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Quality Management of Municipal Road Construction Projects Based on 5M1E Theory and Fuzzy Comprehensive Evaluation Method

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Abstract: In the quality management evaluation of Municipal Road Construction (MRC) projects, traditional methods often fall prey to influence from expert experience and fragmented evaluation dimensions. To address these issues, the study examines the urban secondary road Z Avenue project, which spans 2.8 km and took 320 days to complete, as the empirical case. Based on the Man, Material, Machine, Method, Measurement, and Environment (5M1E) theory, a system of quality influencing factors is developed, which includes six primary indicators: personnel, materials, machinery, methods, measurement, and environment, and 15 secondary indicators. The Fuzzy Comprehensive Evaluation (FCE) method, combined with the entropy weight analytic hierarchy process, is used to calculate the subjective and objective weights for evaluation. The results reveal that method, mechanism, and measurement are the core dimensions with the highest combined weights at the first level, with values of 0.2256, 0.2223, and 0.185, respectively. The FCE yields a comprehensive score of 7.605 points for the Z Avenue construction quality, indicating a level II classification and an overall sound quality. This study offers a multidimensional, quantitative framework for assessing the quality management of MRC projects, with significant practical value for enhancing construction quality control.

Keywords: 5M1E framework, entropy weight analytic hierarchy process (Entropy-AHP), fuzzy comprehensive evaluation, municipal road construction, quality management evaluation.

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1. Introduction

The quality of Municipal Road Construction (MRC) is related to traffic safety, road service life, and urban operational efficiency (Chen et al., 2022; Peng et al., 2023). The current urbanization process is accelerating, the scale of MRC projects is constantly expanding, and the complexity of the process is significantly increasing (Bhardwaj et al., 2022; Sharma et al., 2022). Among the existing evaluation methods, the Analytic Hierarchy Process (AHP) and the Delphi method are susceptible to subjective bias and limited expert samples. Objective methods, such as the Entropy Weight (EW) method, are less effective at reflecting industry experience, and most models lack systematic consideration of the entire construction process (D'Adamo, 2023; Mohammadi et al., 2022; Sforzini et al., 2022). Elraaid et al. (2024) used a separate AHP to explore the main obstacles when establishing a project management office in the Misrata Free Zone. The results showed that the deviation range of indicator weights could reach 15% to 22%. Busch and Rajwade (2024) used a Delphi expert questionnaire to generate more ideas about community-level scientific literacy. However, this method relied on subjective expert judgment and did not clearly define the community background of the expert sample, making it difficult to fully reflect the study's actual characteristics. In response to these issues, this study introduces the theory of personnel, Man, Material, Machine, Method, Measurement, and Environment (5M1E) and the Fuzzy Comprehensive Evaluation (FCE) method to construct an MRC project Quality Influencing Factor (QIF) system, with 6 primary indicators and 15 secondary indicators. FCE and Entropy Weight-Analytic Hierarchy Process (EW-AHP) are combined to determine the subjective and objective combination weights, achieving a scientific MRC project Quality Management Evaluation (QME). The contribution of the research lies in proposing and validating an integrated, socio-technical perspective model for evaluating the quality of MRC. The research is not simply applying the 5M1E model derived from the manufacturing industry but systematically transforming and expanding its context to deeply adapt to the unique attributes of MRC. Meanwhile, a hybrid weighting fuzzy evaluation method is developed, which integrates the extended 5M1E framework, subjective and objective comprehensive weighting combining EW-AHP, and the FCE method. This multi-method fusion path can effectively balance expert experience and objective data, quantify the fuzziness in evaluation, thereby achieving comprehensive evaluation of MRC.

2. Methods and Materials

2.1. Connotation Expansion and Applicability Analysis of the 5M1E Theory in MRC

The 5M1E theory originated from the manufacturing industry, where the production process is standardized, and the working environment is closed. It is a mature quality management analysis framework. When applying this theory to MRC projects, it is necessary to consider the unique industry characteristics of the latter entirely. Compared with the manufacturing industry, the Quality Influencing Factor (QIFs) of MRC show significant differences. Among them, the environmental dimension extends from controllable physical environments to open and dynamic social and technological systems. In addition to natural climate, it also includes complex underground pipeline environments, dynamic transportation and social environments, and tight community public environments. The mechanical dimension emphasizes road adaptability, as the large equipment used in municipal engineering is mobile and must adapt to the narrow, multi-curved, and variable-slope working conditions of urban roads. In the measurement dimension, municipal roads are a type of linear engineering. In addition to conventional material testing, it is also necessary to focus on measuring special geometric parameters such as horizontal alignment, vertical section elevation, and cross-slope. These parameters are related to road driving comfort, drainage effect, and traffic safety.

