A Multistage Fuzzy Comprehensive Evaluation Model based on AHP for Construction Enterprises through Value Chain Analysis

Daoyi Guo

1 College of Architecture and Urban Planning, Shandong Jianzhu University, Jinan, China

Email: guoguoguo8880@gmail.com

Abstract. The comprehensive performance evaluation for engineering project has received much consideration from academic and corporate over the past decade, developing rapidly and becoming a main area of research for dealing with the complexity of construction management. This paper develops a multistage fuzzy comprehensive evaluation model with systematic and synergy-focused appraisal system from a value chain analysis perspective by using Analytical Hierarchy Process (AHP), to help the industrial practitioners conduct the performance evaluation in a fuzzy environment by handling the vagueness and subjectivity with parameterized linguistic values. The work presented in this paper may help managers and business professionals not only to evaluate the efficiency and effectiveness of the management but also to distinguish the important criteria for creation in value chain, to remain competitive in the market.

1. The performance management of construction enterprises through value chain analysis

Due to the fierce competition in the market the impact of the evolution of global value chains in the internet era and increasingly stringent requirements of engineering quality, the construction industry’s profit margin has declined gradually. In Netherlands, Finland and other European regions, the annual growth rate of market demand for construction enterprises is below 5%, which is lower than the annual growth rate of labour costs. This paper uses the value chain analysis method to tease out a series of activities set by construction enterprises aiming at increment of value, extending forward to customers, backward to suppliers and service providers, to deliberate the value creation potential of each link relative to the final product, as shown in Table 1.

It can be seen that the use of information technology and optimization of critical operational processes is the key to realizing enterprise strategy in the Internet Era [1]. By flexibly applying information technology, giving full play to its leverage role and multiplier effect, enterprises can enhance their competitiveness. And through the integration and coordination of the upstream and downstream of the supply chain, the production cycle of construction products can be shortened, so as to reduce the costs of transportation and inventory [2]. The major sources of value creation can be found in the manifold links of the value chain [3].
2. The performance appraisal index system of multistage fuzzy comprehensive evaluation model

The evaluation model of construction projects should be a combination of a series of progressive evaluation activities running through the whole project cycle [4], guided by the unified concept and involving multiple subjects [5]. The evaluation and the project management support each other. Therefore, based on the above value chain analysis, this paper constructs a comprehensive evaluation index system of construction enterprise projects for each link of the project, as shown in Table 2. There is some incomparability due to the different influences of various factors on the engineering project [6], so the index system is divided into two parts: project operation evaluation and project synergy evaluation (including the collaborative communication with customers). Each part has three levels of indicators, including qualitative indicators which are divided into five evaluation levels (as shown in Table 3) and quantitative indicators obtained by the calculation model.

Table 1. The value process production of construction enterprises

| Internal Activities | Human Resource Management | Technology Development | Purchase |
|---------------------|---------------------------|------------------------|----------|
| Organizational Structure | Recruitment | Method Statement | Procurement Scheme |
| Management System | Selection & Training | Construction Schedule | Material Supply Plan |
| Corporate Culture | Appointment | Technical Documents | Equipment Debugging |
| Budget Accounting | Staff Appraisal | Support & Service | Maintenance Facilities |

| External Activities | Internal Logistics | External Logistics | Production Management |
|---------------------|---------------------|--------------------|-----------------------|
| Market Linkage | Receiving Inspection | Supply Chain | Project Supervision |
| Marketing System | Dispatching | Logistics Cost Control | Acceptance Check |
| Marketing Research | Store Management | Activity Management | Assurance System |
| Reasonable Quotation | Data Filing | Schedule Management | Warranty Service |

2. The performance appraisal index system of multistage fuzzy comprehensive evaluation model

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Table 2. The Comprehensive evaluation index system

| Primary Indicator | Secondary Indicators | Three-Level Indicator |
|-------------------|----------------------|-----------------------|
| Project Planning | Project Scope Management | Project Risk Management |
| Evaluation of Project Operation | Schedule Control | Quality Control Coefficient* |
| Project Control | Safety Control Coefficient* | Project On-Time Completion Rate |
| Project Closure | Acceptance Rate | Delivery of Products |
| Collaboration with Customers | Customers Satisfaction Degree | Timely Delivery Rate* |
| Evaluation of Project Synergy | Problem Processing Time | Capital Supply Rate * |
| Financial Synergy | Cost Deviation Rate* | Financial Capital Coordination |
| Collaboration with Stakeholders | Criterion Coordination | Labour Supply Rate * |
| | | Material Supply Rate * |
| | | Equipment Supply Rate * |
The calculation method of the Quality Control Coefficient can be obtained by analysing the historical data of safety/quality management of construction projects and the actual demand for construction projects, and the distribution of engineering funds among projects. The calculation formula of the Quality Control Coefficient of the project is:

