QUANTITATIVE TECHNIQUES FOR DECISION MAKING IN CONSTRUCTION

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CONTENTS

1 ANALYTIC HIERARCHY PROCESS I

1.1 What Is Analytic Hierarchy Process (AHP) ?

The "Analytic Hierarchy Process" (or AHP in short), a mathematical tool for management decision making, was introduced by Thomas L. Saaty (1977 and 1980). The mathematical technique is capable of handling a large number of decision factors and provides a systematic procedure of ranking many decision variables. It is a decision analysis technique which can be very useful in construction management. This chapter will firstly give a brief description of the theory of AHP. Cases will then be used to illustrate how this analysis technique can be applied in the field of construction.

1.2 Mathematical Theory of AHP

1.2.1 We will use the selection of tenders as an example in explaining the AHP theory. Suppose that there are n factors in considering whether a tender should be accepted or not. These n factors have different importance contributing to the acceptance or unacceptance of the tender. In assessing the importance of each factor, pairwise comparisons are used so that any one factor is not compared to all other factors simultaneously but rather *one at a time*. For an easy explanation let us take $n = 3$ in the following example.

Three factors: 1, 2 and 3.
Factor 1 is twice as important as Factor 2.
Factor 2 is three times as important as Factor 3.
Factor 1 is six times as important as Factor 3.
Then, these scores can be entered into a matrix A as follows:

		1	2	3
	1	1	2	6
A =	2	1/2	1	3
	3	1/6	1/3	1

Matrix A is called the "reciprocal matrix" because all its lower triangular elements are equal to the reciprocal of its upper triangular elements. The maximum eigenvalue λ of matrix A can be found by solving

$$| A - \lambda I | = 0$$

The eigenvector X, corresponding to the maximum eigenvalue λ, which satisfies that $AX = \lambda X$, is found to be:

$$X = \begin{bmatrix} 0.6 \\ 0.3 \\ 0.1 \end{bmatrix} \begin{matrix} \text{- Factor 1} \\ \text{- Factor 2} \\ \text{- Factor 3} \end{matrix}$$

The higher the value of the element in X, the more important the factor is.

1.2.2 Readers may find it difficult to understand why the resultant eigenvector can represent importance. The following gives a brief explanation. Details of it can be found in the work of Saaty (1977 and 1980).

Suppose a set of n objects are to be compared in pairs and their individual importance (assumed known) are denoted by $x_1, x_2, ..., x_n$, then the pairwise comparison may be represented by a (n x n) square reciprocal matrix A as follows:

		1	2	...	...	...	n
	1	1	x_1/x_2	...	...	...	x_1/x_n
	2	x_2/x_1	1				x_2/x_n
	:	:					:
A =	:	:					:
	:	:					:
	:	:					:
	n	x_n/x_1	x_n/x_2	...	...	...	1

If a column vector X is defined such that $x_1, x_2, ..., x_n$ (i.e. the individual importance of objects 1, 2, ..., n) are the elements of X such that

$$X = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_n \end{bmatrix}$$

then,

$$AX = \begin{bmatrix} 1 & x_1/x_2 & \cdots & x_1/x_n \\ x_2/x_1 & 1 & & x_2/x_n \\ \vdots & & & \vdots \\ \vdots & & & \vdots \\ x_n/x_1 & x_n/x_2 & \cdots & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_n \end{bmatrix}$$

$$= \begin{bmatrix} x_1 + x_1 + \ldots\ldots + x_1 \\ x_2 + x_2 + \ldots\ldots + x_2 \\ \vdots \\ \vdots \\ x_n + x_n + \ldots\ldots + x_n \end{bmatrix}$$

$$= n \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ \vdots \\ x_n \end{bmatrix}$$

$$= nX$$

Therefore, AX = nX, and n is, by definition, an eigenvalue of matrix A. The matrix X is the solution eigenvector of $AX = \lambda X$ for taking λ=n. n is, by Perron-Frobenius Theorem, the maximum eigenvalue of A. This explains why the eigenvector contains the ranking of the importance of the n objects.