2.2. MRC Project QIF based on 5M1E Theory

The 5M1E theory is an analytical method that explores the root causes of problems from six dimensions. The 5M refers to Man (or personnel), Material, Measurement, Method, Machine, while 1E refers to Environment (Cai et al., 2025; Ramanta et al., 2023; Wang et al., 2024). Personnel are a key factor affecting the quality of MRC projects. Such projects are characterized by substantial investment, prolonged duration, and involvement of numerous stakeholders. Some projects lack effective quality management systems, resulting in substandard quality. This is manifested in high personnel turnover and insufficient professional quality. In terms of materials, core materials such as cement and steel bars are related to construction quality, and risks are concentrated in inadequate entry control and defects in inspection and batching. In terms of machinery, although drilling machines, cranes, and other equipment have improved efficiency, they still pose hidden dangers, including leasing and procurement, operational training, maintenance iteration, and other concerns (Tavana et al., 2023; Willar et al., 2023). In terms of methodology, its scientific validity and standardization are related to engineering quality, and key influencing factors include construction organization design and optimization, process control, and quality inspection. Insufficient thickness of protective layer and insufficient stiffness and strength of formwork will affect concrete construction (Volden et al., 2022). In terms of measurement dimensions, measurement accuracy, standardized use, and tool maintenance affect quality. The MRC project testing methods and equipment are shown in Table 1.

In Table 1, under the method dimension, the compaction degree of the roadbed is achieved through the sand filling method, and the standardized process ensures that the roadbed serves as the foundation. The pavement thickness drilling core method is used to accurately test the effectiveness of the process execution. Regarding measurement dimensions, the standardized use of level gauges and steel tape measures ensures the accuracy of elevation and centerline displacement measurements. Equipment maintenance and repair ensure the reliability of measurement data. In terms of environmental factors, both the natural construction environment and the finished product protection environment can affect the construction quality. Under certain geological conditions, soil defects and insufficient concrete strength can compromise road safety (Abbas et al., 2025; Gazman, 2023). To ensure the scientific validity of the evaluation index system, a systematic process has been established to determine the final evaluation indicators. Based on the analysis of the connotation expansion of the 5M1E theory in MRC, the research team systematically sorts out the literature on keywords such as “municipal roads”, “construction quality”, and “influencing factors” in the core collections of China National Knowledge Infrastructure and Web of Science in the past five years, and initially constructs an indicator pool containing 42 potential influencing factors. Then, two rounds of expert consultation are conducted using the Delphi method. A total of 10 experts with rich experience in municipal engineering are invited to form a consulting group. The specific composition of the 10 experts includes 3 senior project managers from the construction unit, 2 chief engineers from the design institute, 2 senior supervising engineers, 2 project supervisors from the owner’s side, and 1 university professor engaged in infrastructure management research. All experts hold senior professional titles and have an average of over 15 years of work experience in MRC. The first round of consultation will be conducted through an anonymous questionnaire. Experts will be asked to rate the 42 indicators in the preliminary indicator pool on a 5-point Likert scale based on their importance to the quality of MRC. After collecting the questionnaire, the average importance and coefficient of variation of each indicator are calculated. The second stage consultation will provide feedback on the statistical results of the first round and the organized expert opinions to the expert group, and focus on discussing indicators with an importance mean <3.5 or a coefficient of variation >0.3. Experts will be asked to conduct a second round of scoring and judgment. After this round of screening, 18 indicators with insufficient importance are removed, and 9 indicators with similar meanings are merged. Fifteen secondary indicators are selected through the above process, as shown in Fig. 1. Taking these different dimensions into account, 15 factors affecting quality have been identified. Among them, the measurement accuracy (C11) includes two levels: horizontal line accuracy and elevation accuracy. The accuracy of horizontal alignment is assessed by parameters such as the deviation of the centerline and the straightness of the municipal road sidelines. Elevation accuracy focuses on parameters such as vertical section elevation deviation and cross-slope deviation.

