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APPLYING THE AHP TO SUPPORT THE BEST-VALUE CONTRACTOR SELECTION – LESSONS LEARNED FROM TWO CASE STUDIES IN TAIWAN

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Abstract. Lately the Best-Value (BV) method for contractor selection has been receiving considerable attention in the public sector in many countries. However, the operations used in performing the BV method often differ due to the various government procurement requirements. Consequently, some of the methods popular in the academic community are not easily incorporated in the BV method in some countries. To enhance the procurement process, this study aims to gain experience by applying the well-known analytical hierarchy process (AHP) to weight the decision criteria for selecting BV contractors of two construction projects in Taiwan. Through these two case studies, this work confirms that the AHP provides a significant benefit for considering the individual preferences of all decision-makers when weighting the criteria. However, this study finds two major potential obstacles, the legal requirements associated with using the AHP and the time it takes to implement the AHP. To overcome these obstacles, this work suggests guidelines to meet the legal requirements for implementing the AHP in the BV contractor selection, and proposes several strategies to shorten the AHP implementation time. The lessons learned here are relevant to those countries in which BV method must be performed in a transparent and strictly regulated environment.

Keywords: best-value tendering method, analytical hierarchy process, multiple criteria evaluations, contractor selection, case study.

1. Introduction

Selecting an appropriate contractor is essential to the successful implementation of a construction project. Although the lowest-bid method is typically adopted to award contracts for most public construction projects, the Best-Value (BV) approach (also called the most-advantageous tendering approach in Taiwan or the most economically advantageous tender method is European countries) has recently been receiving considerable attention in many countries (Yang, Wang 2003; Ohno, Harada 2006; Scott *et al.* 2006; Waara, Bröchner 2006; Abdelrahman *et al.* 2008; Elyamany, Abdelrahman 2010).

The BV refers to the optimum outcome of a business process (Akintoye *et al.* 2003). In the BV approach, bid price is not the only decision criterion (Herbsman, Ellis 1992; Gransberg, Ellicott 1997). For example, the US Federal Acquisition Regulation states that: (in addition to price) "…the quality of the product or service shall be addressed in every source selection" (FAR 2010). It further states that this shall be done "through consideration of one or more non-cost evaluation factors such as past performance, compliance with solicitation requirements, technical excellence, management capability, personnel qualifications and prior experience". The Swedish Public Procurement Act requires public sector owners that wish to select the most economically advantageous tender to consider the criteria such as cost, delivery date, running costs, quality, aesthetic values, performance, technical features, service, technical support, and environmental impact (Waara, Bröchner 2006; SPPA 2007).

There are several tendering tasks involved in the BV method, including identifying the criteria, weighting the criteria, scoring (or rating) the bidders using the criteria, and determining (or awarding) the winning bid. Although the concepts of these tendering tasks for the BV method are very similar in many countries, the way those tasks are carried out may differ substantially because of different government procurement requirements in these countries (Scott *et al.* 2006; Waara 2008). For example, in Taiwan, a group of representatives or decision-makers (officially called selection committee members in Taiwan) carry out the tendering tasks (PCC 2000) which must be performed in official meetings to ensure that there is no corruption of the selection process. However, in Japan, only a single government officer (rather than several committee members) is responsible for scoring the bidders for deciding the winning bidder (Minutes 2010).

In academia, the BV contractor selection process is a multi-criteria decision-making (MCDM) problem. Numerous MCDM models have been developed for contractor prequalification or final selection, including the utility theory (Hatush, Skitmore 1998; Pongpeng, Liston 2003), the fuzzy theory (Singh, Tiong 2005; Li *et al.* 2007), performance-based model (Alarcón, Mourgues 2002), the analytical hierarchy process (AHP) (Saaty 1978, 1980), as well as many others (Jaselskis, Russell 1991; Alsugair 1999). Among these models, the AHP-based approach has gained great popularity, mainly due to its simple and systematic implementation steps (Saaty 1978; Fong, Choi 2000; Al-Harbi 2001; Anagnostopoulos, Vavatsikos 2006; Padhi, Mohapatra 2009; Dobi *et al.* 2010). Although AHP has been reported of being practically-implemented to weight the decision criteria for selecting BV contractors in some countries (such as the United States) (Abdelrahman *et al.* 2008), it is not so easy to apply in some countries because of the different procurement regulations required. For example, there is no actual application of the AHP in public procurement in Taiwan because of certain procurement requirements that are strictly enforced in Taiwan (Lin 2008). See Section 2 for further illustrations.

To enhance the procurement process in Taiwan, this study aims to gain experience by applying the AHP to weight the decision criteria for BV contractor selection of two public construction projects (case projects I and II) in Taiwan. Following a previous study (Lin *et al.* 2008) which uses the same data of case project I for analysis, the present study also applies the AHP to case project II. In addition, the previous study focused on developing an Adaptive AHP Approach (A^3) to eliminate the iterative reassessment process of the AHP (Lin *et al.* 2008), while the present study emphasizes the application experience of using the AHP.

The rest of this paper is organized as follows. Section 2 further illustrates the obstacles of using the AHP in Taiwan. Section 3 describes the BV contractor-selection process in Taiwan. Then, Section 4 reviews a Simple Weighting method and the AHP method, and introduces a BV contractor-selection procedure that incorporates the AHP in the weight criteria. Sections 5 and 6 present the details of case studies I and II, respectively. Section 7 summarizes the findings and the lessons learned from the case studies which provide prospective users with valuable guidelines in future applications of the AHP. Finally, Section 8 discusses the research significance and suggests directions for future research.

2. An illustration of the obstacles when using the AHP

Different countries have different ways of conducting the tendering tasks of the BV contractor selection (EMAT 2003; Ohno, Harada 2006). Generally speaking, in Japan the practice depends mainly on a single government officer (Minutes 2010); the US practice is diversified (Scott *et al.* 2006); and in Taiwan the practice of BV contractor selection is conducted in a very conservative manner (PCC 2000).

In Japan, in 2009, about 98.8% of the transportation construction projects selected contractors according to the BV method (Minutes 2010). In Japan, a government officer in the public procurement department is responsible for assigning scores to the bidders based on his own judgment (Minutes 2010). Next, a committee (consisting of academic and government officers) provides comments on those assigned scores. Finally, a leader of the procurement department makes the final award decision.

