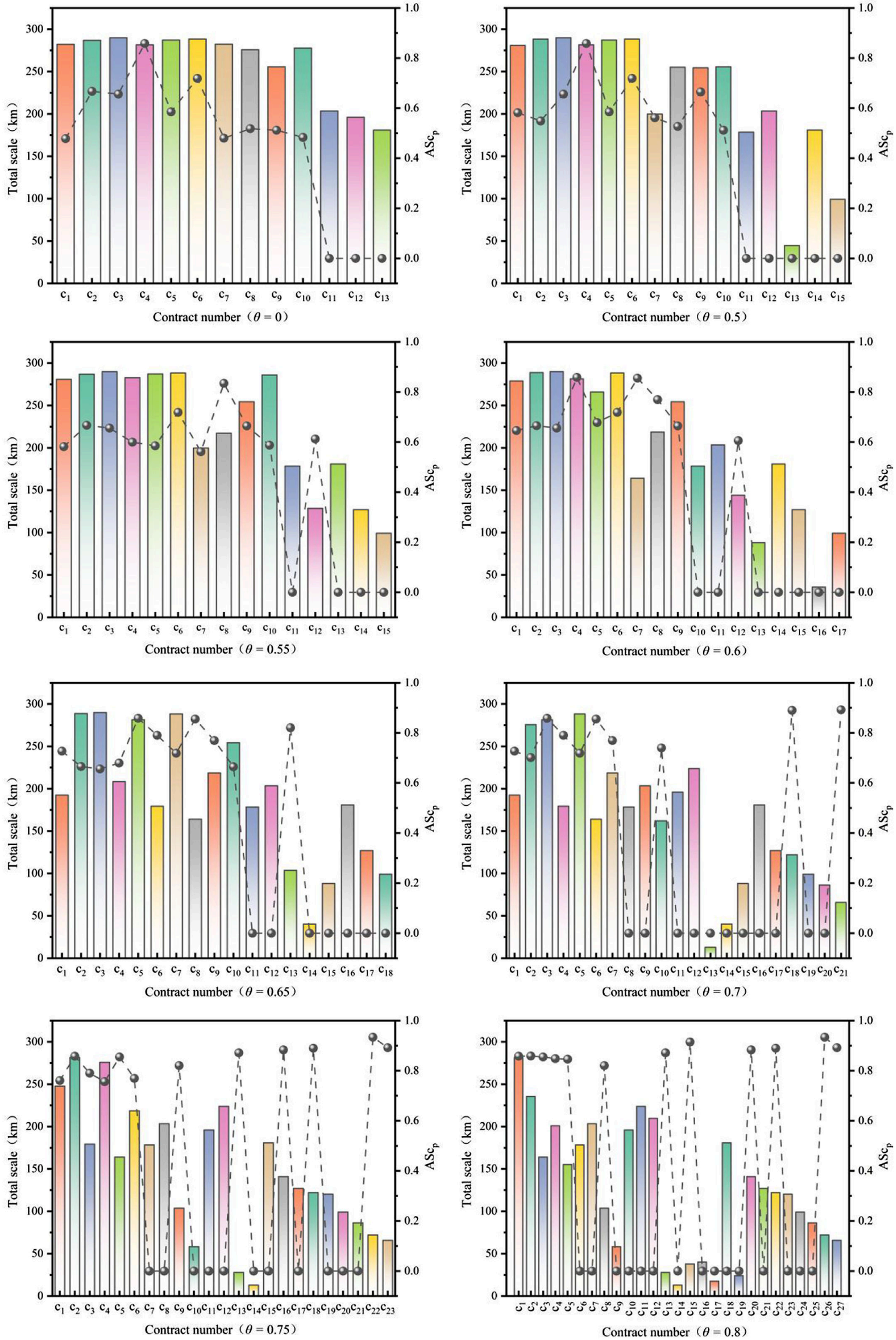

Fig. 5. Bar–line chart of total contract size and average similarity within contracts for different bundling schemes.

