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EXPERIENCE-ORIENTED MODEL OF BUDGET ALLOCATION AND COST CONTROL FOR ENGINEERING CONSULTING PROJECTS

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This paper presents an experience-oriented model of budget allocation and cost control for engineering consulting projects. The proposed model comprised two modules: a work item module and a work duration module. Regarding the work item module, a project manager employed the analytic hierarchy process (AHP) to determine the budget percentage allocated to each work item. Regarding the work duration module, this study compiled all S-curves appearing in each budget percentage range in past projects. A project manager then selected the optimal curve shape for each work item to determine the daily budget allocation and cost control limits throughout the work duration of each work item. Testing revealed that the proposed model facilitates project managers' budget allocation decision-making, determines budget control limits for the overall project and for each work item and identifies work items that may be out of control at an early stage.

Keywords: Engineering Project; Budget Allocation; Cost Control; S-curve; AHP; PERT.

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1. INTRODUCTION

For engineering consulting firms, producing high-quality work depends on the reasonable allocation of the project budget. Budget allocation, which involves the apportionment of funds, constitutes a resource planning process aligned with the goals of a company or project (Teng *et al*., 2010). In budget allocation, decision-makers are required to allot and control available resources through reasonable means such that project outcomes are optimized (Kaplan and Michael, 2002).

Any engineering consulting project has five types of costs: direct salary costs, direct nonsalary costs, indirect salary-related costs, indirect general and administrative costs, and profit (Hurley and Touran, 2002). Direct salary is the total salary paid to all engineers who actively contribute to the completion of work items. The budget allocated to direct salary has a direct effect on the success of an engineering consulting project and represents its central cost management problem (Wang, 2022b). In practice, before a project begins, the engineering consulting firm multiplies the contracted service fee by a percentage (e.g., 10%) to determine the project preparation fee (including profit and risks). Next, the available budget of a project is calculated by subtracting the preparation fee from the service fee. Subsequently, the project manager calculates the budget required for direct nonsalary costs, indirect salary-related costs, indirect general, and administrative costs at a percentage designated by their companies and according to work items that must be outsourced. Third, the calculated budget is subtracted from the available budget to determine the budget available for direct salary (Wang, 2022a). Finally, the project manager allocates the budget, controls the costs, and ensures that the project can be completed within the company-approved direct salary budget.

A project manager is generally the most competent engineer of a project team who has the greatest understanding of the client's requirements and is responsible for allocating and controlling direct salary costs from the work item perspective (Farr, 2001). In an optimal setting, the project manager confirms the work items involved in the project, evaluates the skills required for each work item, selects available engineers whose seniority, experience, and capacity meet the requirements of the work items, estimates the amount of work that each work item involves according to their experience, determines the available work time for each engineer (the hourly rate is then used to calculate the budget required), and schedules the work item deadline. Finally, the project manager calculates the total budget for each work item and ensures that it is within the

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company's approved budget for direct salary costs. In academia, this process is referred to as the bottom-up approach, which is regarded as the most accurate approach for planning and allocating project budgets (Abdelaty *et al*., 2020).

However, managers of engineering consulting projects, particularly projects whose service fee is based on a percentage to construction expense, employing this method may not be able to formulate a detailed budget allocation plan before projects commence. The main reason is that individually estimating the amount of work each work item entails is time-consuming (Abdelaty *et al*., 2020). Moreover, project managers typically have insufficient time for budget planning (McManus *et al*. 1996) because of their numerous work commitments (Tjell and Bosch-Sijtsema, 2017). In addition, clients' demands are variable (Yang and Wei, 2010). Accordingly, some engineering consulting projects lack a basis for the management and control of budget planning, and the project managers are unable to determine whether their funds are sufficient to cover all outstanding work items or to gauge the risks involved in a timely manner. Therefore, an alternative approach is required to help project managers allocate project budgets efficiently and effectively.

In engineering consulting projects, budget planning entails decision-making in two project components: work items (i.e., the budget allocated to each work item) and work duration (i.e., the budget allocated daily across the duration of a work item). Regarding the work items, because engineering consulting firms must approve the budget for direct salary costs before a project begins when the bottom-up approach is unfeasible because a limited timeframe is available for cost estimation, the analytic hierarchy process (AHP) may be used to estimate the relative amount of work that each work item involves, which allows the project manager to assign weights to work items for budgeting. The AHP is systematically breaks down complex decision-making problems into various levels, each of which contains several factors with similar levels of importance. Subsequently, decision-makers perform pairwise comparisons to determine the relative importance and weight of these factors, from which they improve decision-making (Saaty, 1990; Şehitoğlu and Chouseinoglou, 2022).

To achieve the aforementioned goals, tools that provide standardized definitions of work item categories in engineering consulting projects must be used. Wang (2022a) established an engineering work time coding system (EWCS) that standardizes and defines work items in various types of engineering consulting projects. This system is currently used in a large Taiwanese engineering consulting firm. With an EWCS code, a project manager can combine the analytic hierarchy process (AHP) with their experience to estimate the relative difference between the amount of work involved in each type of deliverable, internal activity, or work item before project commencement. This enables the project manager to quickly determine the budget percentage allocated for each type of work. In addition, a timesheet function may be incorporated into the EWCS to record each engineer's job and the hours spent on each job to calculate the actual cost spent on each work item (hours worked multiplied by the engineer's hourly rate). Comparing the budgeted amount and actual costs allows the project manager to have greater control over the cost spent on each work item.

Regarding the work duration, the S-curve, which reveals the relationship between the cumulative project cost and time, is the most common tool for managing the project budget and cost (Pellerin and Perrier, 2019). In practice, engineering consulting projects often adopt the average cost method (with the assumption that the daily work hours remain constant) to calculate the work time for each work item. With this practice, the S-curve of every work item is a 45° straight line, which does not provide an effective basis for cost control (Wang *et al*., 2016). Data on past projects in the EWCS can be employed to plot S-curves corresponding to all ranges of the work item actual cost percentage to the total project actual cost (hereafter "cost percentage"). The project manager can select the most suitable S-curve according to the project characteristics and their experience to quickly determine the most feasible approach for daily budget allocation over the work duration.

However, a single S-curve may not provide sufficient information for cost control. The results of budget allocation for work items provide a static basis for cost control (where the amount of money remains unchanged or undergoes only slight changes). On this basis, project managers can easily compare the available budget with the actual cost and accordingly identify activities that may be challenging to control. Daily budget allocation results under work durations can be plotted as S-curves, offering a dynamic basis for cost control. Specifically, the difference between the available budget and the actual cost varies at different time points throughout the project period. As such, identifying out-of-control activities is difficult for project managers without an effective early warning mechanism.

Construction project managers can refer to the earliest and latest start and finish times in the critical path method (CPM) network to establish the upper control limit (UCL) and lower control limit (LCL) according to the budgeted cost of work scheduled curve. Subsequently, the budgeted cost of work performed curve and the actual cost of work performed curve can be compared for project control and management purposes (Project Management Institute, 2017).

Design iterations, in which multiple engineers repeatedly modify or engage in back-and-forth communication over the same engineering drawings or documents, are inevitable for most of the work items of an engineering consulting project (Piccolo *et al*., 2019). Hence, the CPM network, which is commonly used to schedule construction projects, may not be feasible for an engineering consulting project. This is because the project's start-to-finish, start-to-start, finish-to-start, and finish-to-finish relationships are difficult to define and plan and because design iterations are difficult to control within and between individual work items. Therefore, to manage project procedures, several graphical models, such as the event-driven process chain (Kreimeyer and Lindemann, 2011), the design roadmap approach (Park and Cutkosky 1999), and Applied

Signposting Model 2.0 (Wynn and Clarkson, 2021), have been developed. However, these models are rarely used in engineering consulting projects, which predominantly adopt bar charts to present the milestones of critical work items for project scheduling (Chang, 2001). Because of the inapplicability of CPM networks to engineering consulting projects, such projects cannot set cost control limits according to their budgeted cost of the work scheduled curve.