In the United States, the tendering tasks can be carried out using a variety of weighting and awarding forms (Scott *et al.* 2006). For instance, Abdelrahman *et al.* (2008) calculated the weights of the criteria for two transportation projects based on questionnaires from several field engineers. As indicated earlier, in Taiwan, a selection committee executes the tendering tasks which are conducted within a certain number (usually, two or three) of official meetings. These meeting must be held with government audit officers present so as to ensure the transparency of the selection process.

In the BV approach in Taiwan, a Simple Weighting (SW) approach is used to weight criteria by the selection committee. Any committee member can freely express personal suggestion with regard to weights to be applied during the committee meetings. A final criteria weight will be determined if there is no objection by the members. Unfortunately, the SW method is sometimes criticized for not comprehensively capturing all preferences for the criteria weightings by the individual committee members because the criteria weightings are usually compromised when certain members dominate the discussions (Lin 2008). As a result, the fairness of the BV selection process may be doubtful. Therefore, this study will attempt to overcome such criticism and search for a new method (i.e., AHP) to support the task of criteria weighting.

In addition, based on interviews with certain government officers in the public sector and several practitioners who frequently served as committee members in the BV contractor-selection process in Taiwan, Lin (2008) indicated the following two major obstacles of using the AHP. First, in most existing studies, only hypothetical or simplified projects were used to apply the AHP for contractor selection (Fong, Choi 2000; Al-Harbi 2001; El-Sawalhi *et al.* 2007). Experience and ways to successfully implement the AHP to real-world case studies should be shared to reduce the risk of violating the strict procurement regulations of Taiwan.

Second, a lengthy iterative procedure is often required in applying the AHP in order to improve the Consistency Ratio (CR) when it exceeds 0.1 when assessing the pairwise weighting matrix (PWM) (Saaty 1978). A prolonged application time is not suitable since the committee members are typically unavailable for a series of long reassessments. In addition, delays in the contractor-selection process for public construction projects are frowned upon (since it leaves the members open to accusations of not conducting the tendering process in a transparent manner). Hence, it is imperative that strategies that shorten the AHP reassessment time are explored.

3. Best-value contractor selection process in Taiwan

As mandated by the Taiwan's procurement law, when a governmental entity (called the project owner or client hereafter) adopts the BV approach for contractor selection, approval must first be obtained from a superior entity (PCC 1998, 2000; Yang, Wang 2003). Fig. 1 shows the best-value contractor-selection procedure in Taiwan. The major steps are as follows.

In step 1 (Fig. 1), the project client must prepare a draft of the selection method, including evaluation/decision criteria, criteria weights, the scoring method, and other relevant documents (such as evaluation forms and checklists). A selection committee must be organized to review the draft. The committee comprises of 5–17 members, whose fields of expertise are generally related to the design, construction, or operation of the planned project.

Before advertising the tender, the committee must hold at least one official meeting to confirm the selection method (Step 3). Notably, decision criteria are related to technology, quality, function, commercial terms, or bid prices. For a given criterion, sub-criteria are developed by the committee based on the characteristics of the project. Thus, numerous hierarchical decision criteria are eventually established.

Based on the published tender and contractor-selection method (step 4), interested bidders prepare and submit their bids (step 5). Notably, when the number of bids does not exceed the minimum required number of bids (three bids are needed for the first tendering process), the tender is published again. When the number of bidders is sufficient, the final selection procedure proceeds. Following the prequalification process to eliminate unqualified bidders (step 6), a selection meeting is held in which shortlisted bidders present their proposals; these proposals are then evaluated by the committee to determine the BV contractor (steps 7–9).

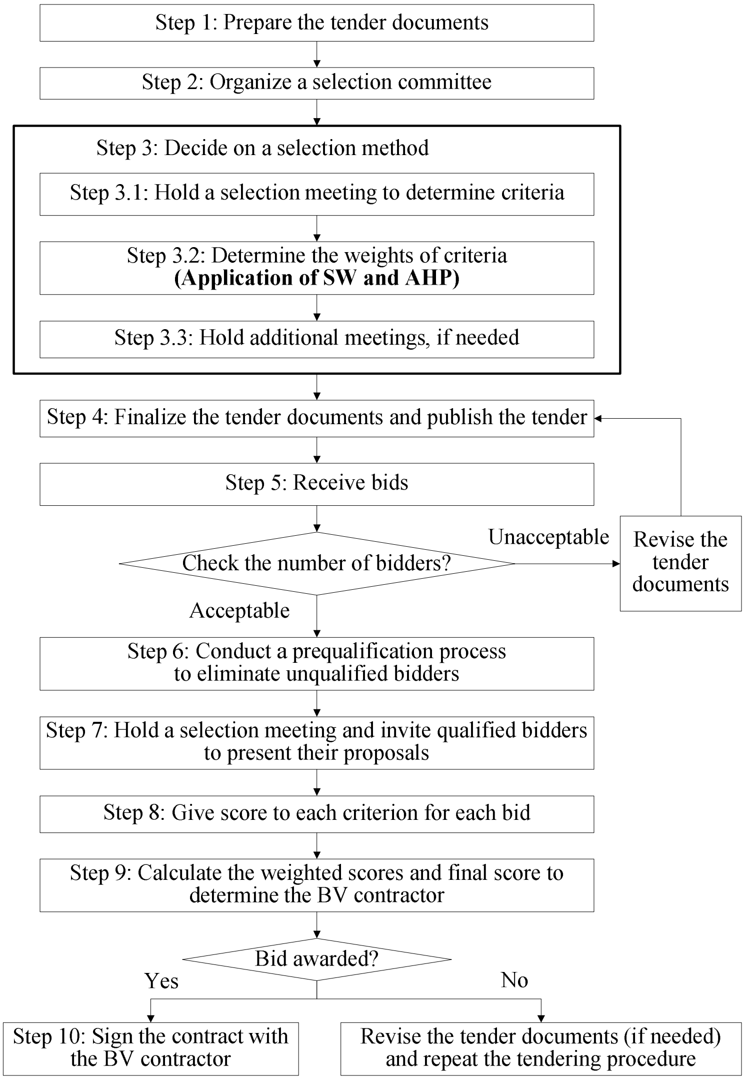

Fig. 1. The best-value contractor-selection procedure in Taiwan

In step 9, three scoring methods, i.e. the weighted score method, score-of-unit-price method, and ranking method, can be utilized to choose the winning contractor. The weighted score method uses the following steps to evaluate each bidder: (1) each committee member first scores each criterion; (2) the weighted score for each criterion is calculated by multiplying criterion score by criterion weight; (3) a total weighted score is obtained by summing the weighted scores of all criteria from a committee member; and (4) a final score is calculated by averaging the total weighted scores from all committee members. Last, the bid that has the highest final score is considered the BV contractor and awarded the contract.