Table 1. Testing methods and equipment for MRC projects

Divisional work	Testing content	Test method	Main testing equipment
Subgrade works	Compactness	Sand filling method/ring knife method	Standard sand, ring knife, electronic balance
	Evenness	3m straightedge method	3m aluminum alloy ruler
	Width	Ruling-method	Steel tape measure
	Vertical elevation	Leveling method	Level gauge, level ruler
Road surface engineering	Pavement thickness	Core drilling method	Road coring machine, electronic balance
	Road surface smoothness	Continuous flatness meter method	Continuous flatness meter
	Road anti-skid performance	Pendulum apparatus method	Pendulum friction coefficient tester
	Road surface deflection	Benkelman Beam testing	Road surface deflectometer
Drainage works	Installation elevation of pipeline foundation and pipe joints	Leveling method	Level gauge, level ruler
	Midline displacement	Ruling-method	Steel tape measure
	Bottom elevation inside the pipe	Leveling method	Level gauge, level ruler
	Check the size of the well chamber	Ruling-method	Steel tape measure, steel ruler
	Height difference between manhole cover and road surface	Ruling-method	Steel tape measure, steel ruler
	The height difference between the rainwater inlet well frame and the road surface	Ruling-method	Steel tape measure, steel ruler
	Height difference between location and adjacent road surface	Ruling-method	Steel tape measure, steel ruler

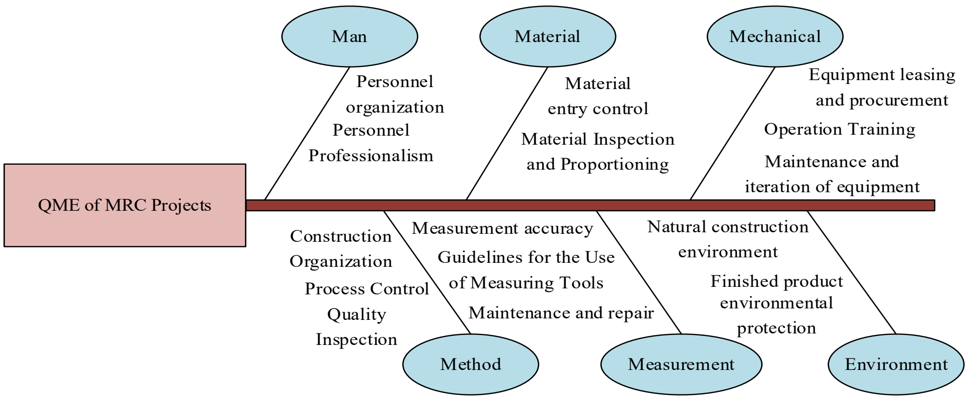

Fig. 1. Factors affecting the construction quality of MRC

2.3. QME based on the FCE Method

After determining the QIF of the MRC project, the FCE method is used to eliminate subjective interference in the engineering quality evaluation. Based on the 5M1E theory, a quality management system is constructed with six dimensions of personnel, material, machine, method, measurement, and environment as primary indicators, and each QIF as secondary indicators. As shown in Table 2, personnel professionalism (C2) is quantified based on the certification rate and annual specialized training duration. Material entry control (C3) is quantified by the qualified rate of material sampling inspection upon entry. Indicators such as construction organization (C8) and finished product environmental protection (C15), which are difficult to quantify directly, will be scored by 10 experts using a 5-point Likert scale. The average score will be taken as the quantitative result.

In response to the quality management issues identified in the MRC project, this study is based on the 5M1E theoretical framework and uses the FCE method to conduct a multidimensional evaluation. Fig. 2 shows the specific process. As shown in Fig. 2, the FCE process begins by constructing an indicator system, then using the EW-AHP to determine the combined weights. Expert ratings are then used to build a membership matrix. The weighted average operator is then used to synthesize the matrix. Finally, the results are compared against the grading standards. The core steps are to select a fuzzy synthesis operator and complete the matrix synthesis operation. The municipal road QME needs to take into account the contribution of all indicators. Therefore, the weighted average fuzzy synthesis operator, through the calculation logic of weight × membership + accumulation, can reflect the combined impact of each indicator and avoid the defect of masking secondary indicator information with the primary factor significance operator. For this reason, the weighted average fuzzy synthesis operator is selected in this study. Assuming that the first-level indicator weight vector is $W=[w_1,w_2,...,w_e]$, where e represents the number of first-level indicators, and the value is 6. The fuzzy membership matrix of the first-level indicators to the evaluation level is $H=[h_{ab}]_{e\times c}$, where c represents the number of evaluation levels, and the value is 5. h_{ab} represents the membership of the first-level indicator a to the evaluation level b. The calculation of the comprehensive evaluation result vector B is shown in Eq. (1).