1.2.3 The above theory is based on the assumption that all entries of the matrix A are consistent which means that $(a_{ij})(a_{jk}) = a_{ik}$. The example in Section 1.2.1 is a consistent case. Such perfect consistency is possible only if we can construct matrix A based on the weightings of individual objects (i.e. x_1, x_2, ..., x_n). However, in the application of AHP, this will not be the case, that is, one can only construct matrix A first by pairwise comparisons and then find out the values of x_1, x_2, ..., x_n. This will create inconsistency in the reciprocal matrix A. Just take a new example of three football teams: if team 1 beats team 2 by 2:1 and team 2 beats team 3 by 3:1, it is not necessarily the case that team 1 will beat team 3 by 6:1 (this is exactly the case in the example in Section 1.2.1), and if not, inconsistency occurs.

When inconsistency occurs, the problem AX = nX becomes $AX = \lambda_{max} X$. For the reciprocal matrix A, λ_{max} will not be equal to n. It has been proved by Saaty that λ_{max} is closer to n when matrix A is closer to consistency. A is consistent if and only if $\lambda_{max} = n$. λ_{max} is always greater than n if A is inconsistent. The further λ_{max} is from n, the more the inconsistent the matrix is.

Let us now modify the example in Section 1.2.1 to an inconsistent case as follows:

Three factors: 1, 2 and 3.
Factor 1 is twice as important as Factor 2.
Factor 2 is three times as important as Factor 3.
Factor 1 is four times as important as Factor 3.

The reciprocal matrix is therefore written as:

$$A = \begin{bmatrix} 1 & 2 & 4 \\ 1/2 & 1 & 3 \\ 1/4 & 1/3 & 1 \end{bmatrix}$$

The maximum eigenvalue is 3.018 and the corresponding eigenvector X (or called **priority vector**) is:

$$x = \begin{bmatrix} 0.56 \\ 0.32 \\ 0.12 \end{bmatrix}$$

Readers can now see the difference of this priority vector and the priority vector in Section 1.2.1.

It is important to note that the summation of all the elements in a priority vector is equal to 1 (see the two previous examples). This is called "normalization" of the priority vector. The normalization is necessary in order to ensure uniqueness of the vector. The two priority vectors we have seen are said to be **normalized additively**, that is, the elements add up to 1. There are, however, cases that need a priority vector to be ***normalized multiplicatively***. We will see such examples in Section 2.3 in Chapter 2. The evaluation of the maximum eigenvalue of a $n \times n$ matrix and hence its corresponding eigenvector (i.e. the priority vector) can be easily found in many mathematics books and software on the market.

Table 1.1 shows the scales of 1 to 9 as recommended by Saaty for inputting values into the reciprocal matrix.

Intensity of relative importance	Definitions	Explanation
1	Equal importance	Two activities contribute equally to the objectives
3	Moderate importance of one over another	Experience and judgement slightly favoured one activity over another
5	Essential or strong importance	Experience and judgement strongly favoured one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance is demonstrated in practice
9	Extreme importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgements	When compromise is needed

Table 1.1 Scales of 1 to 9 for pairwise comparisons (Saaty 1977)

1.3 Three Levels of Hierarchy

So far, only how n objects are ranked based on a single objective has been discussed. Now, a hierarchy of 3 levels (Fig. 1.1) is looked into. The first level has a single goal (or principal objective). The second level has m subordinate objectives (or factors) and their rankings are derived from pairwise comparisons based on the goal of the first level. The third level has n objects (or tenderers) which are to be ranked. The problem is to determine how well the objects meet the goal through the intermediate second level of subordinate objectives. The procedures are described below.

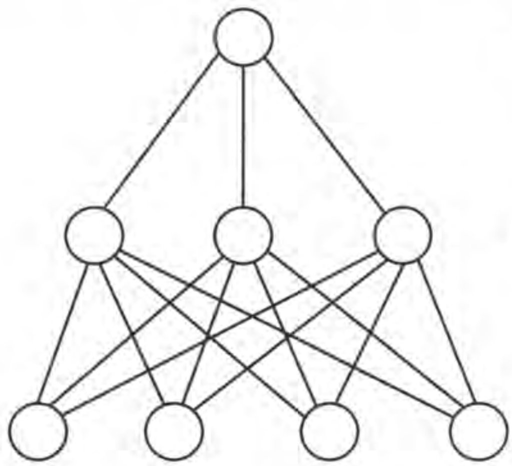


Fig. 1.1 A 3-level hierarchy structure

Step 1 Construct a reciprocal matrix B of dimension m x m with pairwise comparisons of the factors with respect to the principal objective as the elements of B. Then find the priority vector of matrix B and denote it by X_B.