The score-of-unit-price method, which is rarely used, does not consider bid price as an evaluation criterion. However, the score-of-unit-price for a bidder is the final score divided by the proposed bid price. Thus, the bid with the lowest score-of-unit-price wins the contract. The ranking method resembles the weighted score method. However, a committee member ranks the bid with the highest final score as No. 1, and the bid with the second highest final score is ranked second; this ranking process continues until all bids are ranked. Next, each bid is assigned a rank that is the sum of ranks from all committee members. The bid with the lowest sum of ranking values is the BV contractor. Further details of these three scoring methods can be found in PCC (2000).

4. Review of the SW and AHP methods

4.1. Simple Weighting (SW) method

The SW method determines criteria weights via a consensus process (PCC 2000; Lin 2008). During the first selection committee meeting (Step 3 in Fig. 1), the client task force usually proposes a set of initial weights as a basis for discussions. Ideally, high weights are given to the criteria considered more important, and *vice versa*. However, in reality, different decision-makers assess the importance of criteria differently. Thus, committee members freely present their opinions on criteria weights; weights are adjusted until consensus is reached. Voting is implemented when consensus cannot be achieved. Very often, discussions of criteria weights are dominated by a few members, and consensus is usually reached as most members do not want to delay the criteria weighting process by choosing to compromise. Up to date, only the SW method has been practically applied to weight decision criteria for contractor selection with regard to the public construction projects in Taiwan.

4.2. AHP method

The AHP is a structured and systematic approach for determining the relative importance weights of decision criteria in MCDM (Saaty 1978). The AHP has also been applied to many other areas in construction management such as determination of facility location (Yang, Lee 1997), proposal evaluation (Bertolini *et al.* 2006), project selection (Cheng, Li 2004), project ranking, contract evaluation (Podvezko *et al.* 2010), and improving construction productivity (Doloi 2008). Additionally, based on the concept of the AHP, several subsequent models, such as fuzzy AHP (Jaskowski *et al.* 2010), analytic network process (ANP) (Cheng, Li 2004), and fuzzy ANP (Wu *et al.* 2008) have also been developed.

Fig. 2 shows the implementation steps for incorporating the pure AHP into the aforementioned BV contractor-selection procedure. In step 3.2.1 (Fig. 2), the criteria are assumed independent, and the importance of criteria is pairwisely compared by each committee member to derive criteria weights according to AHP algorithms. The scale utilized to derive the relative importance from matrices of pairwise comparisons is 1–9 (Saaty 1978), where 1 represents "equally important", 3 represents "slightly more important", 5 represents "strongly more important", 7 represents "demonstratedly more important", and, 9 represents "absolutely more important", whereas 2, 4, 6, 8 denote the degrees of importance between 1 and 3, 3 and 5, 5 and 7, and 7 and 9, respectively.

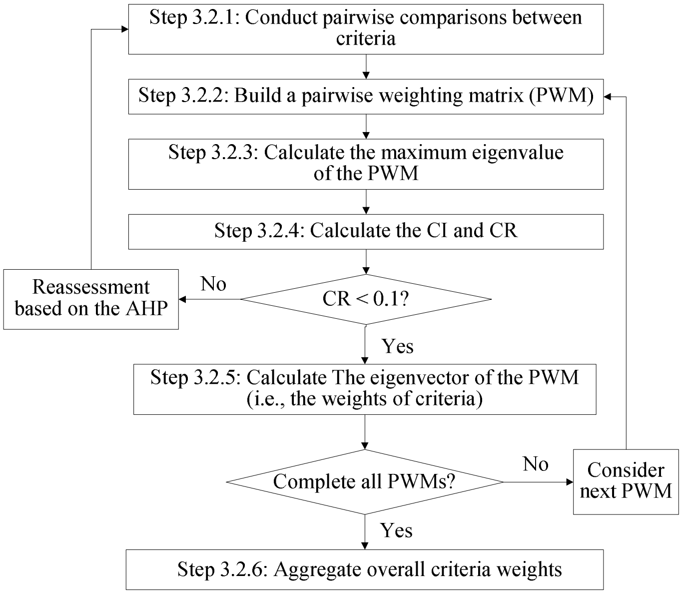

Fig. 2. Implementation steps for the AHP method for each committee member

In step 3.2.2, comparisons are organized in a PWM (see Fig. 3). A PWM is a positive reciprocal matrix $A = \{a_{ij}\}$, where $a_{ij} = \frac{w_i}{w_j}$ and w_i is the weight of the i^{th} criterion (i.e., Z_i) (Lin *et al.* 2008). The PWM is obtained by pairwise comparison between each pair of criteria. Each comparison is transformed into a numerical value of the Saaty's discrete 9-value scale (Saaty 1978) (Fig. 3).

$$\begin{array}{c|cccc} & Z_1 & Z_2 & \cdots & Z_n \\ \hline Z_1 & \frac{w_1}{w_1} & \frac{w_1}{w_2} & \cdots & \frac{w_1}{w_n} \\ Z_2 & \frac{w_2}{w_1} & \frac{w_2}{w_2} & \cdots & \frac{w_2}{w_n} \\ \vdots & \vdots & \vdots & & \vdots \\ Z_n & \frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & \frac{w_n}{w_n} \end{array}$$