Table 3. Evaluation for bundling schemes under different similarity thresholds

Bundling scheme	θ	k_r	EL_r	YZD_r	CYD_r	KUA_r (%)	NSC_r (%)
1	0	13	0.6918	0.5956	0.4362	62	0
2	0.5	15	0.8245	0.6213	0.4269	60	13
3	0.55	15	0.8029	0.6426	0.4137	53	20
4	0.6	17	0.9153	0.7117	0.4188	35	29
5	0.65	18	0.9423	0.7459	0.4177	28	28
6	0.7	21	1.0808	0.7942	0.4305	10	38
7	0.75	23	1.1443	0.8401	0.4331	0	52
8	0.8	27	1.2859	0.8727	0.4314	0	59

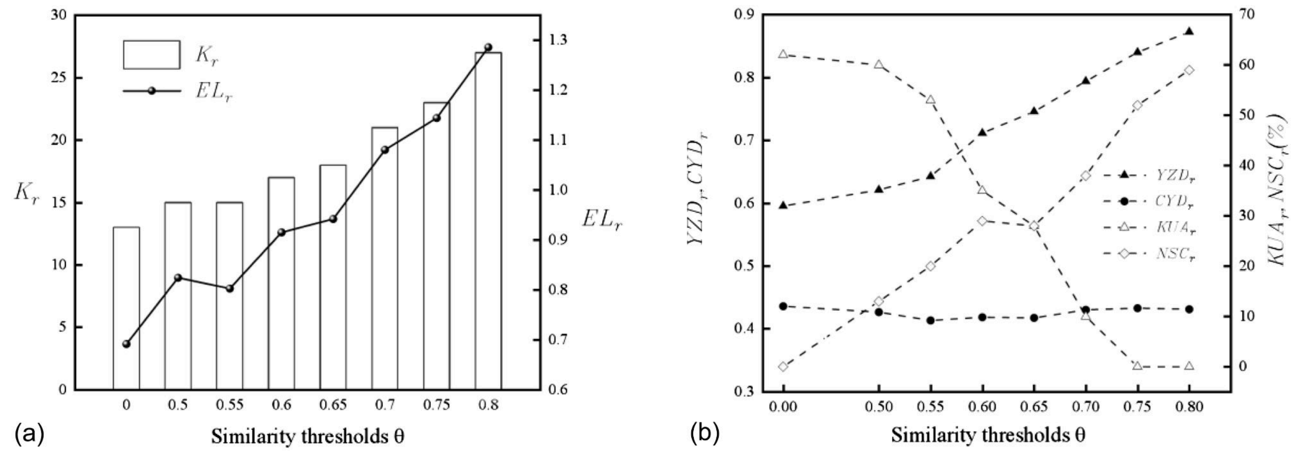

Fig. 6. Variation trends of evaluation indicators across different schemes.

low thresholds facilitate the formation of large-scale contracts, enhancing economies of scale but potentially weakening intracontract coordination, whereas high thresholds emphasize coordination but may result in excessively small contracts, increasing management costs and complexity.

2. Variation in average scale cost elasticity (EL_r): The average scale cost elasticity increased with the similarity threshold. This is because higher thresholds lead to more small-scale contracts, thereby reducing the average contract size and weakening the overall economies of scale of the bundling scheme. When the similarity threshold reached or exceeded 0.7, the average scale cost elasticity exceeded 1, indicating the onset of diseconomies of scale.
3. Variation in intracontract consistency (YZD_r): Intracontract consistency increased steadily as the similarity threshold increased, indicating a gradual improvement in the internal coordination of the bundling scheme. This trend occurs because stricter thresholds allow only highly similar segments to be bundled in the same contract. Thus, although high thresholds improve contract-level coordination, they also restrict contract size, thereby reducing economies of scale.
4. Variation in intercontract dissimilarity (CYD_r): The average intercontract similarity exhibited only minor changes across different thresholds. Although intracontract similarity increased with the threshold, the overall similarity among the contracts remained relatively stable. This suggests that the bundling decision process is robust: regardless of the threshold selected, the intercontract similarity does not fluctuate dramatically. These results demonstrate that the greedy algorithm consistently achieves stable optimization under varying constraints, confirming the robustness and applicability of the proposed bundling decision model.
5. Variation in the proportion of cross-company contracts (KUA_r): As the similarity threshold increased, the proportion of intercompany contracts gradually decreased. When the similarity threshold exceeded 0.7, no intercompany contract bundling occurred. This indicates that, under higher similarity requirements, contract aggregation tends to occur within a single company rather than across different companies. This change may partially reduce the management costs associated with coordinating multiple entities and help improve the standardization of contract execution.
6. Variation in the proportion of contracts not meeting scale constraints (NSC_r): This proportion increased as the similarity threshold increased, implying that stricter similarity requirements produce more small-scale contracts. Although higher thresholds improve intracontract similarity, they simultaneously generate more undersized contracts, which may hinder market competition.