The program evaluation and review technique (PERT) examines the project progress in consideration of uncertainty and evaluates the reasonableness of the project schedule according to the expected value (EV) and standard deviation (SD) of time required to complete each work item (Lermen *et al*., 2016). Project managers can refer to past projects with S-curves similar to that of the current project and then perform the three-point estimation approach in PERT (optimistic estimate, modal estimate, and pessimistic estimate) to examine three corresponding types of cumulative cost percentage (i.e., optimistic, most likely, and pessimistic) at various time points along the S-curves. Subsequently, they calculate the EVs and SDs at those time points and determine cost control limits for the overall project and for various time points over the work duration of individual work items.

This paper proposes an experience-oriented model of budget allocation and cost control for engineering consulting projects (EO-BACC model), which comprises two distinct modules: work items and work duration. Regarding the work item module, a project manager employed the EWCS and analytic hierarchy process (AHP) to determine the budget percentage allocated to each work item. In the work duration module, S-curves for all budget percentage ranges were reviewed, and PERT was employed to plot candidate S-curves under PERT (featuring the EV, SD, and control limits at each time point) for each cost percentage range. Project managers select the most optimal S-curve for each work item category. They can then determine the budget allocation method and cost control limits throughout the project duration and the duration of individual work items accordingly.

2. PREVIOUS STUDIES

Budget allocation refers to how resources are used in a project and are widely considered to be a typical optimization problem (Yu *et al*., 2023). Research on project budget allocation (i.e., resource scheduling problems) has typically approached this topic by viewing it as either a limited-resource problem or a limited-time problem (Hongbo *et al*., 2015).

The optimization goal of a limited-resource problem is to minimize the project time. In practical terms, project resources are allocated depending on how much each work item shortens the project time (Ma *et al*., 2016). Peng and Liu (2022) described project resource scheduling as an unusual and complex optimization problem because the project resources are limited and because the work items of a project vary in terms of the procedures involved, the type and number of resources required, and the work time required. Because of the limited accuracy of the available algorithms, researchers adopting a limited-resource approach have predominantly used heuristic and metaheuristic algorithms in their investigations (Shuvo *et al*., 2021). For example, Liu and Lu (2018) investigated factors such as material supply and cost limitation and developed a labor allocation model that minimizes construction time. They later developed a two-tier cross-project resource scheduling framework (Liu and Lu, 2019).

The optimization goal of a limited-time problem is to ensure project resource leveling without increasing the project time so as to stabilize the supply of resources required by the project, reduce staff turnover, ensure a fair division of workload, and mitigate the complexity of material supply scheduling, thereby reducing the project cost (Tang *et al*., 2018). Among the models that have been developed and used are the branch and bound algorithm and mixed integer programming (Rieck *et al*., 2012), the innovative improved and adaptive harmony search algorithm (Ghoddousi *et al*., 2013), the hybrid estimation of distribution algorithm (Ponz-Tienda *et al*., 2017), the inverse optimization method (Peng and Liu, 2022), and the tabu search algorithm (Yu *et al*., 2023).

Despite the large number of algorithms available for project resource scheduling, the nature of engineering consulting projects has not yet been addressed due to the predominant focus on construction projects. When adopting a limited-resource model, the project manager must first use the CPM network to identify the critical paths of the project and the capacity of each engineering activity to shorten the project time, which allows for determining the allocation of project resources. In practical engineering consulting projects, however, a bar chart is typically used to schedule project activities and manage project progress (Chang, 2001), and the CPM network is rarely used. In a limited-time problem, the basic calculation parameters include the type and number of resources and the time required to complete each work item, meaning that the project manager must refer to historical project data to determine these parameter values objectively before the limited-time model can be implemented. However, the fuzzy nature of the input and output of engineering consulting projects complicates the objective evaluation of the required resources and time for individual work items (Brookes, 2012). The fuzzy nature of resource input refers to when a project staff member concurrently participates in multiple work items under several projects and spends long periods of time in communications or meetings that are not directly related to the project output. Output fuzziness occurs because of the lack of concrete output in work items associated with providing consultation, reviewing, or making suggestions and because of the unquantifiability of the service output and quality (Wang, 2022a). Thus, the customary use of bar charts in engineering consulting projects for scheduling and the lack of objective evaluation data on the resources and time required for individual work items hinder the application of resource scheduling models in such projects.

Studies on the cost management of engineering consulting projects have predominantly relied on the client's perspective to develop estimation models for reasonable project service fees and rarely considered the consulting firm's perspective in their discussions of project budget allocation and cost control. Research on service fee estimation for engineering consulting projects has also predominantly relied on the percentage of estimated construction cost approach, the top-down approach, or the bottom-up approach (Nelson and Waterhouse, 2016).

1. Percentage of estimated construction cost approach: This approach determines the service fee of an engineering consulting project by multiplying the estimated construction cost by a percentage based on the nature and complexity of the project. This approach is simple and rapid, but the service fee results are often questioned by engineering consulting firms (Carr and Beyor, 2005).
2. Top-down approach: This approach involves developing an estimation model for the total cost of engineering consulting projects by using project characteristics (e.g., road condition, road area, and construction cost) and tools such as regression models, artificial neural networks, and decision trees (Gransberg *et al*., 2015). Abdelaty *et al*. (2020) argued that this approach, despite being more accurate than the percentage of estimated construction cost approach, may involve high mean absolute percentage errors (MAPEs) because of the cost record inconsistencies among previous projects resulting from variations in the work items, the price negotiation processes, the experience and competence of engineers in charge of budgeting, and the benefits packages and general competence of engineers at each engineering consulting firm.
3. Bottom-up approach: This approach involves an experienced engineer defining the functional areas of a project, such as the environmental study, topographic survey, and design, and then dividing these areas into subfunctional areas. For example, design can be subdivided into bridge structural type study and structural design. The engineer then estimates the work time and budget required for the individual functional and subfunctional areas of the engineering consulting project, which are then summed to calculate the total project budget (Yu, 2015). Among the three aforementioned approaches, the bottom-up approach yields the most accurate estimates but requires the engineers to collect detailed information beforehand and invest copious amounts of time in cost estimation (Abdelaty *et al*., 2020). To mitigate the difficulty of implementing this approach, researchers have designed standardized implementation procedures and developed methods and models to provide referential information for budgeting. For example, Ogunlana *et al*. (1998) used a system dynamic model to simulate the detailed design process of an engineering consulting project and designed various operation scenarios to evaluate the influence of the cost allocation method on project progress and cost. In their bottom-up approach guidebook, Gransberg *et al*. (2015) proposed an operating procedure and several factors to consider in budgeting. In another study, Abdelaty *et al*. (2020) used a case-based reasoning model to identify five previous projects that were highly similar (including project characteristics, project time, and cost records) to a new project in order to help the engineers budget the new project.

Although the primary goal of the aforementioned approaches is to help clients determine the service fees for their engineering consulting projects, engineering consulting firms are required to also use the bottom-up approach to estimate and allocate their project budget if they have sufficient time to do so (i.e., optimal circumstances) (Wang, 2022a). In other words, auxiliary approaches based on the bottom-up approach are applicable to engineering consulting firms. However, the referential information provided by research for budgeting, which is primarily based on previous projects, reduces the estimation time only to a certain extent. In addition, the project managers working at the engineering consulting firms usually have even tighter schedules than those of the engineers working at the client companies (Griffis and Choi, 2013). Therefore, a more efficient and effective budget allocation and cost control model, specifically for engineering consulting firms, must be developed.