Step 2 Since there are n tenderers to be ranked, a total of m reciprocal matrices A_i $(i = 1, 2, \ldots, m)$ of size $n \times n$ are to be formed, each of which consists of elements of pairwise comparisons of the tenderers with respect to a single factor as objective, that is:

$$A_1 = \begin{array}{c|cccc} & 1 & 2 & \ldots & n \\ \hline 1 & & & & \\ 2 & & & & \\ \vdots & & & & \\ \vdots & & & & \\ n & & & & \end{array}$$

Using factor 1 as objective

$$A_2 = \begin{array}{c|cccc} & 1 & 2 & \dots & n \\ \hline 1 & & & & \\ 2 & & & & \\ \vdots & & & & \\ \vdots & & & & \\ n & & & & \end{array}$$

Using factor 2 as objective

⋮ ⋮

$$A_m = \begin{array}{c|cccc} & 1 & 2 & \dots & n \\ \hline 1 & & & & \\ 2 & & & & \\ \vdots & & & & \\ \vdots & & & & \\ n & & & & \end{array}$$

Using factor m as objective

Step 3 If X_i ($i = 1, 2, \dots, m$) is the priority vector of the corresponding A_i, then an n x m composite matrix C can be formed by taking X_i as columns in C in sequence such that:

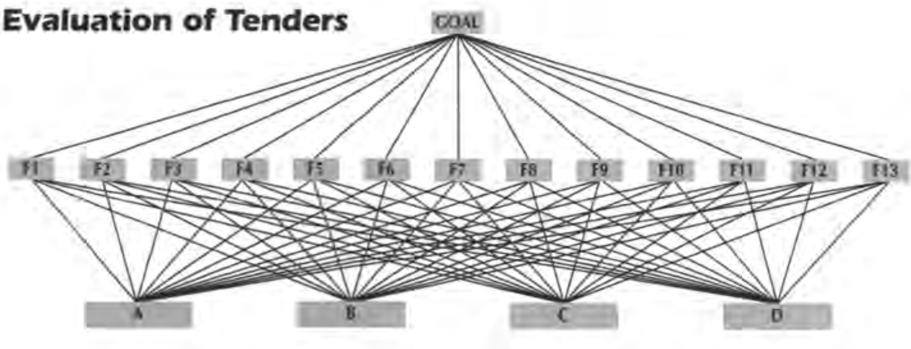
$$C = [X_1, X_2, \dots, X_m]$$

Step 4 The resultant priority vector, X_c, is the result of the multiplication of matrices C and X_b, that is:

$$X_c = C \times X_b$$

From the result of X_c, the ranking of the tenderers can be obtained. These 4 steps will be further illustrated in the next section.

1.4 Evaluation of Tenders



i.e., m=13 & n=4

Fig. 1.2 3-level hierarchy for evaluation of tenders

A tender evaluation example is shown as a 3-level hierarchy AHP problem (Fig. 1.2). Four tenders, A, B, C and D, are to be evaluated. They are from four different consulting firms who wish to bid to undertake the planning, design and supervision of construction for a construction project. So, four tender proposals have been submitted to the client. There are thirteen factors (under five headings) to be considered by the client. These factors are:

Consultant's Experience

F1: Relevant experience and knowledge.

Response to The Brief

F2: Understanding of objectives.

F3: Identification of key issues.

F4: Appreciation of project constraints and special requirements.

F5: Presentation of innovative ideas.

Approach to Cost-Effectiveness

F6: Examples and discussion of past projects to demonstrate the consultant's will and ability to produce cost-effective solutions.

F7: Approach to achieve cost-effectiveness on this project.

Methodology and Work Programme

F8: Technical approach.

F9: Work programme and project implementation programme.

F10: Arrangements for contract management and site supervision.

Staffing

F11: Organization structure.

F12: Relevant experience and qualification of key staff.

F13: Responsibilities and degree of involvement of key staff.

The matrix B (see step 1 of Section 1.3) is shown in Fig. 1.3. Its elements are pairwise comparisons of the factors with respect to the principal objective. For example, F1 and F2 are of equal importance, and therefore element 1-2 of matrix B is entered as 1. F3 is of moderate importance over F10, and therefore element 3-10 is entered as 3.