Discussion of Bundling Schemes

Although the bundling schemes generated by the greedy algorithm achieved predefined objectives and satisfied all constraints, practical management of routine highway maintenance is often complex and dynamic. Decision models cannot fully capture all the real-world factors (e.g., single segments that satisfy neither the scale constraint nor the similarity constraint). Therefore, in actual applications, it sometimes is necessary to fine-tune the algorithmic results based on engineering experience to ensure that

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Table 4. Basic information of Scheme 6

c_p	Segments	Total scale (km)	AS_{c_p}
c_1	35, 38, 39	192.494	0.727
c_2	12, 13, 14, 16, 17	275.7	0.7013
c_3	1, 2, 3	281.422	0.858
c_4	25, 26, 27	179.474	0.7903
c_5	19, 30, 31	288.292	0.7187
c_6	28, 29	164.122	0.8551
c_7	21, 22, 23	218.615	0.7694
c_8	4	178.484	0
c_9	5	203.483	0
c_{10}	8, 9, 6, 7	162.173	0.74
c_{11}	10	196.037	0
c_{12}	11	223.891	0
c_{13}	15	13.091	0
c_{14}	18	40.308	0
c_{15}	20	88.289	0
c_{16}	24	180.912	0
c_{17}	32	127.023	0
c_{18}	33, 34	122.056	0.89
c_{19}	36	99.207	0
c_{20}	37	86.393	0
c_{21}	40, 41	65.949	0.892

the advantages of data-driven decision-making are complemented by the adaptability required in real-world management.

The case study results indicate that the bundling scheme generated with a similarity threshold of 0.7 provided the best overall balance. The resulting contract size aligns with the findings of Qiao et al. (2019a), who reported that contracts comprising two to four projects attract the largest number of bidders. This result also is consistent with the findings of Torkanfar and Azar (2020), who demonstrated that similarity thresholds between 0.7 and 0.75 yield optimal retrieval performance in work breakdown structure–based similarity assessments across multiple construction project types. Because the integrated similarity index in this study incorporates maintenance content that is closely related to the project work breakdown structure, these findings provide external, data-driven support for the selected threshold. Accordingly, Scheme 6, corresponding to a similarity threshold of 0.7, was identified as the optimal bundling scheme, and its basic information is presented in Table 4.

Contract 13 (c_{13}) had a total length of only 13.901 km (Table 4). Managing this small contract independently would result in resource inefficiency, rendering it unsuitable for practical implementation. Notably, Segment 15 in c_{13} and Segments 12, 13, 14, 16, and 17 in c_2 are all under the jurisdiction of Subsidiary company 4. Therefore, Segment 15 was reassigned to c_2. The changes in the scheme evaluation indicators before and after adjustment are summarized in Table 5, in which the difference ratio is defined as the ratio of the difference between the adjusted and original values to the original value.

The results in Table 5 reveal the following:

1. Improved contract scale and efficiency: After Segment 15 was merged into c_2, the total scale of the contract increased to 288.791 km, which remained within the optimal scale range. The total number of contracts decreased from 21 to 20. This adjustment mitigates resource inefficiency associated with small-scale contracts, reduces contract fragmentation, and enhances management efficiency.
2. Slight reduction in intracontract similarity but manageable in practice: The average similarity within c_2 decreased by 5.09% after incorporating Segment 15. However, because the new and original segments have the same management authority (Subcompany 4), the negative impact of reduced similarity can be offset through coordinated management during actual maintenance.
3. Stable intercontract differentiation: Intercontract dissimilarity increased by only 0.16%, indicating minimal impact on the overall contract division. Intracontract consistency remained stable, confirming that despite the reduced similarity in c_2, the adjusted scheme maintained strong feasibility in terms of coordinated maintenance operations.
4. Enhanced economies of scale: The average scale cost elasticity decreased from 1.0808 to 1.0085, moving closer to 1. The number of contracts that did not meet the scale constraint decreased by one, and the proportion decreased from 38% to 35%. This suggests that the adjusted scheme achieves stronger economies of scale overall.
5. Minor impact on cross-company contracts: The number of cross-company contracts remained unchanged at two. However, as the total number of contracts decreases, their proportion increases slightly. The effect is negligible, because Segment 15 already belongs to Subcompany 4, meaning that the adjustment does not introduce additional cross-company coordination issues.
6. Balanced contract scale distribution and market implications: Using 150 km as the threshold, the ratio of large-scale (>150 km) to small-scale contracts (<150 km) was 13:7. This indicates a more balanced allocation of contract sizes, ensuring that large firms can leverage economies of scale to enhance efficiency and competitiveness, and medium- and small-sized enterprises have reasonable market entry opportunities. Such a balance prevents market monopolization by a few large firms, enhances market vitality, and contributes to the sustainable development of maintenance marketization.