\[
\lambda^{C} \text{ (Project Quality Control Coefficient)} = \left( \lambda_{i1}, \lambda_{i2}, ..., \lambda_{in} \right) \left( \eta_{i1}/\eta_{0i1}, \eta_{i2}/\eta_{0i2}, ..., \eta_{in}/\eta_{0in} \right)^T
\]

\( \lambda_{ij} \) --- the contribution rate of each safety/quality measure to the safety/quality of construction projects, which can be comprehensively evaluated through the analysis of historical data and the fuzzy scores of the importance of the construction of the measures; \( \eta_{ij} \) --- The actual assessment of safety/quality measures, the quantitative ones can be scored by calculation, the ones that cannot be quantified are comprehensively scored by the expert matrix method; \( \eta_{0ij} \) --- the requirements of the safety/quality measures of the project, the method of obtaining is equivalent to \( \eta_{ij} \).

(2) Capital Supply Rate reflects the difference between the funds available for construction in progress and the actual demand for construction projects, and the distribution of engineering funds among tasks. The calculation formula of Capital Supply Rate is:

\[
C = \sum_{j=1}^{n} \eta_{ij} / \sum_{j=1}^{n} \eta_{0ij}
\]

\( \eta_{ij} \) --- the actual acquisition of funds for each sub-project; \( \eta_{0ij} \) --- the funds required for each project. The sensitivity of each sub-project to the funds can be additionally calculated by analysing the historical data, providing the basis for the next step fund allocation.

(3) The Material Supply Rate reflects the difference between the raw materials that can be used in construction projects and the actual construction needs of the project. The calculation formula of Material Supply Rate is:

\[
M = \sum_{j=1}^{n} \lambda_{ij} \frac{\eta_{ij}^{+} v_{ij}}{p_{ij}}
\]

In order to eliminate the problem that various influencing factors cannot be compared due to different statistical calibres and dimensions; factors are converted into dimensionless percentages to obtain the calculation model of quantitative indicators reflecting project performance as follows:

1. Safety Control Coefficient, which indicates whether the project has set up safety protection measures and organized work in accordance with the requirements of safe production. The Safety Control Coefficient reflects the ability of the quality assurance measures of the project under construction to meet the quality requirements of the project. The calculation method of the Safety Control Coefficient of the project is the same as that of the Safety Control Coefficient. The calculation model of the two is:

\[
S = \sum_{j=1}^{n} \lambda_{ij} x_{ij} = (\hat{\lambda}_{i1}, \hat{\lambda}_{i2}, ..., \hat{\lambda}_{in}) (\eta_{i1}/\eta_{0i1}, \eta_{i2}/\eta_{0i2}, ..., \eta_{in}/\eta_{0in})^T
\]

\( \hat{\lambda}_{ij} \) --- the contribution rate of each safety/quality measure to the safety/quality of construction projects, which can be comprehensively evaluated through the analysis of historical data and the fuzzy scores of the importance of the construction of the measures; \( \eta_{ij} \) --- The actual assessment of safety/quality measures, the quantitative ones can be scored by calculation, the ones that cannot be quantified are comprehensively scored by the expert matrix method; \( \eta_{0ij} \) --- the requirements of the safety/quality measures of the project, the method of obtaining is equivalent to \( \eta_{ij} \).

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3. Material Supply Rate reflects the difference between the raw materials that can be used in construction projects and the actual construction needs of the project. The calculation formula of Material Supply Rate is:

\[
M = \sum_{j=1}^{n} \lambda_{ij} \frac{\eta_{ij}^{+} v_{ij}}{p_{ij}}
\]
\( \eta_i \) --- the amount of reserves of various raw materials; \( v_i \) --- the quantity of expected purchases; \( \mu_i \) --- the amount of raw materials required for the current project; \( \lambda_i \) --- the impact factor of this raw material on the progress of the project.