Fig. 3. Pairwise weighting matrix (PWM) of AHP

In step 3.2.3, the vector of preferences is generated. An approach is usually applied for that which employs the eigenvector corresponding to the maximum eigenvalue of a matrix (Saaty 1978). Due to the limitation of Saaty's discrete 9-value scale and the inconsistency inherent in human judgment while weights are assessed during the pairwise comparison process, the aggregation weight vector may be invalid. Hence, in step 3.2.4, the consistency index (CI) is used to measure inconsistency (Saaty 1978). The CI is defined as follows:

$$\text{CI} = \frac{\lambda\,\max - n}{n-1}, \tag{1}$$

where n is the number of criteria, and $\lambda_{\max}$ is the maximum eigenvalue. The CI is then divided by the average random consistency index (RI) to obtain the consistency ratio (CR) (Saaty 1980):

$$\text{CR} = \frac{CI}{RI}. \tag{2}$$

Next, when CR > 0.1, pairwise comparison results must be rejected. A reassessment cycle of the relative importance between criteria is required until CR < 0.1. When CR < 0.1 for a PWM, the matrix of preferences in step 3.2.5 is manipulated via a method that determines the eigenvector corresponding to the maximum eigenvalue of a matrix (Saaty 1978; Lin 2008). The criteria weights for a particular PWM can be thus calculated. The sum of all criteria weights equals 1. After all PWMs are processed in step 3.2.6, the weights of all criteria in the hierarchy are obtained. Notably, steps 3.2.1–3.2.6 are executed by each committee member. After these steps are repeated to estimate the criteria weights from all members, an average weight of each criterion can be determined by averaging the weights assigned by all committee members.

5. Application to the case project I

This section describes the background, organization of the selection committee, evaluation criteria, weights of criteria generated by the SW and AHP approaches, and contractor-selection results for the case project I.

5.1. Project background

The case project I pertains to construction of the National Laboratory Animal Center in southern Taiwan. The project includes construction of a high-tech laboratory for raising laboratory animals. The five-floor facility is to be made of reinforced concrete with two floors underground. Total floor area is about 15,992 m^2. The construction budget is approximately US$ 18 million. Project duration is 450 calendar days.

The construction project has three main components: (1) civil and building (C&B) construction; (2) mechanical, electrical, and plumbing (MEP) works; and (3) specific pathogen-free (SPF) construction. Project complexity is high because the project involves the construction of several class-10,000 clean rooms and four complex SPF barrier systems (consisting of air showers, passing box, and autoclave units). As the project is extremely complex, the BV tendering method was utilized for contractor selection. The project client established a task force to manage the project tendering process. The research team worked closely with this task force.

5.2. Members of the selection committee

When the tender document of the project was almost complete, the project client established a 17-member committee with members who possess the C&B, MEP, or SPF expertise required by this project. Some members are selected from the Public Construction Commission database (the highest government agency for public works in Taiwan), while others are chosen from the expertise domains. Notably, only 14 members were able to attend selection meetings. Among these 14 members, three members are from the C&B domain (architectural design and construction management), five members are from the MEP domain (heating-ventilating, air-conditioning, electrical engineering, and industrial safety), and six members are from the SPF domain (animal laboratory researchers). All of these members are either from academia or government agencies.

5.3. Decision criteria

After the committee members were chosen, the project owner held a meeting to determine a three-level hierarchy for decision criteria. This hierarchy consists of four level-one criteria (*bid price*, criterion 1; *technical*, criterion 2; *organization*, criterion 3; and *question and answer (Q&A)*, criterion 4) (Fig. 4). Moreover, three level-one criteria (*bid price*, *technical*, and *organization*) are broken down further into sub-criteria.

The *bid price* criterion consists of two level-two criteria: *total bid price* (criterion 1.1) and *item bid prices* (criterion 1.2). The *technical* criterion comprises three level-two criteria: *C&B*, *MEP*, and *SPF*. The organization criterion consists of three level-two criteria: integration ability (*integration*), joint contract experience (*experience*), and team member reputation (*reputation*).

Moreover, the *C&B* (criterion 2.1) and *MEP* (criterion 2.2) criteria consist of six level-three criteria, namely, quality assurance (*QA*), schedule planning and control capabilities (*schedule*), product specifications (*SPECs*), construction management capability (*CM*), safety and environmental protection (*S&E*), and previous performance (*perform*). Furthermore, the *SPF* criterion (criterion 2.3) has seven level-three criteria: *QA*, *schedule*, *SPECs*, *S&E*, *perform*, subcontractor management capability (*SC*), and service post installation (*service*).

However, to simplify the weighting process, the committee applied a simplified decision hierarchy (Fig. 5). This simplified hierarchy only consists of four level-one criteria and three level-two criteria under the *technical* criterion. Notably, although level-two and level-three criteria in the simplified decision hierarchy haven't been assigned weights, they are explicitly shown in the description of evaluation criteria in tender documents.

5.4. Weights of criteria

The SW method was applied to weight the criteria shown in Fig. 5. Additionally, the AHP method was implemented based on decision criteria displayed in Fig. 4. Table 1 summarizes the average weights of criteria obtained using the SW and AHP methods. The following subsections describe the working details of each method.

5.4.1. Implementation of the SW method

After decision criteria (Fig. 5) were identified in the selection meeting, the committee then further discussed the weights of criteria. According to a set of initial weights proposed by the task force, the committee took approximately one hour to finalize the criteria weights (left side of Table 1).

5.4.2. Implementation of AHP

In AHP weightings, the relative importance of criteria in the same level is compared to obtain PWMs using the 9-value scale by Saaty. Fourteen members (three C&B members, five MEP members, and six SPF members) in the committee assessed the AHP weights. Each member completed seven relative importance assessment tables and, thus, generated seven PWMs: one level-one PWM; three level-two PWMs (*bid price*, *technical* and *organization*), and three level-three PWMs (*C&B*, *MEP*, and *SPF*). In total, 98 (= 7×14) PWMs are acquired.