Table 5. Comparative results of evaluation indicators for Scheme 6 before and after adjustment

Scheme characteristic	Before adjustment	After adjustment	Difference ratio (%)
Total scale of c_2 (km)	275.7	288.791	4.75
AS_{c_2}	0.7013	0.6656	−5.09
k_6	21	20	−4.76
CYD_6	0.4305	0.4312	0.16
YZD_6	0.7924	0.7906	−0.23
E_6	1.0808	1.0085	−6.69
Number of cross-company contracts	2	2	0
KUA_6 (%)	9.5	10	5.26
Number of contracts not meeting scale constraints	8	7	−12.50
NSC_6 (%)	38	35	−7.89

In summary, the adjusted scheme aligns better with practical requirements, striking a balance between management efficiency, economies of scale, market competition, and maintenance coordination. Thus, it demonstrates strong feasibility for real-world implementation.

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Conclusions

This study formulated the bundling problem of routine highway maintenance projects as a combinatorial optimization problem. A decision-making model was developed with the objective of maximizing the average project similarity, subject to optimal scale constraints, and a greedy-based algorithm was designed to solve it. To overcome the inherent limitations of the greedy algorithm, a similarity threshold was introduced as an additional constraint, and the resulting bundling schemes were evaluated from six perspectives. Considering the complexity and dynamic nature of routine maintenance management, this study proposes and demonstrated the necessity of manual adjustments to the selected optimal scheme to ensure that the advantages of data-driven analysis are complemented by practical management experience.

The results indicate that the similarity threshold has a significant effect on bundling schemes. When the threshold is relatively low, larger contracts are allowed, enabling economies of scale. However, these contracts often suffer from poor internal coordination and higher management complexity. Conversely, as the threshold increases, internal consistency and coordination improve, and the number of cross-company contracts decreases, enhancing contract executability. However, this also leads to more small-scale contracts, reducing economies of scale and increasing management costs. Therefore, in practice, the selection of the similarity threshold should comprehensively consider the management requirements, market competition, and contract execution capacity to achieve a balance between economies of scale and management coordination, thereby improving the overall efficiency of highway maintenance. Although the greedy algorithm produces schemes that meet the preset objectives and constraints, real-world conditions are more complex, necessitating manual fine-tuning of the schemes to adapt them to practical management requirements.

This study contributes to the body of knowledge by presenting a novel quantitative framework and solution approach for project bundling decisions, addressing the key questions of which projects should be bundled together and at what similarity level bundling is appropriate. The proposed methodology offers valuable insights for enhancing resource allocation efficiency and economic performance. Practitioners applying this decision-support model should note the following:

1. The comprehensive similarity measure integrates geographical proximity, segment connectivity, basic project information, and maintenance content, tailored to routine highway maintenance projects. For other project types, factors and weights can be adjusted according to project characteristics.
2. The optimal contract scale range was determined from the management authority's perspective to stimulate market competition and achieve economies of scale. Contractor capacity was not considered, and the range is context-dependent; practitioners should define appropriate sizes based on local data and project contexts.
3. A similarity threshold of 0.7 was selected as optimal, but threshold choice should be treated as a strategic decision, balancing multiple delivery considerations rather than applying a fixed value.

Overall, the model functions as a flexible, context-aware decision-support tool, combining systematic analysis with managerial judgment to accommodate diverse organizational and project-specific requirements. Future work could integrate contractor capabilities and their alignment with contract requirements to account for contractor heterogeneity in bundling decisions.

Data Availability Statement

Some or all the data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

Xiaoli Shi: Conceptualization; Funding acquisition; Methodology; Project administration; Validation; Writing – original draft; Writing – review and editing. Xiaotian Gong: Data curation; Investigation; Software; Visualization; Writing – original draft. Yongjian Ke: Conceptualization; Methodology; Supervision. Xuelian Wu: Data curation; Software; Validation.

Notation

The following symbols are used in this paper:

AS_{c_p} = average similarity of projects within contract p;
C = contract set, $C = \{c_1, c_2, c_3, \ldots, c_k\}$;
c_p = set of project numbers included in contract p;
$|c_p|$ = number of projects included in contract p;
l_i = scale of project i;
n = number of projects;
P = project number set, $P = \{1, 2, 3, \ldots, n\}$; and
$\mathrm{Sim}(i, j)$ = similarity between project i and project j.

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