(4) Equipment Supply Rate reflects the difference between the mechanical equipment that can be used in construction projects and the actual construction of engineering projects. The Labour Supply Rate reflects the difference between the amount of labour that can be used in construction projects and the actual labour required for construction of the project. The calculation formulas for the two supply rates are the same as follows:

\[
E = \sum_{i=1}^{n} \eta_i \lambda_i \left( \frac{\eta_i v_i}{\eta_0 v_0} \right)
\]

(4)

\( \eta_i \) --- the number of engineering machinery and equipment / the quantity of labour force; \( \eta_{0i} \) --- the number of mechanical equipment / the quantity of labour force required for each sub-project construction; \( v_i \) --- the efficiency of each mechanical equipment / each unit of labour; \( v_{0i} \) --- The optimal efficiency (or quota) of each equipment/ each unit of labour; \( \lambda_i \) --- the impact factor of each mechanical equipment/ each unit of labour on the construction of the project.

(5) Timely Delivery Rate’s calculation formula is:

\[
D = \frac{\eta}{\eta_0}
\]

(5)

\( \eta \) --- times of timely delivery; \( \eta_0 \) --- total delivery times.

(6) Cost Deviation Rate is the basis for calculating the economic efficiency of capital construction investment plan, construction organization plan and structural technical plan by calculating the quantity of labour, material and machinery consumption in a certain unit of products according to the requirements of itemized projects and structural components.

\[
L = \sum_{i=1}^{n} \lambda_i \left( \frac{\eta_{0i} v_{0i} - \eta_i v_i}{\eta_0 v_0} \right)
\]

(6)

\( \eta_{0i} \) --- the amount of completed work for each sub-project; \( v_i \) --- the actual cost of each sub-project; \( v_{0i} \) --- the budget quota for each sub-project; \( \lambda_i \) --- the proportion of each sub-project cost to the total cost of construction.

3. The multistage fuzzy comprehensive evaluation model

The construction project is a multi-factor complex system with a certain ambiguity, consisting of both quantitative and qualitative indicators in the project performance evaluation index system [7]. Therefore, by using single-factor fuzzy evaluation related to the evaluation objects to constitute the evaluation matrix under the action of the weight vector, the multistage fuzzy comprehensive evaluation model for project performance was established [8]. The general steps are shown as follows:

3.1. Set indicator sets and evaluation sets at all levels

There are two finite universes: \( U = \{X_1, X_2, \ldots, X_n\} \) and \( V = \{Y_1, Y_2, Y_3, Y_4, Y_5\} \), where \( U \) represents a collection of multiple evaluation indicators of the comprehensive evaluation system of the construction enterprise project, called the indicator set; \( V \) is a collection of multiple judgments. It is called an evaluation set, using five levels of excellent, good, medium, average, and poor. According to the comprehensive evaluation index system of construction enterprise projects established in the previous section, the three-layer fuzzy comprehensive evaluation index set is established as follow \( U = \{X_1, X_2, X_3, X_4, X_5, X_6, X_7, X_8\} \)

\( X_1 = \{X_{11}(Project Planning), X_{12}(Project Control), X_{13}(Project Closure)\} \)

\( X_2 = \{X_{21}(Collaboration with Customers), X_{22}(Financial Synergy), X_{23}(Collaboration with Stakeholders) \}

\( X_{11} = \{X_{111}(Project Scope Management), X_{112}(Risk Management)\} \)

\( X_{12} = \{X_{121}(Schedule Control), X_{122}(Quality Control Coefficient), X_{123}(Safety Control Coefficient)\} \)

\( X_{13} = \{X_{131}(Project On-Time Completion Rate), X_{132}(Acceptance Rate), X_{133}(Delivery of Products)\} \)

\( X_3 = \{X_{31}(Customers Satisfaction Degree), X_{32}(Timely Delivery Rate), X_{33}(Problem Processing Time)\} \)

\( X_4 = \{X_{41}(Capital Supply Rate), X_{42}(Cost Deviation Rate), X_{43}(Financial Capital Coordination)\} \)

\( X_5 = \{X_{51}(Product Quality), X_{52}(Project Manager Performance), X_{53}(Project Synergy)\} \)