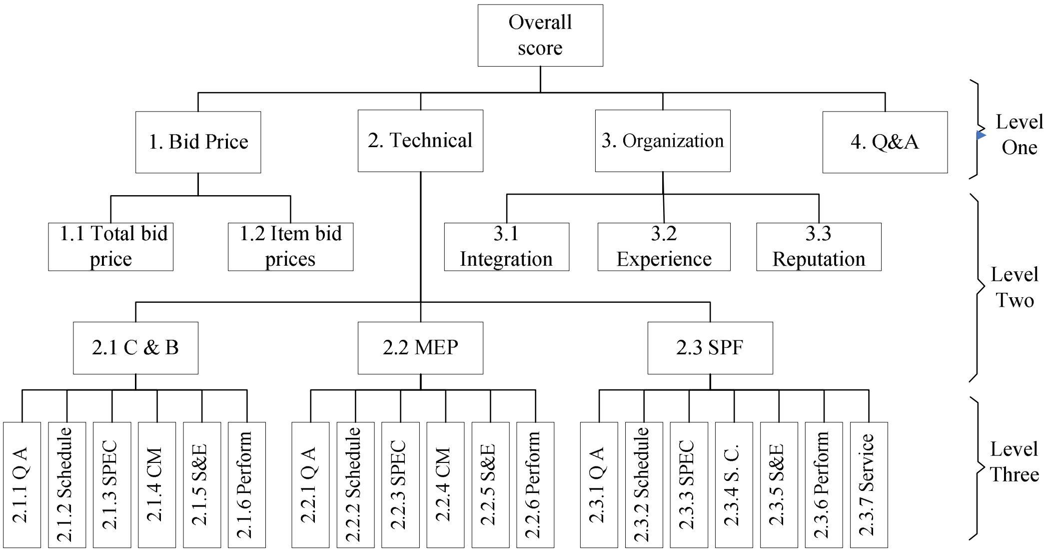

Fig. 4. Hierarchy of decision criteria applied in the AHP method for the case project I

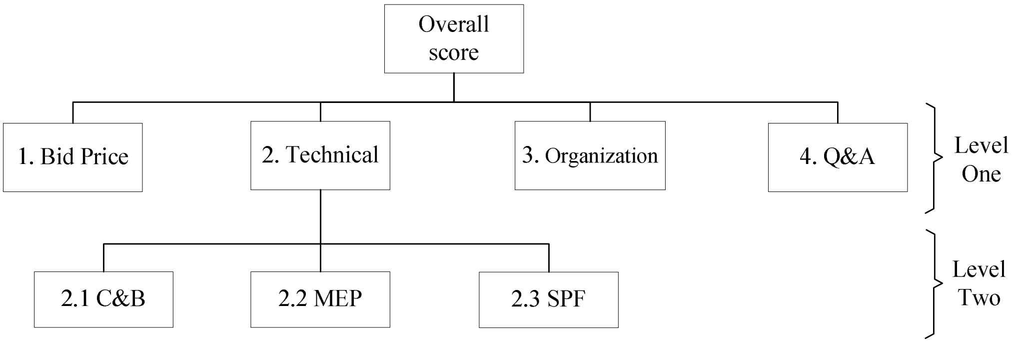

Fig. 5. Decision criteria applied in the SW method for the case project I

Table 1. The average weights of criteria for each method for the case project I

Criteria	SW		AHP		
	Level 1	Level 2	Level 1	Level 2	Level 3
1. Bid price	0.20		0.123		
1.1 Total bid price				0.082	
1.2 Item bid prices				0.041	
2. Technical	0.60		0.543		
2.1 C&B		0.20		0.084	
2.1.1 Q A					0.017
2.1.2 Schedule					0.019
2.1.3 SPEC					0.016
2.1.4 CM					0.016
2.1.5 S&E					0.007
2.1.6 Perform					0.009
2.2 MEP		0.25		0.207	
2.2.1 Q A					0.050
2.2.2 Schedule					0.043
2.2.3 SPEC					0.058
2.2.4 CM					0.023
2.2.5 S&E					0.016
2.2.6 Perform					0.017
2.3 SPF		0.15		0.252	
2.3.1 Q A					0.050
2.3.2 Schedule					0.032
2.3.3 SPEC					0.065
2.3.4 S. C.					0.017
2.3.5 S&E					0.023
2.3.6 Perform					0.030
2.3.7 Service					0.034
3. Organization	0.15		0.271		
3.1 Integration				0.110	
3.2 Experience				0.046	
3.3 Reputation				0.113	
4. Q&A	0.05		0.063		

During the first cycle of AHP assessment, questionnaires were sent to members via e-mail, land mail or personal delivery. To ensure completion of each questionnaire, a personal or telephone interview was conducted to explain the AHP procedure and questionnaire to each member. Every member completed the questionnaires independently. Among the 98 PWMs, 49 are acceptable (i.e. $CR < 0.1$) during the first assessment; the remaining 49 PWMs are unacceptable and require reassessment.

After the second assessment, 33 (of 49) PWMs are acceptable; the remaining 16 PWMs need reassessment. Thirteen (of 16) PWMs are acceptable after the third assessment, and the remaining three PWMs are acceptable after the fourth assessment. No PWMs need a fifth assessment. To summarize, 166 (= 98 + 49 + 16 + 3) PWMs are constructed. The details of each PWM are found in Lin (2008).

After completing the 98 PWMs, criteria weights are then computed. Finally, an average weight for each criterion is derived by averaging the weights assigned by the 14 committee members. The right of Table 1 displays the average weight of each criterion.

Table 2 presents the number (and percentage) of unacceptable PWMs and average *CR* values for each of the four cycles of AHP assessments. Additionally, Table 2 reveals that the committee members seem adept at adjusting their preferences to meet the required CR. This observation is confirmed by the decreasing percentages of unacceptable PWMs of 50%, 32.7%, 18.75%, and 0% for the first, the second, the third and the fourth assessment cycle, respectively, and the decreasing average CR values of 0.142, 0.101, 0.085, and 0.063 for the first, the second, the third and the fourth assessment cycle, respectively.

Table 2. The average *CR* values obtained using the AHP method for the case project I

Assessment cycle Attributes	AHP			
	First	Second	Third	Fourth
No. of PWMs performed	98	49	16	3
No. and % of unacceptable PWMs	49(50%)	16(32.70%)	3(18.75%)	0(0%)
Average consistency ratio (CR)	0.142	0.101	0.085	0.063

5.5. Contractor selection results

After the tender documents were published, less than the minimum required 3 bids were received, and thus the tender was published again. At the second tender, only two bidders (A and B) bid on the case project I. After reviewing submitted bids, analyzing their oral presentations, and clarifying their bids via a Q&A, the committee members scored the six criteria (*bid price*, *C&B*, *MEP*, *SPF*, *organization*, and *Q&A*) (Fig. 5) for each bidder. The weighted score method was adopted to make a final decision. Table 3 shows the average of weighted scores from all members for each criterion, and the final score for each bidder using the SW and AHP approaches. Both approaches obtain the same result, namely, bidder B is the BV bidder.