Table 2. QME system for MRC projects

Target layer	First level indicator	Secondary indicators
QME of MRC Projects (A)	Personnel (B1)	Personnel organization (C1)
		Personnel Professionalism (C2)
	Material (B2)	Material entry control (C3)
		Material Inspection and Proportioning (C4)
	Mechanical (B3)	Equipment leasing and procurement (C5)
		Operation Training (C6)
		Maintenance and iteration of equipment (C7)
	Method (B4)	Construction Organization (C8)
		Process Control (C9)
		Quality Inspection (C10)
	Measurement (B5)	Measurement accuracy (C11)
		Guidelines for the Use of Measuring Tools (C12)
		Maintenance and repair (C13)
	Environment (B6)	Natural construction environment (C14)
		Finished product environmental protection (C15)

$$B=W\circ H=\left(\sum_{a=1}^{e}w_a\cdot h_{a1},\sum_{a=1}^{e}w_a\cdot h_{a2},...,\sum_{a=1}^{e}w_a\cdot h_{ac}\right) \tag{1}$$

The combination weight of EW-AHP adopts a linear weighted synthesis formula, as shown in Eq. (2).

$$W_i=\alpha\cdot W_{A,i}+(1-\alpha)\cdot W_{S,i} \tag{2}$$

In Eq. (2), $W_{A,i}$ is the subjective weight of the hierarchical analysis of the i th indicator. $W_{S,i}$ is the objective weight of the EW of the i th indicator. α is the coefficient for the distribution of subjective and objective weights. The study determines α=0.5 through the deviation maximization method.

In the calculation of indicator weights, the study combines subjective and objective weight calculations. In the division of proportions, the study adopts a subjective and objective weight integration method based on maximizing the deviation. This method maximizes the overall deviation of the evaluation results, so that the indicators with higher information contribution can obtain reasonable weights (Şahin 2024). The objective weight calculation of indicators adopts the EW method. This study focuses on the QME of MRC projects, dividing the system into five levels: excellent, good, medium, low, and poor. Assuming there are m projects to be evaluated in municipal road engineering, each project contains n evaluation indicators. X_{ij} is defined as the specific numerical value of the indicator, where i is the evaluation object and j is the evaluation indicator. Based on this, the original indicator matrix r constructed is shown in Eq. (3) (Jin et al., 2024; Yudhistira et al., 2024).

$$r=\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \tag{3}$$

To eliminate the influence of dimensionality, the original matrix data are compressed to the interval [0, 1] and normalized using the range method (Wen, 2023), as shown in Eq. (4).

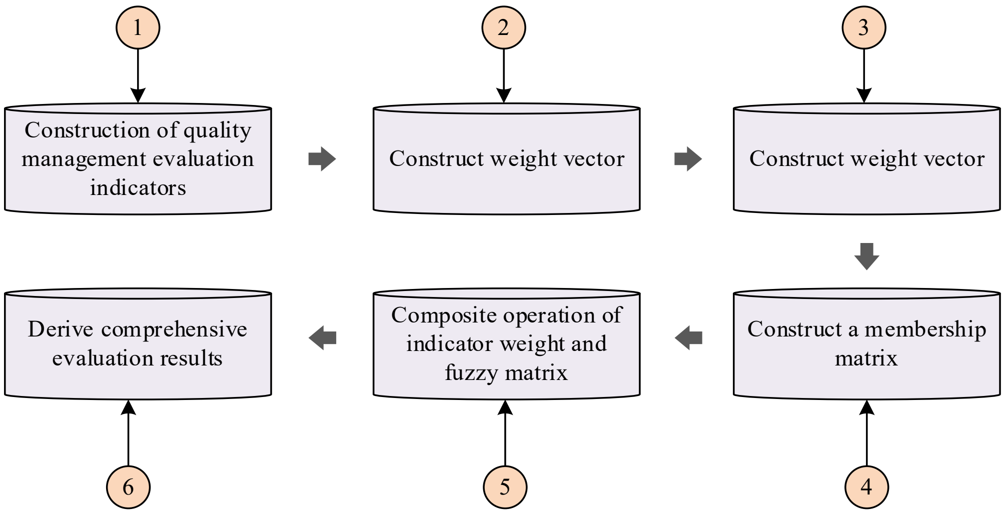

Fig. 2. The basic steps of the FCE method

$$R_{ij} = \frac{X_{ij} - \min(X_j)}{\max(X_j) - \min(X_j)} \tag{4}$$

In Eq. (4), k and $\max(X_j)$ are the minimum and maximum of the i -th indicator. After normalization, the minimum corresponds to 0, and the maximum corresponds to 1, resulting in the normalization matrix R as given by Eq. (5).