\( X_6 = \{X_{61}(Project Budget Coordination), X_{62}(Project Schedule Coordination), X_{63}(Project Synergy)\} \)

\( X_7 = \{X_{71}(Buyer Satisfaction Degree), X_{72}(Project Manager Performance), X_{73}(Project Synergy)\} \)

\( X_8 = \{X_{81}(Project Budget Coordination), X_{82}(Project Schedule Coordination), X_{83}(Project Synergy)\} \)
X_{23} = \{X_{231}, X_{232}, X_{233}, X_{234}\}

3.2. Determine the weight coefficient of the index system with AHP method

Generally, the influence of each indicator in the indicator set on the evaluated object is inconsistent, so the weight distribution of the indicator set is required as a fuzzy vector on the evaluation set V [9]. In theory, the method of determining the weight of indicators is divided into two categories: subjective weighting method and objective weighting method which’s disadvantages are the cumbersome calculation and poor practicality. So, the analytic hierarchy process (AHP) method combining qualitative analysis with quantitative analysis with strong operability is selected [10], using less quantitative information to conduct a scientific quantitative analysis of problems that are difficult to directly measure [11].

The analytic hierarchy process refers to grouping the system indicators according to the dominance relationship by scale comparison to form an ordered hierarchical structure [12]. Therefore, the relative importance of the indicators in each level should be determined by means of pairwise comparison judgment. The weight assignment reference table is shown in Table 4:

| Importance degree | \( P_n \) |
|-------------------|-----------|
| Indicator \( X_{n,i} \) is as important as the indicator \( X_n \) | 1 |
| Indicator \( X_{n,i} \) is slightly more important than indicator \( X_n \) | 3 |
| Indicator \( X_{n,i} \) is significantly more important than indicator \( X_n \) | 5 |
| Indicator \( X_{n,i} \) is more important than indicator \( X_n \) | 7 |
| Indicator \( X_{n,i} \) is extremely important than indicator \( X_n \) | 9 |
| The median of the above judgments | 2, 4, 6, 8 |

The synthesis is then performed within the hierarchical structure to obtain the relative importance of the indicator to the target [13]. The index evaluation matrix can be obtained by asking relevant experts to assign the indicators of each level of the evaluation index system. And the weight distribution of each level of the evaluation index system, \( A=(a_1, a_2, \ldots, a_n) \), \( A_n \in F(U) \) would be drawn subsequently by analysing the assignments through the data processing system software (DPS) [14]. In the formula, \( A_n \) is the weight coefficient corresponding to the \( n \)th index \( X_n \) and satisfies \( A_1+A_2+\ldots+A_n=I \). The weight set is as follows:

\[
\begin{align*}
A_1 &= (A_{111}, A_{112}, A_{113}) \\
A_2 &= (A_{211}, A_{222}, A_{223}) \\
A_{11} &= (A_{111}, A_{112}) \\
A_{12} &= (A_{121}, A_{122}, A_{123}) \\
A_{13} &= (A_{131}, A_{132}, A_{133}) \\
A_{21} &= (A_{212}, A_{222}, A_{223}) \\
A_{22} &= (A_{221}, A_{222}, A_{223}) \\
A_{23} &= (A_{231}, A_{232}, A_{233}, A_{234})
\end{align*}
\]

3.3. Establish the multistage fuzzy evaluation matrix

3.3.1. The first level comprehensive evaluation. By making a comprehensive evaluation of each indicator in \( A_i (i=1,2) \) and look for the membership relationship of each indicator in the index set \( U \) to each element in the evaluation set \( V \), the paper established a membership function. The evaluation value of the quantitative indicator in this paper can be obtained according to the calculation result (evaluation score = indicator calculation value/indicator historical optimum value), and the evaluation value of the qualitative index can be judged by experts according to the indicator evaluation table, thus
obtaining the membership \( Y_{ijk} (t=1,2,\cdots ; m; k=1,2,\cdots ,p) \) of the index \( X_{ij} \) belongs to the \( k \)th comment. Each indicator constitutes a fuzzy evaluation vector \( R_{ij} = (r_{ij1}, r_{ij2}, \cdots , r_{ijp}) \), the fuzzy evaluation matrix \( R_{ij} \) composed of all single-factor fuzzy vectors is as follows:

\[
R_{ij} = \begin{bmatrix}
r_{ij1} & r_{ij2} & \cdots & r_{ijp} \\
r_{ij21} & r_{ij22} & \cdots & r_{ij2p} \\
\vdots & \vdots & \ddots & \vdots \\
r_{ijm1} & r_{ijm2} & \cdots & r_{ijmp}
\end{bmatrix} \quad (i = 1,2; j=1,2,3)
\]