Table 3. Final score and weighted scores of bids using the SW and AHP methods for the case project I

	SW		AHP	
Bidder	A	B	A	B
1. Bid price	16.54	16.86	10.7	10.78
2.1 C&B	16.55	15.6	16.26	15.57
2.2 MEP	19.83	21	14.51	15.78
2.3 SPF	11.78	12.93	10.35	11.16
3. Organization	12.4	11.64	21.26	20.04
4. Q&A	4.15	4.05	5.03	4.96
Final score	81.25	82.08	78.11	78.29

5.6. Differences in weighting results between the SW method and AHP

The weighting results obtained using the SW approach and AHP for the case project I are compared as follows.

1. *Overall, the weight of a particular criterion by the SW approach and AHP differ significantly.* Fig. 6 depicts the average weights of first-level and second-level criteria using the SW approach and AHP. For instance, the differences in weights acquired using the SW approach and AHP are roughly 58% (= |0.084 − 0.2|/0.2) for *C&B*, 68% (= |0.252 − 0.15|/0.15) for *SPF* and 80% (= |0.27 − 0.15|/0.15) for the *organization* criterion, respectively. During the SW process, members typically emphasize the importance of the *price* and *C&B* criteria, while in the AHP, they generally place relatively more weight on the *SPF* and *organization* criteria. Additionally, the *MEP* criterion has the largest weight (= 0.25) using the SW method, and the *organization* criterion has the highest weight (= 0.27) using the AHP. In other words, the ranks of criteria using the two methods vary. However, both methods give the lowest weight to the *Q&A* criterion. These differences in criterion weights may be due to the influence of specific members who dominate weighting discussions in the SW method. Conversely, in the AHP, decisions are made by members independently and, thus, reflect the true opinions of the selection committee.

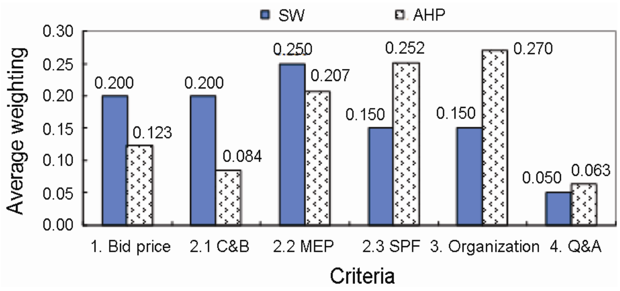

Fig. 6. Comparison of criteria weights using the SW method and AHP for the case project I

2. *As various domain experts weight the criteria differently, choosing committee members from different backgrounds can reduce bias*. The C&B, MEP and SPF domain experts have similar views on the importance of first-level criteria (i.e., *bid price*, *technical*, *organization* and *Q&A*) (Fig. 7). That is, all three domain experts generally agree that the *technical* criterion is most important, followed by the *organization*, *bid price* and *Q/A* criteria.

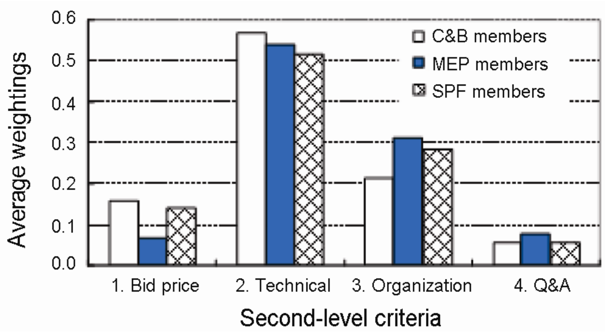

Fig. 7. Average weights assigned by different domain members to first-level criteria for the case project I

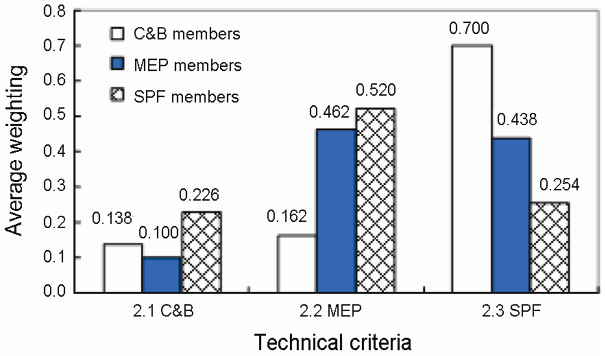

Fig. 8. Average weights assigned by different domain members to second-level criteria under the technical criterion for the case project I

However, the weights of second-level criteria under the first-level *technical* criterion imply that a domain expert may overweight those criteria he/she is unfamiliar with, and underweight those criteria for which he/she has specialized knowledge (Fig. 8). For example, the C&B experts weight the *SPF* criterion highest, and assign the lowest weight to the *C&B* criterion. Furthermore, the MEP experts consider *SPF* and *MEP* criteria as almost equally important. Moreover, the SPF members consider the *MEP* criterion more important than the *SPF* criterion. Such analytical results likely indicate that humans tend to exaggerate the importance (or risk) of those areas with which they are unacquainted. Conversely, people tend to overlook the importance (or risk) of those areas in which they are specialized. To minimize such bias, we recommend including as many committee members from different backgrounds as possible.

6. Application to the case project II

This section describes the background and weights of the criteria generated by the SW and AHP approaches for the case project II.

6.1. Project description

The case project II involves the construction of a high-tech facility for a national research center located in northern Taiwan. This project is comprised of three main components: (1) civil work and building construction (Civil); (2) mechanical, electrical and plumbing (MEP) works; and (3) special equipment construction (SEC). The design and construction of this case project is very complex because it requires particular domain knowledge, such as synchrotron accelerators and resistance against micro-vibrations. The case project II relates to the construction of the Civil component which was tendered based on the BV method. The total floor area of the facility is approximately 53,000 m^2. The total budget for the construction of the Civil component is approximately 43 million USD.