$$R = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1n} \\ R_{21} & R_{22} & \cdots & R_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ R_{m1} & R_{m2} & \cdots & R_{mn} \end{bmatrix} \tag{5}$$

Next, the expression for calculating entropy is shown in Eq. (6) (Xu et al., 2022).

$$E_j = -k \sum_{i=1}^{m} R_{ij} \ln R_{ij} \tag{6}$$

In Eq. (6), E_j is the entropy value. k is a constant related to the number of projects m, satisfying $k = \frac{1}{\ln m}$. The expression for the index difference coefficient d_j is shown in Eq. (7).

$$d_j = 1 - E_j \tag{7}$$

In Eq. (7), d_j the larger the value, the stronger the indicator's discreteness and the higher the weight contribution. Then, the EW of each indicator is solved, and the calculation of the evaluation indicator W_{Sj} is shown in Eq. (8).

$$W_{Sj} = \frac{1 - E_j}{n - \sum_{j=1}^{n} E_j} \tag{8}$$

In Eq. (8), the sum of the weights of all secondary indicators is equal to the weight of the primary indicator. In establishing subjective weights, the AHP is used for quantification, and the specific comparison scale is listed in Table 3.

3. Results

3.1. Objective Weight Calculation of QME Indicators

In the methods section, the study developed a multicriteria evaluation framework that incorporates an expanded 5M1E dimension, a Delphi-validated key performance indicator hierarchy, and a hybrid weighting system that incorporates the AHP and the EW Method. This section moves on to the empirical application of this framework. Z Avenue is designated as a secondary urban road with a design life of 15 years. This avenue serves as a key north-south traffic artery in the southern part of a particular city's old town. The project, with a total investment of 180 million yuan, spans 2.8 kilometers. The overall road width is 32 meters, with a 16-meter main road, a 3-meter central divider, and 6-meter-wide dividers on either side of the main road. This MRC project, which crosses a silty clay area, shortened the original construction period from 360 days to 320 days. Construction of the six-lane, two-way road is also required to ensure traffic flow through the surrounding residential areas. In the QME of the Z Avenue MRC project, a trapezoidal membership function is selected to construct the membership relationship between each indicator and the evaluation level. The function parameters are determined based on the "Code for Construction and Quality Acceptance of Urban Road Engineering" (CJJ 1-2008) and industry expert experience. A 7-level evaluation can easily lead to a decrease in the division of expert evaluations, while the coefficient of variation of expert ratings for a 5-level evaluation is only 0.21, which conforms to the quality grading conventions in the "Quality Evaluation Standards for Municipal Infrastructure Engineering" (GB/T 50375-2016) and is more suitable for industry practice. The study uses the language comment set during the initial expert review to establish a corresponding standard between the evaluation score range and the quality level (Unigwe and Egbueri 2023). The classification criteria are shown in Table 4.

Table 3. Comparative scale of indicator elements

Standard value	Definition	Description
1	Equally important	The importance of factors x and y is comparable
3	Slightly important	Factor x is slightly more important than y
5	Clearly important	The importance of factor x is significantly higher than that of y
7	Strongly important	Factor x is much more important than y
9	Absolute important	The importance of factor x is significantly higher than that of y
2, 4, 6, 8	Median of adjacent judgments	Used to refine the importance differences between intervals 1-3, 3-5, 5-7, 7-9
Count backwards	Reverse comparison	When comparing factors y and x, take the reciprocal of the corresponding scale

Table 4. Classification criteria for comprehensive quality evaluation levels

Score range	Rating Level	Level description
(8.0, 10.0]	I	Excellent
(6.0, 8.0]	II	Good
(4.0, 6.0]	III	Medium
(2.0, 4.0]	IV	Lower
[0.0, 2.0]	V	Poor

The evaluation results are shown in Table 5. The score distribution in Table 5 shows that the proportion of excellent ratings for each indicator was low, reflecting that the case project still has room for improvement in key quality control aspects. Further optimization of problem attribution analysis will be required based on construction logs and quality inspection data.