Since the comments in the evaluation set are not absolutely positive or negative, the comprehensive evaluation can be regarded as a fuzzy set on \( V \), which is recorded as \( B_{ij} = (b_{ij1}, b_{ij2}, \cdots , b_{ijp}) e F(V) \). The fuzzy transform \( T_k: F(U) \rightarrow F(V) \), \( A \rightarrow A \times R \) could be constructed, so that the ternary equation \((U, V, R)\) constitutes a fuzzy comprehensive evaluation mathematical model. Therefore, the weight distribution \( A_i \) of the input index layer \( X_i \) is:

\[
A_{11} = (A_{111}, A_{112}) \\
A_{12} = (A_{121}, A_{122}, A_{123}) \\
A_{13} = (A_{131}, A_{132}, A_{133}) \\
A_{21} = (A_{211}, A_{212}, A_{213}) \\
A_{22} = (A_{221}, A_{222}, A_{223}) \\
A_{23} = (A_{231}, A_{232}, A_{233}, A_{234})
\]

Therefore, \( B_{ij} = A_i \ast R_{ij} = (b_{ij1}, b_{ij2}, \cdots , b_{ijp}) (i=1,2; j=1,2,3) \)

3.3.2. The second level comprehensive evaluation. By taking each \( B_{ij} \) as an indicator, the fuzzy comprehensive evaluation matrix of \( R_i = (r_{i1}, r_{i2}, \cdots , r_{ip}) \) is as follows:

\[
R_i = \begin{bmatrix}
r_{i11} & r_{i12} & \cdots & r_{i1p} \\
r_{i21} & r_{i22} & \cdots & r_{i2p} \\
\vdots & \vdots & \ddots & \vdots \\
r_{iij1} & r_{iij2} & \cdots & r_{iijp}
\end{bmatrix} (i=1,2)
\]

From the previous section, the weight distribution \( A_i \) of the index layer \( X_i \) to the target layer is obtained.

\[
A_i = (A_{i11}, A_{i12}, A_{i13}) \\
A_i = (A_{i21}, A_{i22}, A_{i23})
\]

Secondary evaluation vector \( B_i = A_i \ast R_i = (b_{i1}, b_{i2}, \cdots , b_{ip}) (i=1,2) \) would be obtained.

3.3.3. The third level comprehensive evaluation. By taking each \( B_1 \) as an indicator, the fuzzy comprehensive evaluation matrix of \( R = (r_{11}, r_{12}) \) is as follows:

\[
R = \begin{bmatrix}
r_{111} & r_{112} & \cdots & r_{11p} \\
r_{121} & r_{122} & \cdots & r_{12p} \\
\vdots & \vdots & \ddots & \vdots \\
r_{1i1} & r_{1i2} & \cdots & r_{1ip} 
\end{bmatrix}
\]

From the previous section, the weight distribution \( A \) of the index layer \( X \) to the target layer is obtained.

\[
A_{11} = (A_{111}, A_{112})
\]

The three-level evaluation vector would be obtained: \( B = A \ast R = (b_1, b_2, \cdots , b_p) \), in accordance with the principle of maximum membership degree, it could be drawn that \( B_0 = \max \{b_1, b_2, \cdots , b_p\} \), leading to the comprehensive evaluation result for the project is \( B_0 \).

4. Conclusion

This paper adopts a multi-level comprehensive fuzzy evaluation method to realize the performance evaluation of engineering projects through the value chain analysis. It should be pointed out that in addition to the evaluation of the project after completion, the model can also be used in the implementation process of the engineering task. By making objective predictions on the construction
conditions in the task, the ideal project progress can be calculated depending on circumstances, analysing the impact of factors such as capital supply, equipment supply, raw material supply and other factors on the operation in the original plan [15]. Furthermore, due to the complexity of project management of construction enterprises and the long-term value-added management, the model should focus adapt to the actual situation of construction enterprises to enhance the implement ability and theoretical significance of the model for better application to the construction management in future.

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