The project client established a 12-member committee with members who have Civil, MEP, or SEC expertise as required by the project. All of these members are either from academia, the industry or from a government agency. Following the tendering steps as shown in Fig. 1, the committee members of the case project II determined a two-level hierarchy for the decision criteria, as shown in the left of Table 4. This hierarchy consists of six level-one criteria (*technical and quality, management*, *past performance*, *commercial terms*, *price*, and *question and answer*). In addition it involves thirteen level-two criteria.

6.2. Results of the criteria weighting

The SW method and the AHP were applied to weight the decision criteria for the same hierarchy of criteria. The middle and the right-hand sides of Table 4 summarize the average weights of the criteria obtained by using the SW method and the AHP for the case project II, respectively. It is evident that the weights of the *management* criteria *obtained by the SW approach and the AHP are significantly different.* In addition, Table 5 presents the number and the percentage of the unacceptable PWMs as well as the average *CR* values for each of the four cycles of the AHP assessments.

Table 4. The average weights of criteria for each method for the case project II

Criteria	SW		AHP	
	Level 1	Level 2	Level 1	Level 2
1. Technical and quality	0.30		0.362	
1.1 technical ability		0.15		0.254
1.2 Environmental protection		0.05		0.047
1.3 Quality management plan		0.10		0.061
2. Management	0.15		0.239	
2.1 Organization		0.05		0.126
2.2 Financial condition		0.05		0.067
2.3 Emergency management		0.05		0.046
3. Past performance	0.15		0.196	
3.1 Experience		0.10		0.070
3.2 Performance records		0.05		0.126
4. Commercial terms	0.10		0.077	
4.1 Construction duration		0.06		0.049
4.2 Bidder's promises		0.02		0.011
4.3 Maintenance service		0.02		0.017
5. Price	0.20		0.090	
5.1 Total bid price		0.10		0.035
5.2 Item bid price		0.10		0.055
6. Question/ answer	0.10		0.036	

Table 5. The average *CR* values obtained using the AHP method for the case project II

Assessment cycle Attributes	AHP			
	First	Second	Third	Fourth
No. of PWMs performed	66	27	14	2
No. and % of unacceptable PWMs	27(40.9%)	14(51.90%)	2(14.3%)	0(0%)
Average consistency ratio (CR)	0.094	0.065	0.029	0.028

6.3. Contractor selection results

The tendering process of the case project II also failed in the first round because of insufficient bids. Two bidders (C and D) bid on the case project II in the second tendering process. This project adopted the ranking method to select the winner. Table 6 summarizes the contractor-selection results using the SW and AHP methods. Let's take member M1 in the SW method for example. After reviewing the submitted bids, analyzing their oral presentations, and clarifying their bids via a Q&A session, committee member M1 scored the six criteria (*technical and quality, management*, *past performance*, *commercial terms*, *price*, and *question and answer*) (left of Table 4) for each bidder. Then, a weighted score is calculated for each bidder. Bidder D was thus ranked No. 1 because he received the highest weighted score. Bidder C received the second highest weighted score and was ranked as No. 2. Each member assigned rank No. 1 or No. 2 to either bidder C or bidder D. Finally, the sums of the ranking numbers were calculated to be 19 and 17 for bidders C and D, respectively. Thus, bidder D was the winning contractor because the total of his ranking numbers was the smallest.

Table 6. The bidding results using the SW and AHP methods for the case project II

Committee Member	SW		AHP	
	Bidder C	Bidder D	Bidder C	Bidder D
M 1	Rank 2	Rank 1	Rank 2	Rank 1
M 2	Rank 2	Rank 1	Rank 2	Rank 1
M 3	Rank 2	Rank 1	Rank 1	Rank 2
M 4	Rank 2	Rank 1	Rank 1	Rank 2
M 5	Rank 2	Rank 1	Rank 1	Rank 2
M 6	Rank 2	Rank 1	Rank 2	Rank 1
M 7	Rank 1	Rank 2	Rank 2	Rank 1
M 8	Rank 2	Rank 1	Rank 2	Rank 1
M 9	Rank 1	Rank 2	Rank 2	Rank 1
M 10	Rank 1	Rank 2	Rank 2	Rank 1
M 11	Rank 1	Rank 2	Rank 2	Rank 1
M 12	Rank 1	Rank 2	Rank 2	Rank 1
Sum of ranking numbers	19	17	16	20
Final ranking	2	1	1	2

Next, the AHP criteria weightings (right-hand side of Table 4) were used to generate the selection results for the case project II. It should be noted here that in the AHP analysis of the case project II, the scores assigned by each committee member are assumed, because these scores are not disclosed after the contractor-selection evaluations are finalized. The right-hand side of Table 6 shows the new rankings for each member based on the assumed scores and the AHP weightings. The AHP results show possibility of change in the rankings provided by the committee members. This is really the case of the M3, M4, and M5 committee members. More importantly, bidder C may become the winner when AHP weightings are used.

7. Other lessons learned

After conducting the two case studies, several lessons are identified via discussions with some committee members. These lessons are associated with the major concerns of practitioner using the AHP. The lessons are as follows: (1) the legality of implementing the AHP; (2) implementation time; and (3) strategies to shorten AHP implementation time.

7.1. Legality of implementing the AHP

This work designed an operation-level AHP-based BV contractor-selection procedure (Figs 1 and 2) which was tested in two real-world public construction projects. However, the following three tasks should be performed carefully in order to meet the legal requirements of Taiwan's procurement law:

1. *The determined criteria weights must be enclosed in the publicized tender documents (step 4 in Fig. 1) to ensure that the tendering procedure is fair and transparent for all potential bidders*. A late announcement of a contractor-selection method (including criteria weights) could be construed as favoring particular bidders. Thus, step 2 (organize a selection committee) and step 3 (decide on a selection method) (Fig. 1) should be finished no later than when tender documents, such as design drawings and specifications, are published;
2. *The AHP steps should be executed in a transplant manner.* In these two case studies, the data required to establish the PWMs are acquired informally after selection meetings. In practice, when the AHP is applied, such data should be collected during formal meeting(s) to ensure openness and fairness of the tender process. Audit officers should be formally invited to attend these meetings. Notably, more than one selection meeting may be needed when executing the AHP requires more than one day;
3. *All AHP implementation materials should be formally documented.* The AHP-related materials include meeting minutes and accepted/unaccepted PWMs. Again, this task is implemented to ensure that the tender process is open and fair.