Based on the scoring results, the information entropy and utility values of each indicator were calculated, and the weights were determined. The weight coefficients are shown in Table 6. The weights of the first-level indicators indicated that the method dimension was 0.1931, the mechanical dimension was 0.1886, and the measurement dimension was 0.1891, which was higher than the personnel dimension of 0.1245, the material dimension of 0.0904, and the environmental dimension of 0.1439. This indicated that methods, machinery, and measurement are key areas of quality management. To avoid pseudo-objective bias caused by minimal variation in indicator values, a sensitivity test was conducted on the EW calculation results. By fine-tuning the expert scores for each indicator (±5%), the rate of change in the EWs is observed. The results showed that the rate of change in the EWs for all indicators was less than 3%, indicating that variation in indicator values had a minimal impact on the EW results and a minimal risk of pseudo-objective bias.

3.2. Establishment of Subjective Weights for QME Indicators

To calculate the subjective weights, experts are first invited to conduct pairwise comparisons of the six primary indicators to construct a judgment matrix. The results are shown in Table 7. Using the eigenvalue method to calculate the weights and perform a consistency test, the weight vectors for primary indicators B1-B6 were 0.105, 0.105, 0.256, 0.258, 0.182, and 0.094, respectively. The largest eigenvalue root was calculated to be 6.031. The random consistency index was 1.24. The resulting consistency ratio was 0.005, well below 0.1 and thus passing the test. It is worth noting that the construction of the judgment matrix is not a simple arithmetic average of expert opinions, but rather a structured consensus process involving multiple rounds of discussion and feedback. The results of this discussion demonstrate that, in MRC, "methodology" is a key determinant of project quality. If the framework of methodology is flawed, even high-quality personnel and materials will be significantly reduced. Meanwhile, "personnel" is considered slightly more important than "materials" because the skills, sense of responsibility, and management level of personnel directly determine whether materials can be adequately inspected, stored, and used (Questions 1-6) (3-3).

Table 5. Expert rating results

Criterion layer	Indicator layer	Excellent (8,10]	Good (6,8]	Medium (4,6]	Low (3,4]	Poor (1,2]
Personnel (B1)	Personnel organization (C1)	6	4	0	0	0
	Personnel Professionalism (C2)	4	6	0	0	0
Material (B2)	Material entry control (C3)	5	4	1	0	0
	Material inspection ratio (C4)	4	5	1	0	0
Mechanical (B3)	Equipment leasing and procurement (C5)	5	5	0	0	0
	Operation Training (C6)	5	5	0	0	0
	Maintenance iteration (C7)	5	3	2	0	0
Method (B4)	Construction Organization (C8)	3	7	0	0	0
	Process Control (C9)	5	5	0	0	0
	Quality Inspection (C10)	5	4	1	0	0
Measurement (B5)	Measurement accuracy (C11)	4	6	0	0	0
	Tool Usage Specification (C12)	5	5	0	0	0
	Maintenance and repair (C13)	5	4	1	0	0
Environment (B6)	Natural construction environment (C14)	5	5	0	0	0
	Finished product environmental protection (C15)	4	6	0	0	0

Table 6. The information entropy, utility, and weight coefficients of each indicator

Criterion layer	Indicator layer	Information entropy (E)	Information utility (d)	Weight coefficient (w)
Personnel (B1)	Personnel organization (C1)	0.6220	0.3780	0.419
	Personnel Professionalism (C2)	0.4778	0.5222	0.581
Material (B2)	Material entry control (C3)	0.6731	0.3269	0.500
	Material inspection ratio (C4)	0.6731	0.3269	0.500
Mechanical (B3)	Equipment leasing and procurement (C5)	0.4818	0.5182	0.333
	Operation Training (C6)	0.4818	0.5182	0.333
	Maintenance iteration (C7)	0.6731	0.3269	0.334
Method (B4)	Construction Organization (C8)	0.4487	0.5513	0.385
	Process control (C9)	0.4818	0.5182	0.361
	Quality inspection (C10)	0.6731	0.3269	0.254
Measurement (B5)	Measurement accuracy (C11)	0.4778	0.5222	0.382
	Tool usage specification (C12)	0.4818	0.5182	0.379
	Maintenance and repair (C13)	0.6731	0.3269	0.239
Environment (B6)	Natural construction environment (C14)	0.4818	0.5182	0.498
	Finished product environmental protection (C15)	0.4778	0.5222	0.502