3. DEFINITIONS

3.1 Work Items

The EWCS (Figure 1) was used to define work items in a project. The first three digits of the EWCS code represent the contractual unit and, in compliance with the consulting regulations of Taiwan (PCC, 2020), differentiate between engineering types and deliverables (including basic and additional deliverables) under a product breakdown structure. The three digits represent either deliverable (nine subtypes) or support (one subtype), which refers to work time that cannot be attributed to a specific deliverable). Regarding the deliverables, digits represent the direct salary paid for a period of work time ascribed to a specific deliverable. For example, C denotes supervision (digit 1), and 03 denotes the supervision and investigation of the contractor's work (digits 2–3). Regarding support, digits represent the direct salary paid for a period of work time that cannot be attributed to a specific deliverable. For example, S denotes support (digit 1), and 02 represents company quality assurance (digits 2–3). Digits 4 – 8 represent the implementation unit. They define internal activities that the engineering consulting firm must perform to complete a deliverable (or support) under the work breakdown structure. The implementation unit falls into three levels: profession division (digit 4), profession task (digits 5–6), and profession subtask (digits 7–8; optional). For example, C denotes structure (digit 4), 35 refers to a reinforced concrete bridge (digits 5–6), and 73 refers to a cable-stayed bridge (digits 7–8). The complete set of codes (digits 1–8) represents one work item of the project (Wang, 2022a).

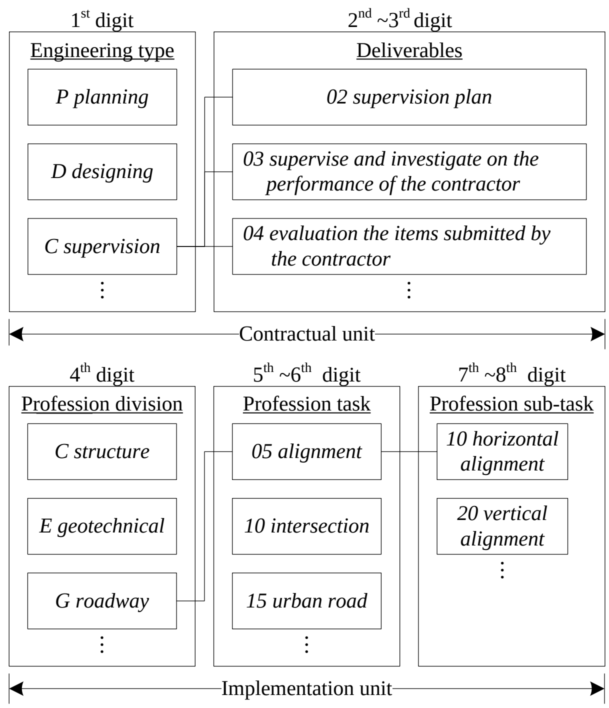


Figure 1. EWCS system

In practice, project managers first determine the eight-digit EWCS code of each project work item defined in the contract. Using the code either regularly or irregularly, they then assign these work items to project staff members. Concurrently, the available work time for each work item is defined, and staff members are required to document the actual time they spend on the assigned work items on a daily basis.

3.2 Selection and Source of Modeling Cases

In Taiwan, supervision projects have relatively low profitability and are the most susceptible to losses (CICHE, 2021). Given the possibility of budget deficits, establishing a reasonable overall budget plan and an effective early warning mechanism is a viable means to avoiding (or reducing) project losses (Pellerin and Perrier, 2019). Supervision projects were selected to test the proposed model. The modeling cases were sourced from a sample of 10 road construction supervision projects completed by a large-scale Taiwanese engineering consulting firm (hereafter referred to as the case firm) that adopted the EWCS.

4. EO-BACC MODEL

To help project managers make reasonable budget allocation decisions quickly and to provide a basis for project cost control, this study developed the EO-BACC model (Figure 2). The EO-BACC model consists of a work item module and a work duration module. The work item module determines the available budget for each work item, and the work duration module determines the budget allocation percentage and cost control limit throughout the implementation course of each work item.

Because engineering consulting firms approve the budget for direct salary costs before performing budget allocation, the work item module does not require project managers to accurately estimate the amount of work (i.e., work time) involved in each work item. Instead, these project managers can simply complete the budget allocation process by using the appropriate tool and relying on their experience to provide an approximate estimate of the relative difference in the amount of work that each work item involves (i.e., the top-down approach). Notably, the bottom-up approach (the optimal approach in current practice) involves determining the budget percentages by establishing the resources or costs required for each individual work item. By contrast, the top-down approach involves determining the budget percentages by using the relative amount of work that each work item involves and reveals the maximum allowable direct salary costs for each work item within the approved budget. In the work duration module, graphical tools are used to visualize the final results of a complex analysis process such that the information is readily accessible and easy to use (Coutinho-Rodrigues *et al*., 2011). This module produces candidate curve shapes and costs control limits throughout the implementation process of each work item based on previous projects and graphical tools. The project managers then select the most applicable curve shape according to their experience of budget allocation and control costs based on the control limits.

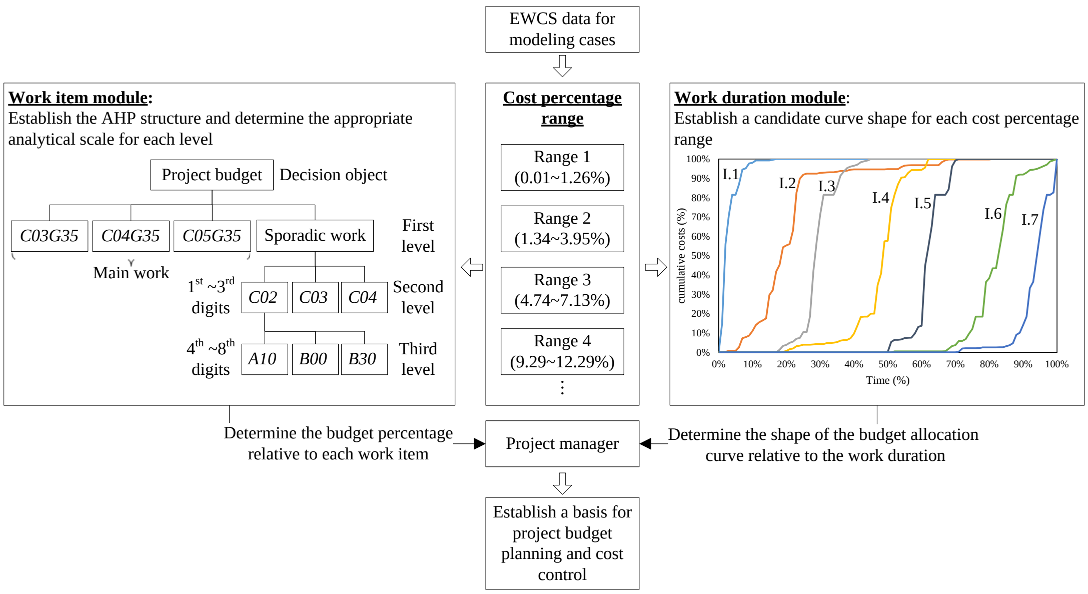


Figure 2. EO-PBACC model

Various multi-criteria decision-making approaches, such as the weighted sum model (WSM), the AHP, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and the VIseKriterijumska Optimizacija I kompromisno Resenje (VIKOR) approach (Greco *et al*., 2016), have been developed. The TOPSIS and VIKOR approaches emphasize the comparison and ordering of candidate solutions, whereas the WSM and AHP approaches determine the weight of the criteria affecting the decision-making targets. Unlike the WSM, the AHP can be used to indicate the consistency between the decisions made by the decision-maker (Greco *et al*., 2016). Therefore, this study used the AHP for budget allocation. In terms of graphical tools, S-curves are a widely used management tool in engineering consulting projects. Their candidate curve shapes, and control limits can present budget allocation percentages in a clear manner, thereby allowing project managers to grasp information rapidly without spending too much time interpreting the graphics.