Goal	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13
F1	1	1	1	1	1	1	1/5	1/7	1/3	3	1	1/7	1/7
F2		1	1	1	1	1	1/5	1/7	1/3	3	1	1/7	1/7
F3			1	1	1	1	1/5	1/7	1/3	3	1	1/7	1/7
F4				1	1	1	1/5	1/7	1/3	3	1	1/7	1/7
F5					1	1	1/5	1/7	1/3	3	1	1/7	1/7
F6						1	1/5	1/7	1/3	3	1	1/7	1/7
F7							1	1/5	4	7	5	1/5	1/5
F8								1	6	9	7	1	1
F9	All lower triangular elements								1	5	3	1/6	1/6
F10	$=a_{ji}$									1	1/3	1/9	1/9
F11	$=1/a_{ij}$										1	1/7	1/7
F12												1	1
F13													1

Fig. 1.3 Matrix B for tender evaluation

The priority vector X_b of matrix B is:

$$X_b = \begin{bmatrix} 0.0258 \\ 0.0258 \\ 0.0258 \\ 0.0258 \\ 0.0258 \\ 0.0258 \\ 0.1074 \\ 0.2136 \\ 0.0586 \\ 0.0126 \\ 0.0258 \\ 0.2136 \\ 0.2136 \end{bmatrix}$$

The next step is to construct 13 matrices of size 4×4, each of which consists of elements of pairwise comparisons of the 4 tenders with respect to a single factor as objective. It is impossible to show all the 13 matrices here and only A_1, A_2 and A_{13} are shown below:

$A_1 =$ Using Factor 1 as objective

	A	B	C	D
A	1	1	1	2
B	1	1	1	2
C	1	1	1	2
D	1/2	1/2	1/2	1

$A_2 =$ Using Factor 2 as objective

	A	B	C	D
A	1	1/2	2	1
B	2	1	4	2
C	1/2	1/4	1	1/2
D	1	1/2	2	1

⋮ ⋮

$A_{13} =$ Using Factor 13 as objective

	A	B	C	D
A	1	2	5	5
B	1/2	1	3	3
C	1/5	1/3	1	1
D	1/5	1/3	1	1

The priority vectors, $X_1, X_2, \ldots, X_{13}$, of the matrices, $A_1, A_2, \ldots, A_{13}$ respectively are:

$$X_1 = \begin{bmatrix} 0.2857 \\ 0.2857 \\ 0.2857 \\ 0.1428 \end{bmatrix} \quad X_2 = \begin{bmatrix} 0.2222 \\ 0.4444 \\ 0.1111 \\ 0.2222 \end{bmatrix} \quad \ldots\ldots \; X_{13} = \begin{bmatrix} 0.5183 \\ 0.2839 \\ 0.0989 \\ 0.0989 \end{bmatrix}$$

Hence, a composite matrix C can be formed as follows. Note that the 1st, 2nd and 13th columns of C are X_1, X_2 and X_{13} respectively.

$$C = \begin{bmatrix} 0.2857 & 0.2222 & \ldots\ldots & 0.5183 \\ 0.2857 & 0.4444 & \ldots\ldots & 0.2839 \\ 0.2857 & 0.1111 & \ldots\ldots & 0.0989 \\ 0.1428 & 0.2222 & \ldots\ldots & 0.0989 \end{bmatrix}$$

The ranking of the four tenders = C x X_b

$$= \begin{bmatrix} 0.3548 \\ 0.2599 \\ 0.0851 \\ 0.3002 \end{bmatrix}$$

Therefore, the best tender is A, which scores 0.3548; the second best tender is D, which scores 0.3002; and so on.

1.5 Four Levels Hierarchy — Tender Evaluation

A 3-level hierarchy has just been discussed. The following will illustrate a more complicated tender evaluation example in which a 4-level hierarchy is involved (Tang, 1995).

There are four international contractors tendering for a large civil engineering design-and-build contract involving earth work, road work, tunnel work, building work and E&M work. Each of these works forms a part of the contract but each is significant enough to form a contract by itself if it is not a large turn-key international contract requiring high standard of workmanship and reliability. Hence, the selection of tender must be carried out with exceptional care. Fig. 1.4 shows a 4-level hierarchy, following which the client evaluates the tenders.