This study then compares each secondary indicator pairwise and obtains the weights of each secondary indicator, as exhibited in Table 8. As shown in Table 8, method B4 receives the highest weight, reaching 0.258. The experts who participated in this weight assessment primarily come from the fields of engineering management and project coordination, and based on their long-term practice, they tend to view the method dimension as a core factor in quality control. Next is

Mechanical B3, with a weight of 0.256, which emphasizes the professionalism of equipment management and the importance of operational training. In the secondary indicator evaluation, the weight of personnel professionalism C2 is higher than that of organizational management C1, indicating the need to prioritize strengthening technical personnel training. The weight of entry control C3 is higher than that of the inspection ratio, reflecting the subjective importance of source control of raw materials. In addition, the weight of finished product protection is higher than that of the natural environment, highlighting the expert's awareness of protecting the completed parts during the construction process.

Table 7. First-level indicator pairwise judgment matrix

Evaluation	B1	B2	B3	B4	B5	B6
B1	1	1	1/2	1/3	1/2	2
B2	1	1	1/2	1/3	1/2	2
B3	2	2	1	1/2	2	3
B4	3	3	2	1	2	4
B5	2	2	1/2	1/2	1	3
B6	1/2	1/2	1/3	1/4	1/3	1

Table 8. Weight of secondary indicators

First level indicator	Weight	Secondary indicators	Weight
Personnel (B1)	0.105	Personnel organization (C1)	0.250
		Personnel professionalism (C2)	0.750
Material (B2)	0.105	Material entry control (C3)	0.667
		Material inspection and proportioning (C4)	0.333
Mechanical (B3)	0.256	Equipment leasing and procurement (C5)	0.545
		Operation training (C6)	0.309
		Maintenance and iteration of equipment (C7)	0.146
Method (B4)	0.258	Construction organization (C8)	0.637
		Process control (C9)	0.258
		Quality inspection (C10)	0.105
Measurement (B5)	0.182	Measurement accuracy (C11)	0.545
		Guidelines for the use of measuring tools (C12)	0.309
		Maintenance and repair (C13)	0.146
Environment (B7)	0.094	Natural construction environment (C14)	0.333
		Finished product environmental protection (C15)	0.667

3.3. Weight Calculation of QME Index Combination

Based on the calculation results of the EW method and AHP, this study calculates the comprehensive weight of primary indicators, as displayed in Table 9. The combination weight of method B4 is the highest, reaching 0.2506, indicating that it is recognized as the core of quality management by both subjective experience and objective data, and needs to focus on optimizing construction organization and process control. Next is mechanical B3, with a combined weight of 0.2223, reflecting the importance of equipment management in both subjective and objective evaluations. It is necessary to strengthen leasing procurement, operation training, and maintenance iteration. The combined weight of measurement B5 is 0.1856, ranking third, indicating that measurement accuracy is also a key factor affecting quality. The impact of personnel and environmental factors on the quality of MRC is low.

Table 10 shows the calculation of combined weights for each secondary indicator. The combination weight of personnel professionalism C2 is 0.6655, indicating that, in the personnel dimension, the professional level of technical personnel is the core driving force of quality, and it is necessary to strengthen certification and specialized on-the-job training. Under the material dimension B2, the combined weight of material incoming control C3 was 0.5835, and the combined weight of material inspection and proportion C4 was 0.4165. This difference is consistent with the quality control logic of municipal road projects, which prioritizes raw material sources over process inspection. The combined weight of the construction organization C8 is 0.5110, and that of the material entry control C3 is 0.5835, indicating that scientific construction design and raw material source control are recognized as quality control points both subjectively and objectively. In addition, the combined weight of the finished product environmental protection C15 is 0.5845, which is higher than that of the natural construction environment C14. reflecting that the protection of completed results during the construction process needs to be prioritized over adaptation to natural conditions.