Additionally, the curve shapes are available for direct application in projects. Control limits can be simply established by calculating the mean and SD at each time point if the data to be analyzed are normally distributed (Pallant, 2005). However, in this study, reviewing the cost records of previous projects revealed that none of the project data met the normal distribution requirement, and thus an alternative approach was required. The PERT is less susceptible to data distribution (according to the central limit theorem assumption), is easy to use, and produces EVs and SDs that are comparable to the actual values (Lau and Somarajan 1995). Therefore, this study used the PERT to establish cost control limits.

4.1 Work Item Module

Step 1.1 Determine the AHP Structure Suitable for the Project Type

An appropriate AHP structure and evaluation scale are key to producing simulation results comparable to the actual project cost percentage. The hierarchical structure represents the categories of work items, and the evaluation scale is a measurement standard of the relative amount of work (i.e., cost percentage) each work item involves. From the perspective of project budget allocation, a favorable AHP structure must clearly define the order of budget allocation decisions, and the items at the same level for comparison must have similar cost percentages (to reduce their relative differences).

Cluster analysis, a commonly used data classification technique, involves clustering objects with high similarity and a small relative distance (Pallant, 2005; Zou *et al.*, 2019). Herein, k-means cluster analysis was conducted to examine the similarity among the cost percentages of 332 work items involved in the 10 modeling cases. Subsequently, the three indexes recommended by Sharma (1996), namely the root-mean-square standard deviation, determination coefficient, and Semi-partial R-Square, were used to determine the appropriate number of clusters. Table 1 presents the cluster analysis results corresponding to the cost percentages of the work items.

The 332 items formed 13 clusters according to their cost percentage; 286 work items had a cost percentage of ≤1.26% (cluster 1, accounting for 86.14% of all work items), and 46 items had a cost percentage of ≥1.34% (clusters 2–13). The results demonstrate that a supervision project had a high average cost percentage of 4.6 (46/10) main work items. The remaining work items were considered sporadic work items (i.e., items with a low-cost percentage of ≤1.26%). On average, the collective cost of all sporadic work items accounted for 4.29% (0.15% × 286/10) of the total cost of the supervision project. Comparison items on the first AHP level comprised the main work items, with all sporadic work items regarded collectively as one main work item. Sporadic work items (having similar cost percentages) were obtained by excluding all main work items. The EWCS codes were employed to establish comparison items for the second and third AHP levels. The second level represents deliverables (digits 1–3) corresponding to sporadic work items, and the third level denotes the internal activities (digits 4–8) required for each deliverable (digits 1–3). Figure 3 displays the proposed AHP structure.

Table 1. Results of cluster analysis on the cost percentages of work items

Cluster	Work items	Mean (%)	Range (%)
1	286	0.15%	0.01~1.26%
2	19	2.41%	1.34~3.95%
3	9	6.15%	4.74~7.13%
4	4	10.89%	9.29~12.29%
5	2	21.21%	20.57~21.86%
6	1	25.13%	25.13%
7	1	42.95%	42.95%
8	1	46.53%	46.53%
9	2	51.54%	51.32~51.76%
10	1	56.58%	56.58%
11	2	70.71%	69.47~71.95%
12	1	77.39%	77.39%
13	3	89.88%	88.96～90.79%

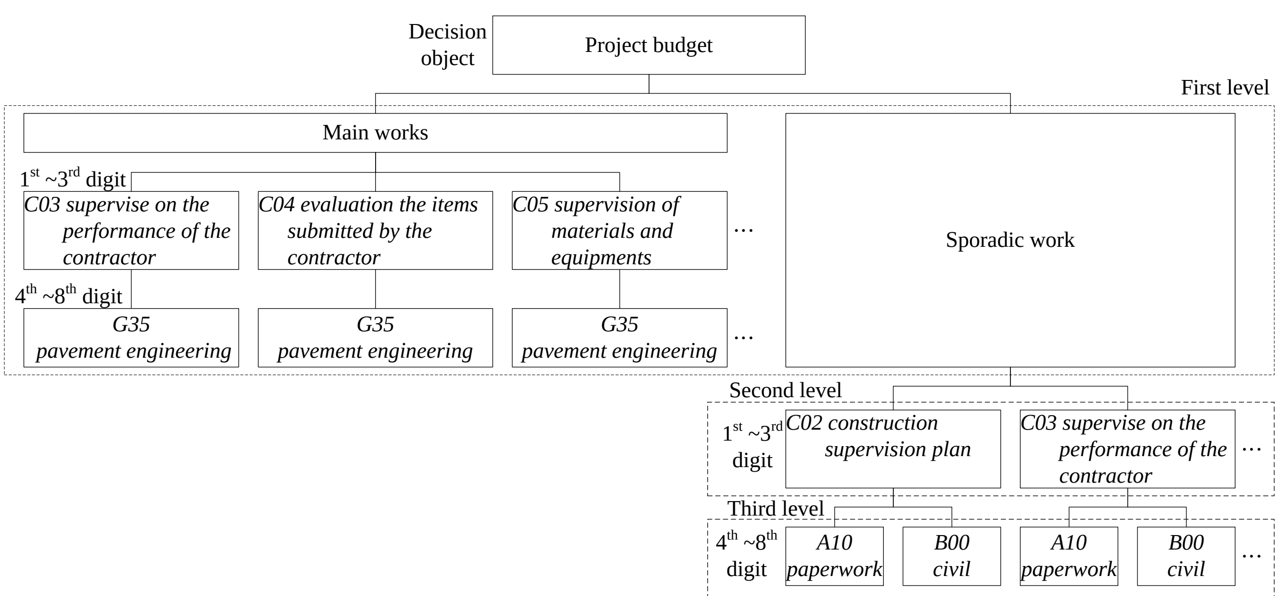


Figure 3. AHP structure and levels of construction supervision projects

Step 1.2 Determine the Appropriate Evaluation Scale for Each Level

The maximum and minimum cost percentages in the modeling cases were used to determine the appropriate evaluation scale (linear) for each AHP level. For the first level (Table 1, clusters 2–13), the minimum and maximum cost percentages were 1.34% and 90.79%, respectively, with a relative difference of 67.75 (90.79/1.34); thus, the evaluation scale was set at 1–68. For the second and third levels (Table 1, cluster 1), the minimum and maximum cost percentages were 0.01% and 1.26%, respectively, with a relative difference of 126 (1.26/0.01); thus, the evaluation scale was 1–126. A scale of 1 indicates that two work items have the same cost percentage; a scale of 68 (or 126) indicates that a work item's cost percentage is 68 (or 126) times that of the other. Scale testing revealed that pairwise comparisons involved frequent conflicting judgments. Furthermore, few comparison results passed the consistency check because of the large scale range and the between-level variations in scales.

To resolve these problems, two types of scales were proposed—for manual comparison and for comparison by the proposed model (hereafter referred to as a manual scale and model scale, respectively). The manual scale, used for pairwise comparison by a project manager, was set at 1–100. The model scale was the AHP calculation scale and conformed to the established scale ranges (first level: 1–68; second and third levels: 1–126). In the comparison process, the project manager determined the relative differences between work items under the manual scale, which were then converted proportionally to those under the model scale before AHP calculations were performed. For example, two work items with a relative difference of 90 (manual scale) at the first level were converted to 61.2 ([90 × 68]/100) on the model scale.

Step 1.3 Establish Work Items and AHP Structure for a New Project

Before project managers apply the proposed model, they must familiarize themselves with and assign an EWCS code to each work item. Next, according to the EWCS codes and their experience, they select work items with the highest cost percentages (main works) and add a sporadic work, a collective set of all other work items excluding the main work item of a project. Once comparison criteria were established for the first AHP level, those for the second and third levels were established according to the EWCS codes of sporadic works. Figure 3 displays the proposed AHP levels.