7.2. Implementation time

The research team successfully controlled the AHP weights to be determined before completing the tender documents, indicating that using the AHP can meet the schedule required by the BV contractor-selection procedure. Nevertheless, AHP implementation time should be as short as possible to minimize the number of required meetings. Too many selection meetings will likely discourage committee members from participating the AHP as most members typically have busy schedules.

As indicated in the case project I, the committee adopted the SW method to determine the criteria weights within about one hour. The AHP, however, took on average 2.5 hours to generate a PWM. The 166 PWMs in four cycles of AHP assessment required approximately 25 calendar days; the first cycle of initial assessments took seven days and the following three cycles took 18

Table 7. Time required to weight criteria using the SW and AHP-based methods for the case project I

	Methods			
	SW	AHP	AHP-1	AHP-2
No. of PWMs in a cycle		7	7	7
Processing time of a PWM		2.5 hours	15 minutes	15 minutes
Processing time of 1 cycle		7 days	105 min (= 7 × 15)	105 min (= 7 × 15)
Processing time of 4 cycles		7 + 18 days	420 min (= 105 × 4)	210 min (= 105 × 2)
Total duration	1 hour	25 days	7 hours	3.5 hours

Note: AHP: the process is done manually; AHP-1: the process is computerized; AHP-2: the process is computerized and is reduced to two cycles.

days. The left of Table 7 summarizes the time required for weighting criteria using the SW method and AHP in case project I. In total, 25 calendar days were required to complete the AHP, mainly because members were not given any time pressure to fill out questionnaires, and AHP weights were calculated using only spreadsheets (not automatically). According to observations of the research team, an average of 2.5 hours was required to finish a PWM, in which roughly 0.5 hours was spent generating input data of relative importance between criteria, and the remaining 2 hours were spent processing AHP calculations. Nevertheless, several members indicate that 15 minutes should be sufficient to fill out the questionnaire.

7.3. Strategies to shorten AHP implementation time

Several strategies to shorten AHP implementation time are as follows:

1. *Computerization of AHP can significantly reduce implementation time.* A computerized AHP Weighting System (AWS) is developed by the research team using Matlab® 7.0. After keying in data from a PWM, the required calculation time of AWS to automatically obtain criteria weights of the PWM is less than one second for a PC with an Intel® Core™ 2 CPU 6600 @2.4 GHz. Hence, the research team proposes an alternative AHP method, called AHP-1. With AHP-1, processing a PWM requires only approximately 15 minutes (= 15 minutes to fill out assessments and one second for processing AHP calculations). In the case project I, seven PWMs are processed for each member. Thus, 105 minutes (= 15 × 7) are needed for each cycle of AHP assessment. In total, 420 minutes (= 105 × 4) or 7 hours are needed for four cycles of AHP assessments. Thus, holding three selection meetings (assuming about 3 hours is required for each meeting) is within the seven hours needed for the AHP. The middle of Table 7 compares the estimated time for weighting criteria using AHP-1. In summary, computerization of the AHP can significantly increase its applicability;

2. *Education can reduce the number of reassessment cycles.* Although AHP-1 can improve the applicability of AHP implementation, holding three selection meetings is still impractical for most committee members. Eliminating the reassessment process can solve this problem. Educating committee members is another solution. Most committee members involved in AHP assessments are unfamiliar with the AHP. Consequently, in the case project I, the initial acceptance rate for primitive PWMs is only 50%. After explanations by the research team, the rejection rate decreases significantly. Some members believe that four cycles of AHP assessment can be reduced to two cycles if they are familiar with the AHP algorithms prior to assessments. When members are educated in the AHP algorithms (called the AHP-2 method), only 210 minutes (= 105 × 2) or 3.5 hours or one selection meeting will be needed. This AHP-2 will be welcome in future applications. The right of Table 7 shows the estimated time using AHP-2;

3. *Reducing the number of criteria levels can reduce the number of PWMs.* In case project I, three levels of criteria were involved and 166 PWMs were required for the AHP assessment. In case project II which involves only two criteria levels, only 119 PWMs are required for all 12 members. Furthermore, reducing the number of criteria levels simplifies the complexity of the problem, thereby increasing the accuracy of the judgments by the decision-makers in pairwise comparisons. It should be noted however, that the selection of the proper criteria should be rational and may not be changed arbitrarily just to shorten the AHP implementation time;

4. *Any method that can shorten the AHP processing time is desirable.* For example, the aforementioned A^3 model only requires the time needed for the first AHP assessment cycle plus adaptation time (Lin *et al.* 2008). Alternatively, Tam *et al.* (2006) proposed a simplified tool that aids AHP decision-making. This tool uses a 3-value scale rather than a 9-value scale for relative importance assessment, thereby reducing the time required to handle inconsistencies.

8. Conclusions

This work tests the AHP application suitability for assessment of the criterion weights in the BV contractor-selection process for two real-world construction projects in Taiwan. The empirical studies demonstrated that concerns by practitioners regarding the use of the AHP can be resolved. At first, an operation-level AHP-based procedure was developed that meets Taiwan's legal requirements. Guidelines to meet the legality of implementing the AHP were provided. At second, the long time required by the AHP iterative procedure can be shortened by eliminating the reassessment process. Education prior to implementation is also suggested with this regard. Moreover, properly using only two levels of decision criteria can improve the time efficiency of the AHP implementation too.

The two case studies also indicated that the weighting results calculated by the AHP and the SW method differ significantly. The SW method is prone to become dominated by certain members who lead the discussions during the weighting meetings. On the other hand the AHP better reflects the opinions of each individual member and is therefore a more objective method. The case study I indicated that committee members typically overlook the importance of the technical criteria in their own specialty, but they overemphasize those with which they are unfamiliar. As a result, we suggest using a strategy that includes as many domain experts as possible with different backgrounds in the selection committee. Furthermore, the AHP application for the case study II showed that AHP weightings may have a significant impact on results of the BV contractor selection. Overall, the lessons learned here are relevant to those countries whose BV method must be operated in a transparent and strictly regulated environment. Future work should focus on the application of additional projects to share practical experience. The long time required to implement the AHP limits its use. Thus, any tool that shortens the AHP implementation time deserves attention.

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