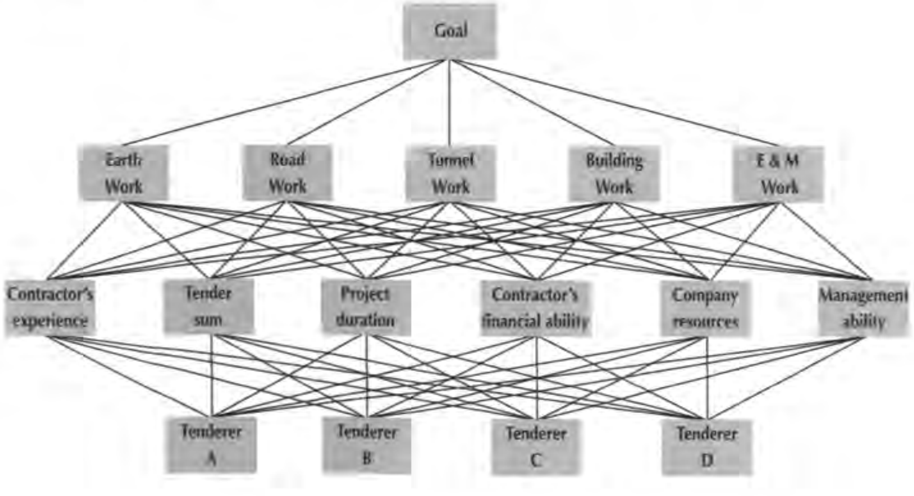


Fig. 1.4 4-level hierarchy for evaluation of tenders

The procedures of evaluating a 4-level hierarchy are described as follows:

Step 1 Construct a reciprocal matrix P of dimension 5×5 with pairwise comparisons of the different works with respect to the principal objective as the elements of P. The higher the percentage of the work in the contract, the more important that work is. Then find the priority vector of matrix P and denote it by P_b.

Step 2 Construct five reciprocal matrices Q_i ($i = 1, 2, 3, 4, 5$) of size 6×6, each of which consists of elements of pairwise comparisons of the six factors with respect to a particular work as objective.

Step 3 If X_i ($i = 1, 2, 3, 4, 5$) is the priority vector of the corresponding Q_i, then a 6 x 5 composite matrix R is formed by taking X_i as columns in R in sequence such that:

$$R = [X_1, X_2, X_3, X_4, X_5]$$

Step 4 Construct six reciprocal matrices S_i ($i = 1, 2, 3, 4, 5, 6$) of size 4×4, each of which consist of elements of pairwise comparisons of the four tenderers with respect to a single factor as objective.

Step 5 If Y_i ($i = 1, 2, 3, 4, 5, 6$) is the priority vector of the corresponding S_i, then a 4×6 composite matrix T can be formed by taking S_i as columns in T in sequence such that:

$$T = [Y_1, Y_2, Y_3, Y_4, Y_5, Y_6]$$

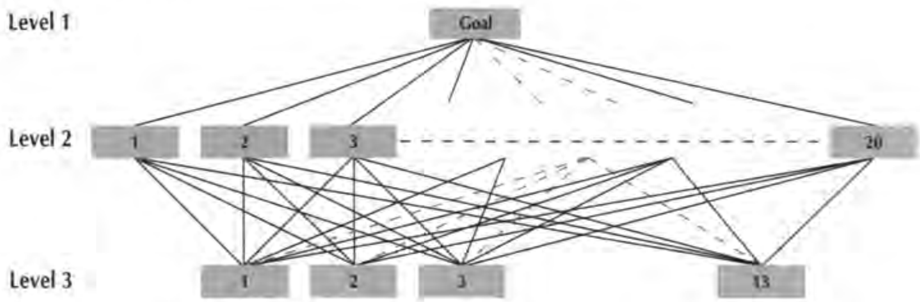
Step 6 The resultant priority vector, X_c, is the result of the multiplication of matrices T, R and P_b, that is:

$$X_c = T \times R \times P_b$$

Similar to the previous example, the ranking of the tenderers can be known after the result of X_c is obtained.

1.6 More Examples on Applications of AHP

Example 1.1 A 3- level hierarchy decision problem



Level 1

Goal: Select the best wastewater treatment alternative

Level 2

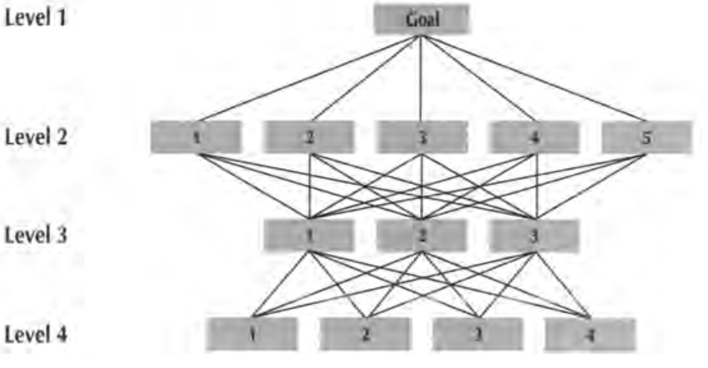
Factors for consideration:

1. Sewage flow
2. Influent/Effluent standard
3. Size of site
4. Nature of site
5. Land cost
6. Local money for construction
7. Foreign money component for construction
8. Local skill for construction
9. Community support
10. Power source
11. Availability of local material
12. Cost of operation and maintenance
13. Professional skill available for operation and maintenance
14. Local technical skill available for operation and maintenance
15. Administration set-up
16. Training
17. Professional ethics
18. Climate
19. Local water-borne diseases
20. Endemic vector-borne (water-related) diseases

Level 3

Wastewater treatment alternatives:
1. Stabilization ponds
2. Fully aerated lagoons + Secondary settlement
3. Fully/Partially aerated lagoons
4. Simple percolating filtration
5. Modified percolating filtration
6. Conventional activated sludge process
7. Deep-shaft/High-purity oxygen processes
8. Primary settlement
9. Land application
10. Rotating biological contactors
11. Oxidation ditches
12. Package activated sludge plants
13. Package high-purity oxygen plants

Example 1.2 A 4-level hierarchy decision problem



Level 1

Goal: Select the optimal alignment for a road project

Level 2

Design aspects:
1. Project sum
2. Project duration
3. Construction risks
4. Operation and maintenance
5. Environmental impact

Level 3

Construction methods:

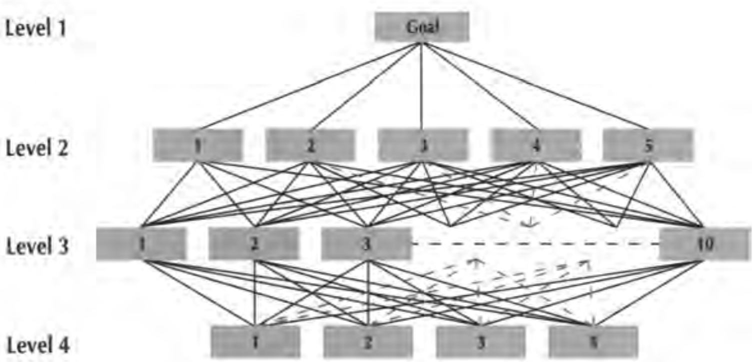
1. Tunnel
2. Bridge
3. Immersed tube

Level 4

Alignment alternatives:

1. Alignment 1
2. Alignment 2
3. Alignment 3
4. Alignment 4

Example 1.3 Another 4-level hierarchy decision problem



Level 1

Goal: Select the most appropriate contractual arrangement for a construction project

Level 2

Components of the project:

1. Earthwork
2. Roadwork
3. Drainage and sewerage work
4. Building work
5. Utility work

Level 3

Factors affecting the choice of contractual agreement:

1. Project definition
2. Owner preferences
3. Public laws
4. Current market conditions
5. Project location
6. Project financing
7. Schedule
8. Assumption of risks
9. Scope of work
10. Duration of work

Level 4

Contractual arrangement alternatives

1. Cost plus contract
2. Target price contract
3. Unit price contract
4. Lump sum contract

1.7 Advantages of Using AHP in Decision Making

The advantages of using AHP are as follows:

1.7.1 It provides a systematic procedure for comparisons between objects under a large number of factors. It facilitates the employment of subjective weighing of objects based on experience.

1.7.2 Besides quantifiable factors (e.g. tender sum, project duration, etc.), the method enables the consideration of unquantifiable/subjective factors which are important in decision making processes.

1.7.3 The size and the complexity of a problem can be broken down into small items (or called clusters) for analysis. For the number of levels of the hierarchy is flexible depending on the size and the requirements of the problem.

1.7.4 The resultant priority vector obtained from this method can give an indication of how much one object is better than another. This can hardly be achieved by intuition alone.

Exercise Questions

Question 1

Explain the consistency and inconsistency of a reciprocal matrix in the Analytic Hierarchy Process (AHP). How is the matrix's largest eigenvalue (λ_{max}) related to the consistency?

In the application of AHP, what type of reciprocal matrix (consistent or inconsistent) is usually used? Why?

Question 2

Construct a 5-level hierarchy problem related to construction, the 1st level being the goal and the 5th level being the alternatives for selection.

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