Step 1.4 AHP Analysis

Project managers start the AHP analysis process by performing pairwise comparisons at the first AHP level on the basis of the amount of work that each work item involves. They use main work items with a sporadic work item as the criteria to determine the budget percentages of main work items and sporadic work items. Subsequently, they perform pairwise comparisons at the second AHP level, with the criteria being deliverables included in sporadic work, to determine the budget percentages for each deliverable under sporadic work items. Finally, they perform pairwise comparisons at the third AHP level, with the criteria being internal activities included in each deliverable under sporadic work items, to determine the budget percentages for the internal activities that each deliverable involves. In the present study, the budget percentages of work items were calculated using the AHP procedure outlined by Saaty (1990).

1. Establish the pairwise comparison matrix

As shown in (1), a pairwise comparison matrix was established under the manual scale (1–100) according to the number of comparison items at the same level. Subsequently, the project manager determined the relative difference between work items based on project characteristics and their personal experience. In (1), a_{ij} denotes the relative difference between work items A_i and A_j.

$$A_{ij} = [a_{ij}]_{n\times n} = \begin{pmatrix} 1 & a_{12} & a_{13} \\ \frac{1}{a_{12}} & 1 & a_{23} \\ \frac{1}{a_{13}} & \frac{1}{a_{23}} & 1 \end{pmatrix} \tag{1}$$

2. Calculate budget allocation weights

The pairwise comparison matrix, established under the manual scale, was converted to that at the model scale and then substituted into (2) to normalize the pairwise matrix, where X_{ij} represents the standardized relative difference. Subsequently, (3) was used to calculate the budget allocation weight of each type of comparison item, where n denotes the number of comparison items.

$$X_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} = \begin{pmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{pmatrix} \tag{2}$$

$$W_{ij} = \frac{\sum_{j=1}^{n} x_{ij}}{n} \begin{bmatrix} W_{11} \\ W_{12} \\ W_{13} \end{bmatrix} \tag{3}$$

3. Consistency check

A consistency check was performed using (4) and (5), where CI refers to the consistency index, λmax is the maximum eigenvalue of the pairwise comparison matrix, CR is the consistency ratio, and RI is the random index.

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{4}$$

$$CR = \frac{CI}{RI} \tag{5}$$

If CR < 0.1, the calculation result passes the consistency check; if not, the project manager should repeat the pairwise comparison until the result passes the consistency check.

Step 1.5 Determine the Budget Allocation Method and Cost Control Basis for Work Items

The AHP enables project managers to calculate the budget percentage of each work item, by which the total project budget approved by their companies is multiplied to calculate the budget for each work item and to control the project cost.

4.2 Work Duration Module

Step 2.1 Establish Standardized S-curves

Based on the cost data collected from the EWCS, this study plotted S-curves for the 332 work items in the 10 modeling cases. The project time percentage was on the x-axis, whereas the cumulative cost percentage of work items was on the y-axis. Interpolation was employed to calculate the cumulative cost percentage at each integral point along the x-axis.

Step 2.2 Identify the Shapes of S-curves Corresponding to Each Cost Percentage Range

The cost percentage–based classification in this step involved a different approach from that in the work item module. In the work item module, work items were clustered according to their cost percentages to determine the appropriate AHP structure (Table 1). Further clustering was not necessary for the work duration module; therefore, the shapes of S-curves corresponding to the 13 clusters were examined individually. However, given the limited number of modeling cases, some of the ranges contained a small sample of only 1–3 work items. PERT could not be applied; therefore, clusters 4–13 were combined into one cost percentage range.

The cumulative cost percentage at each integral time point was employed as a variable in the k-means cluster analysis (using the same procedure described in Step 1.1) on S-curves appearing in the four cost percentage ranges. For example, nine S-curves of work items were observed in the third (cluster 3) cost percentage range ([Figure 4(a)]. Figure 4(b) displays the clustering results, with the nine S-curves classified into three types of curve shape. Moreover, the S-curve shape classification results revealed the following. First, the cost percentage of work items considerably affected the shape of the S-curves. Specifically, a low-cost percentage resulted in a steep S-curve, and a high-cost percentage resulted in a flat S-curve. Second, each cost percentage range exhibited various S-curve shapes. Third, different work items may have S-curves of similar shapes. Fourth, the same work item may have different S-curve shapes in different projects. Fifth, none of the S-curve shape categories had a normally distributed sample at any time point. These findings indicate that the study methodology was appropriate. First, due to the strong effect of the cost percentage on the S-curve shape, the cost percentage of work items must be established before the daily budget is allocated under work durations. Second, because data distributions were not normal at all-time points, using PERT to establish cost control limits was reasonable. Third, the analytical results revealed the complexity and uncertainty involved in determining the proportion of the budget to allocate daily over the work duration. Thus, establishing possible S-curve shapes in each cost percentage range before asking project managers to select the optimal S-curve according to project characteristics and their experience was an effective and time-saving method.

Step 2.3 Establish S-curves Under PERT

After the S-curve classification, the PERT model proposed by Perry and Greig (1975) was used to calculate the EV and SD of the cumulative cost percentage (the x-axis) for each type of S-curve shape at various time points. The EVs (te) and SD (σ) were then used to establish candidate curve shapes and cost control limits for each type of work item. They were calculated using (6) and (7), where $t_{0.05}$, $t_{0.50}$, and $t_{0.95}$ represent the 5_{th}, 50_{th}, and 95_{th} percentiles, respectively, of cumulative cost percentage at each time point.

$$t_e = t_{0.5} + 0.185(t_{0.05} + t_{0.95} - 2t_{0.5}) \tag{6}$$

$$\sigma = \frac{t_{0.95} - t_{0.05}}{3.25} \tag{7}$$

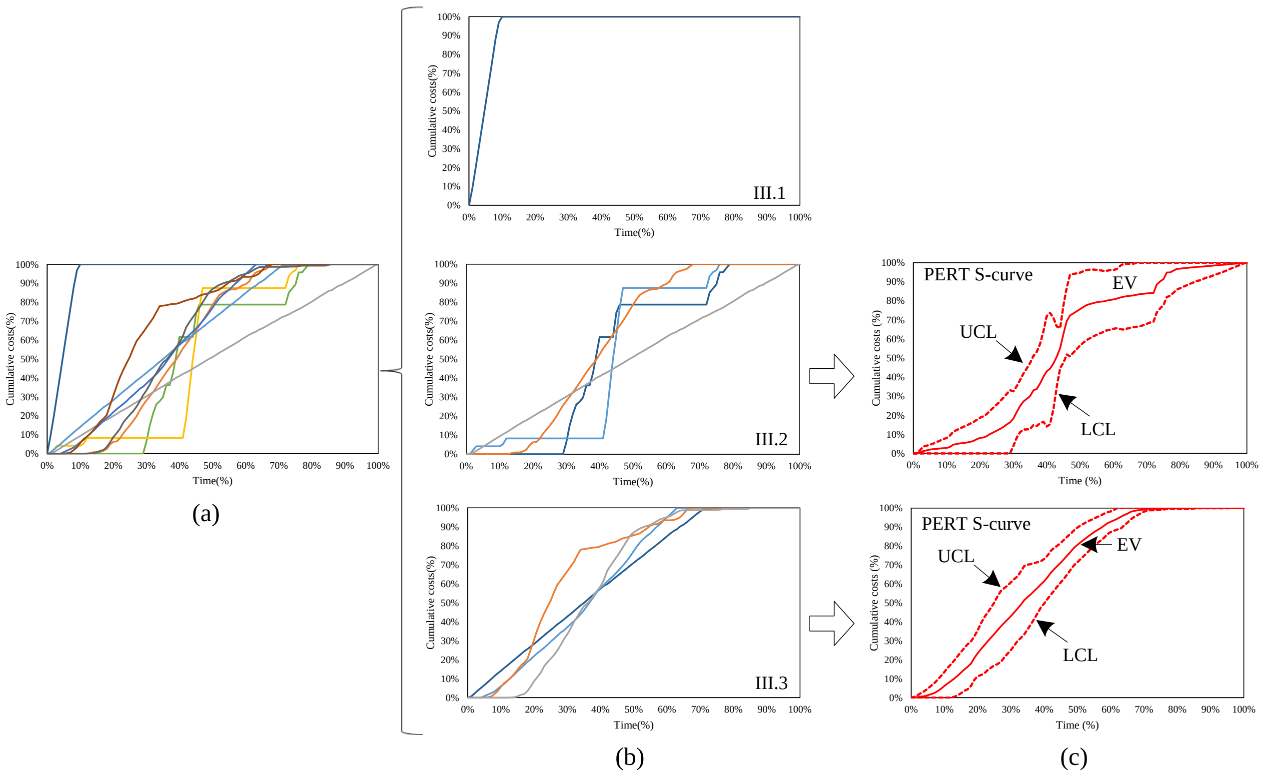


Figure 4. S-curve types in the moderately high (third) cost percentage range

Consider curve shape III.3. It comprised four S-curves, meaning that four cumulative cost percentages could be used as reference values for each integral time point. Subsequently, the Microsoft Excel PERCENTILE function and linear interpolation were employed to calculate the cumulative cost percentages at the 5th, 50th, and 95th percentiles. These percentages were then substituted into (6) and (7) to obtain the EV and SD at each time point. Finally, the EV was used to determine the budget percentage for this curve shape, and the EV ± 2σ (95% significance level) was used to establish the UCL and LCL at each time point [Figure 4(c)]. These control limits constitute threshold values for determining whether the implementation status of a work item is normal at the 95% significance level. PERT could not be applied to establish an S-curve for curve shape III.1 because the sample consisted of only one S-curve.

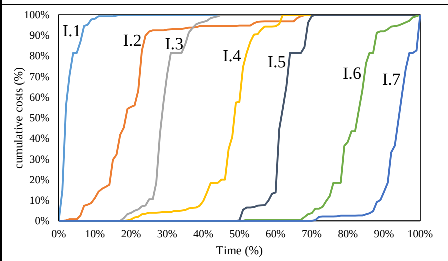
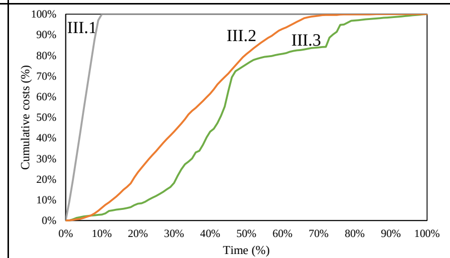
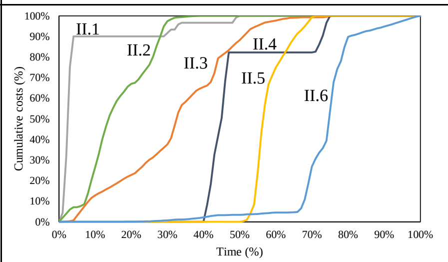
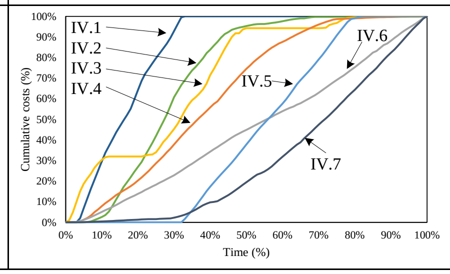
Step 2.4 Establish Candidate S-curves for Each Type of Work Item

The expected value of each curve shape was used to plot candidate S-curves under PERT for each cost percentage range (Table 2), thereby providing a basis from which project managers could select the appropriate method for daily budget allocation under the work duration.

Step 2.5 Determine the Budget Allocation Method and Control Limits in Work Duration

On the basis of the work item cost percentages (Step 1.4) and their experience, project managers selected the optimal S-curve for each work item from Table 2. The study recommended that all S-curve shapes under PERT that had appeared in the corresponding cost percentage of a work item be listed to facilitate the selection process. Specifically, through this procedure, project managers were able to determine the budget percentage and cost control limits for each day under the work duration of a work item. The same can be achieved by adding up the EVs and SDs (i.e., the square root of the sum of variances) of all work items' S-curves under PERT for the overall project period.

Table 2. Candidate S-curves under PERT

Range	S-curve under PERT	Range	S-curve under PERT
Extremely low-cost percentage (0.01%–1.26%)		Moderately high-cost percentage (4.74%–7.13%)	
Low-cost percentage (1.34%–3.95%)		High-cost percentage (9.29%–90.79%)	

5. TESTING AND VERIFICATION WITH A PROJECT CASE

The test case was a road construction supervision project completed by the case firm. The service fee for this project was NT$64,953,427, the contract period was 990 days, and the length of the road constructed was 2,030 m. According to the cost data, the total budgetary amount corresponding to direct salary payments was NT$17,200,000, and the actual cost was NT$17,145,783. The project manager of the test case was recruited to perform the test. The test objective was to verify whether the proposed model could help experienced project managers with an adequate understanding of the content of their projects establish budget percentages comparable to the actual project cost percentages.

5.1 Work Item Module

In an engineering consulting project, the work items encompass feasibility research, planning, design, construction supervision, and professional construction management activities, and the content and relative amount of work involved in each individual work item may vary across project types. Therefore, engineering consulting firms must refer to the EWCS codes of previous projects before using the work item module to determine the number of main work items and the applicable AHP structure for each project type (Step 1.1) and decide on the appropriate evaluation scale for each AHP level (Step 1.2).

In this study, to conduct the test, Steps 1.1 and 1.2 were first completed in the construction projects, and the project manager was asked to skip to Step 1.3. The project manager was then asked to encode the work items of the test case with the EWCS codes defined in the contract. The results indicated that the case had 17 deliverables (digit 1–3), in which 18 types of internal activities (digits 4–8) were involved. These deliverables and internal activities formed 42 work items (digits 1–8). After all work items of the test case were established, the project managers were asked to select the main work items from all 42 work items as comparison items for the first level. Before the project manager determined which work items were the main work items of this case project, they were informed that the supervision projects used by this model had an average of only 4.6 work items with high-cost percentages. The project manager, therefore, selected C03G35, C06G35, C04G35, C99G35, and S06A00 as the main work items, and the remaining 37 work items were collectively regarded as main work items. Hence, the first AHP level comprised six criteria (five main work items with a single sporadic work item). Subsequently, the EWCS codes were used to construct criteria at the second (the sporadic work items included 15 deliverables) and third (in sporadic work, each deliverable had 2–10 internal activities) levels.

According to the number of comparison items at each level, a Microsoft Excel spreadsheet that contained a manual-scale pairwise comparison matrix, a model-scale pairwise comparison matrix, functions for weight calculation, and a consistency check. Next, the project managers entered relative difference data into the manual-scale pairwise comparison matrix, which was automatically converted into a model-scale matrix in the spreadsheet by using the mentioned functions

(Step 1.4). The test demonstrated that the proposed manual scale facilitated easy pairwise comparison; the result usually passed the consistency check within three attempts.

Figure 5 presents the AHP results of the test case. The budget percentages of the work items were used to establish the overall budget plan for the project (Table 3) (Step 1.5). Comparison between the root-mean-square errors (RMSEs) of budget percentages estimated using the test case approach (as described in the supervision plan of the test case) and those estimated using the proposed AHP with respect to the actual costs spent in the 42 work items indicated that the proposed model (RMSE = 0.11%) outperformed the approach of the test case (RMSE = 0.24%).

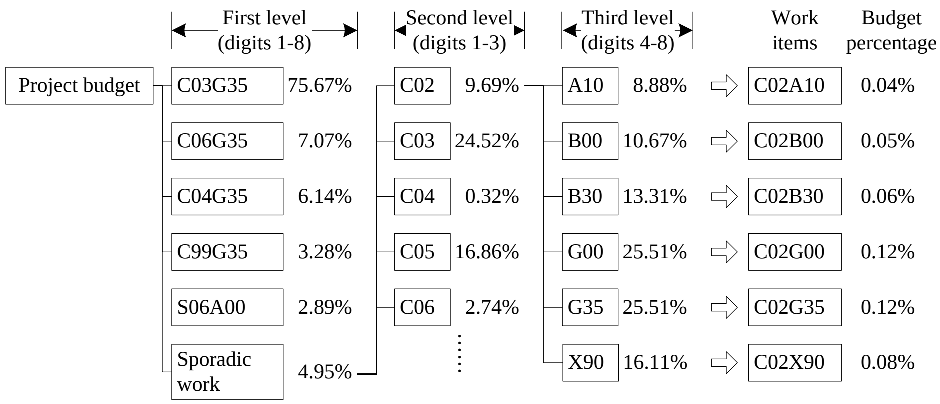


Figure 5. AHP results of the test case

Table 3. Budget plan for the test case

Work item		Estimates made by the proposed model				Actual cost	
Service item (digits 1–3)	Internal activity (digits 4–8)	Service item (digits 1–3)	Internal activity (digits 4–8)	Budget percentage	Direct salary (NT$)	Cost percentage	Direct salary (NT$)
D03	G35	3.06%	100.00%	0.15%	26,058	0.14%	23,974
D04	G00	1.67%	100.00%	0.08%	14,234	0.08%	13,186
C02	A10	9.69%	8.88%	0.04%	7,324	0.04%	7,192
C02	B00	9.69%	10.67%	0.05%	8,802	0.06%	9,590
C02	B30	9.69%	13.31%	0.06%	10,982	0.07%	11,987
C02	G00	9.69%	25.51%	0.12%	21,048	0.15%	25,473
C02	G35	9.69%	25.51%	0.12%	21,048	0.15%	25,772
C02	X90	9.69%	16.11%	0.08%	13,292	0.02%	3,596
C03	A00	24.52%	1.60%	0.02%	3,337	0.03%	5,394
C03	B00	24.52%	36.70%	0.45%	76,617	0.54%	92,301
C03	B20	24.52%	0.93%	0.01%	1,948	0.01%	2,397
C03	B30	24.52%	1.38%	0.02%	2,888	0.02%	3,596
C03	G00	24.52%	11.55%	0.14%	24,105	0.17%	29,368
C03	G30	24.52%	4.68%	0.06%	9,763	0.07%	11,987
C03	G35	—	—	75.67%	13,015,088	77.39%	13,268,698
C03	G45	24.52%	38.25%	0.46%	79,846	0.56%	95,897
C03	X10	24.52%	2.82%	0.03%	5,890	0.05%	8,391
C03	X15	24.52%	1.05%	0.01%	2,191	0.01%	1,199
C03	X90	24.52%	1.05%	0.01%	2,191	0.01%	1,199
C04	G35	—	—	6.14%	1,055,909	6.05%	1,036,886
C04	Q50	0.32%	100.00%	0.02%	2,758	0.01%	2,397
⋮							
S06	A00	—	—	2.89%	497,815	2.37%	406,364
S09	G00	0.32%	100.00%	0.02%	2,758	0.01%	2,397
S10	B00	0.58%	100.00%	0.03%	4,945	0.03%	4,795
Total				100%	17,200,000	100%	17,145,783

5.2 Work Duration Module

Each project type involves unique work items and uses budgets differently throughout its implementation. Therefore, before the work duration module can be used, engineering consulting firms must establish an S-curve for each project type on the basis of the EWCS cost records of previous projects. The x- and y-axis scales must be standardized by following Step 2.1 before proceeding to Step 2.2 to define the cost percentage range for each project type and the cluster curves that appear within each cost percentage range through cluster analysis. Step 2.3 is subsequently performed to establish cost control limits with the PERT for each curve shape. Finally, the analysis results of Steps 2.1–2.3 are compiled to determine the candidate S-curves of each cost percentage range for the project type in question (Step 2.4). In this study, to conduct the test, Steps 2.1–2.4 were completed in advance for the construction projects (Table 2), and the project manager was asked to skip to Step 2.5.

Furthermore, to simplify the process by which project managers select the appropriate S-curves under PERT, this study compiled all curve shapes under PERT that had appeared in the corresponding cost percentage range of each work item. For example, while evaluating the applicability of the curve shape, the project manager was advised to start with curve shape I.4, II.5, and III.2, which appeared in work item D03G35 of previous projects. After completing the S-curve shape selection, the project managers obtained the EV of the budget percentage and cost control limits at each time point for each work item. For example, curve shape I.4 was selected for work item D03G35 (Figure 6).

As presented in Figure 6, the control limits helped project managers identify work items at risk of going out of control at an early stage. Next, project managers combined the S-curves under PERT of all work items to obtain the overall budget percentages and cost control limits for the entire project period (Figure 7). According to the RMSE results of budget percentages estimated using the test case approach (as described in the supervision plan of the test case) and those estimated using the proposed method with respect to the actual costs spent throughout the project period, the proposed model substantially outperformed the approach of the test case (RMSE = 2.33% vs. 12.32%).

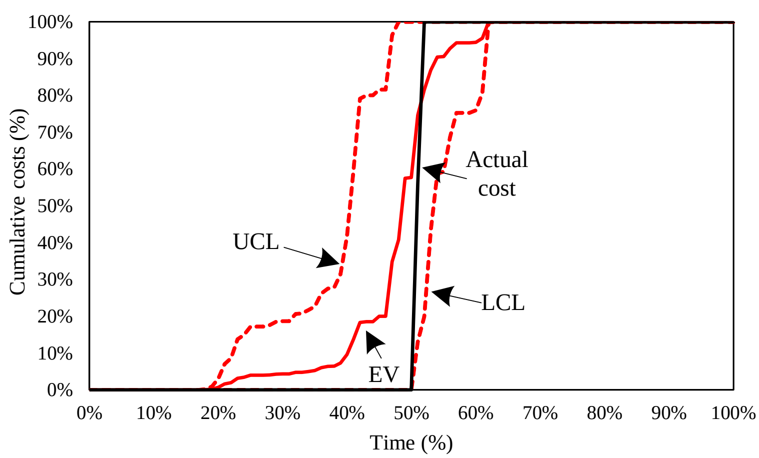


Figure 6. EV of the budget percentage and cost control limits for work item D03G35.

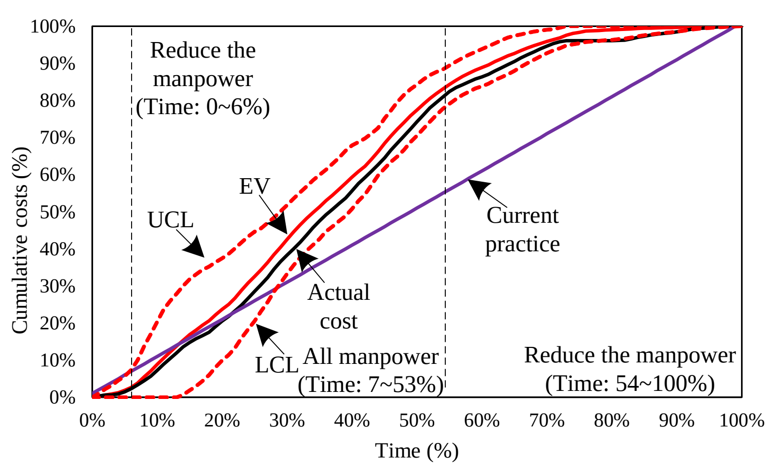


Figure 7. Overall project budget percentages and cost control limits for the test case.

6. PROCEDURE FOR MODEL USE

In practice, numerous worktime coding systems adopted by engineering consulting firms fail to reach the deliverable level (Wang, 2022b). In this study, a work time coding system with deliverable-level codes (e.g., EWCS codes) was used before the proposed model was adopted to ensure the practicality of the budget percentage results. Generally, before the model is used, sufficient historical project data must first be available because such data constitute the foundation of the model. The following details the procedure of using the EO-BACC model.

1. Work items module
   - Step 1.1 Gather the work time and cost data of previous projects and establish the cost percentage ranges of work items for the project type in question (e.g., construction supervision) to determine the appropriate AHP structure and levels.
   - Step 1.2 Determine the appropriate evaluation scale of each AHP level for the project type on the basis of the work time and cost data of previous projects.
   - Step 1.3 Encode all the work items of the new project with EWCS codes as defined in the contract, identify the main work items, and establish the AHP structure and levels of the new project.
   - Step 1.4 Conduct the AHP level by level and perform pairwise comparisons in the following order: main work with sporadic work (first AHP level), deliverables included in sporadic work (second AHP level), and internal activities included in each deliverable (third AHP level).
   - Step 1.5 Multiply the budget allocation weight of each work item by the budget that the company approved for direct salary costs to complete the budget allocation process.

2. Work duration module
   - Step 2.1 Identify all S-curves that appeared in each work item under the project type in question according to the EWCS cost records of previous projects and standardize the x- and y-axis scales.
   - Step 2.2 Perform cluster analysis to cluster and organize the curve shapes that appeared within each cost percentage range according to Step 1.1.
   - Step 2.3 Use the PERT to establish cost control limits for each curve shape.
   - Step 2.4 Select candidate S-curves for each cost percentage range for the project type in question.
   - Step 2.5 Determine the cost percentage range for each work item according to the results of Step 1.5, select the budget allocation curve shape for each work item, and calculate the available budget and cost control limits throughout the implementation process (Step 2.5).

7. CONCLUSIONS AND RECOMMENDATIONS

In engineering consulting projects, the effective use of project managers' experience and viewpoints is critical to budget allocation decisions because of the complexity and uncertainty involved. Herein, the EO-BACC model, comprising a work item module and a work duration module, was developed.

Table 4 compares the proposed model to similar models developed in previous studies. These previous models were developed to facilitate the bottom-up approach. They generate information of referential value to project budgeting through simulation or by providing data on previous projects with a similar nature. With such information and their own experience, engineers (project managers) at client companies or engineering consulting firms generate more accurate budgets for their engineering consulting projects. However, the fact that these engineers (especially project managers at engineering consulting firms) are often too busy to provide budget details for each work item limits the applicability of these models. By contrast, the proposed budget allocation model relies on a top-down technique and facilitates comprehensive planning for the total project budget, the budget allocated to each deliverable and internal activity, and the budget of each work item throughout its implementation process. Using the work item module, project managers can complete budget allocation simply by determining the relative amount of work that each work item involves without having to calculate the exact budget required for each individual work item. In this study, the test results indicated that this module reduced the time required for budget planning, improved the accuracy of budget allocation percentages, and outperformed other modules currently used in practice. The work duration module allows project managers to select the appropriate budget allocation curve shape to rapidly determine the budget allocation of each work item over time, to provide an accurate budget allocation estimate (compared with the commonly adopted average cost method), and to set up cost control limits for each work item and the total project cost.

Table 4. Comparison of the proposed model with similar models developed in previous studies

Model developer		Ogunlana *et al.* (1998)	Gransberg *et al.* (2015)	Abdelaty *et al.* (2020)	This study
Target user of the model		Engineering consulting firm	Client	Client	Engineering consulting firm
Objectives		Review work efficiency and progress of project goals	Estimate total project budget	Estimate total project budget	Allocate project budget and establish cost control limits
Method		The parameters of design activities are defined, and the design procedure is simulated to determine whether the management strategy satisfies goals related to project progress, personnel, and budget.	An experienced engineer defines the functional areas covered by the project, determines the effects of project requirements (e.g., bridge length, design complexity, and road class) on the work time required, provides an approximate estimate of the budget required for each functional area, and sums the budgets to obtain the total project budget.	The case-based reasoning technique is used to identify five previous projects that are highly similar to the new project. Depending on the characteristics, costs, and work time records of these previous projects and using their own experience, the engineer estimates the work time and budget for the project and respective functional areas.	With consideration to the project characteristics and work content and by using their own experience, the project manager employs the AHP to determine the relative amount of work that each work item involves and thereby determine the budget for each work item. They then refer to the S-curves of previous projects to determine the budget allocation and cost control limits throughout the implementation of each work item.
Cost estimation approach		Bottom-up approach	Bottom-up approach	Bottom-up approach	Top-down approach
Tool used for model development		System dynamic (SD) model	Personal experience	Case-based reasoning technique and personal experience	Personal experience, AHP, PERT, and cluster analysis
Model function	Total project budget	YES	YES	YES	YES
	Deliverable (functional area) budget	N/A	YES	YES	YES
	Internal activity budget	Yes (cost of design activities)	N/A	N/A	YES
	Budget throughout implementation	N/A	N/A	N/A	YES
Model characteristics	Previous projects	Required	Required	Required	Required
	Data accessibility	Low (regular records do not contain simulation parameters)	High (related records are available)	High (related records are available)	High (related records are available)
	Model use	Long procedure (modeling is difficult, and solutions must be tested), difficult to use (the outcomes must be converted into costs)	Long procedure (the work time must be estimated for each functional area), easy to use (based on experience)	Long procedure (the work time must be estimated for each functional area), easy to use (based on experience)	Short procedure (an AHP structure, an evaluation scale, and candidate S-curves are established), easy to use (based on experience)

The contributions of this study are summarized as follows. First, the proposed model helped project managers make reasonable decisions regarding budget allocation quickly. Using their experience in combination with the proposed AHP structure and the candidate S-curves along, project managers were able to decide on the amount of funds available for each work item, as well as on the daily budget throughout the duration of a work item. Under the premise that an experienced project manager had an adequate understanding of the project content, the proposed model was more accurate than the approach employed by the test case. Second, the proposed model was effectively used to determine budget control limits for the overall project and for each work item. According to these limits, project managers made accurate judgments of the implementation status of the overall project and of individual work items. This enabled them to identify potentially out-of-control work items at an early stage and adopt mitigation measures accordingly. Third, an objective approach was employed to establish the AHP structure and evaluation scale; cluster analysis was conducted to categorize the work items of past projects according to their cost percentages. Thus, the AHP structure and evaluation scale suitable for each project were determined. Fourth, this study expanded the range of decision-making solutions the AHP can generate. Specifically, the proposed method of converting the manual scale to the model scale enabled solutions to decision-making problems involving large relative differences or level-variant evaluation scales to be generated through the AHP.

Recommendations for the proposed model's applications and for future research are discussed as follows. First, the testing results should be considered a theoretical ideal, and thus a greater number of tests should be conducted and in greater depth to further verify the model's effectiveness. Second, in practice, each engineering consulting firm uses its own coding system to document the work time spent on projects. Although the coding structure differs from that of the EWCS, the proposed model remains applicable for establishing an AHP structure and evaluation scale suitable for a given project, as well as candidate S-curves under PERT. Third, the proposed model should not be used by decision-makers with inadequate experience.

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