Table 9. Comprehensive weight of primary indicators

First level indicator	Subjective weight	Objective weight	Combined weight
Personnel (B1)	0.105	0.1245	0.1148
Material (B2)	0.105	0.0904	0.0977
Mechanical (B3)	0.256	0.1886	0.2223
Method (B4)	0.258	0.1931	0.2256
Measurement (B5)	0.182	0.1891	0.1856
Environment (B6)	0.094	0.1439	0.1189

Table 10. The combined weight of each secondary indicator

Secondary indicators	Subjective weight	Objective weight	Combined weight
Personnel organization (C1)	0.250	0.419	0.3345
Personnel Professionalism (C2)	0.750	0.581	0.6655
Material entry control (C3)	0.667	0.500	0.5835
Material inspection and proportioning (C4)	0.333	0.500	0.4165
Equipment leasing and procurement (C5)	0.545	0.333	0.4390
Operation training (C6)	0.309	0.333	0.3210
Maintenance and iteration of equipment (C7)	0.146	0.334	0.2400
Construction Organization (C8)	0.637	0.385	0.5110
Process Control (C9)	0.258	0.361	0.3095
Quality inspection (C10)	0.105	0.254	0.1795
Measurement accuracy (C11)	0.545	0.359	0.4520
Guidelines for the use of measuring tools (C12)	0.309	0.356	0.3325
Maintenance and repair (C13)	0.146	0.225	0.1855
Natural construction environment (C14)	0.333	0.498	0.4155
Finished product environmental protection (C15)	0.667	0.502	0.5845

3.4. Z Avenue MRC Project Quality FCE

This study normalizes the number of evaluators at each level based on the expert ratings of various indicators on Z Avenue and obtains the membership matrix of each level indicator. Table 11 shows the membership matrix of each secondary indicator.

This study combines combination weights and uses fuzzy operators to calculate the evaluation results of each primary indicator, as shown in Table 12. According to Table 12, the score of Mechanical B3 was as high as 8.014 points, with a grade of I and an excellent overall level. This reflected the management standards of the construction unit in equipment selection and operator training. However, there is still room for improvement in the timeliness and systematicity of equipment maintenance. The reason is that there is a compression of the project schedule, resulting in an increase in the daily operating hours of the equipment and a decrease in maintenance frequency. In addition, due to a lack of maintenance personnel, hydraulic leaks on the drilling machine are not promptly repaired. The score for method B4 was 7.728 points, with a level of II. Only 0.3% of the construction organization indicators had a good membership degree. The reason is that geological radar was not used to detect underground pipelines in the early stage, resulting in the omission of old water supply pipelines. During the construction process, multiple pipeline fractures occur, leading to planning adjustments. However, the number of traffic diversion channels has been reduced from 3 to 2, resulting in delays in material transportation during the morning rush hour. The measurement B5 score was 7.938 points, with a level of II. The membership degrees of measurement accuracy and tool usage standards in terms of excellence and goodness were 0.46 and 0.55, respectively. The main reason is that the calibration cycle of the level exceeds the standard, and the deviation of the sight axis exceeds the standard, resulting in multiple deviations in the elevation of the roadbed beyond the standard. The scores for personnel B1 and material B2 were 7.936 and 7.824, respectively, both at level II. The main loophole was that 30% of the construction personnel are newly hired and lack professionalism, only receiving basic safety training, resulting in multiple deviations in road surface smoothness. Regarding materials, no drainage ditch is installed during the rainy season, and the moisture content of the 100 m water-stable layer exceeds the standard. Meanwhile, the night roller crushed the asphalt pavement that had not reached the maintenance period, causing local sanding. It indicates that the technical personnel's professional skills meet the construction requirements, but the construction team structure still needs to be optimized. In the material dimension, it is necessary to strengthen the dynamic review of supplier qualifications and improve the coverage of material sampling inspection. The score for Environment B6 was 7.826, with a level of II. Regarding natural construction environment protection C14, the standard for PM1 daily average (≤ 0.05 mg/m³) from the "Emission Standards for Environmental Noise at the Boundary of Construction Sites" (GB 12523-2011) was implemented for dust control during the construction period. This resulted in a dust compliance rate of over 90%. During periods of heavy rain and turbulent weather, delayed drainage from the temporary ditch may cause localized subgrade ponding. Such conditions fail to satisfy the requirements for a good rating, thereby diminishing the overall performance of this indicator.

Table 11. Membership matrix of each secondary indicator

Secondary indicators	Excellent	Good	Average	Poor	Very Poor
Personnel organization (C1)	0.6	0.4	0	0	0
Personnel professionalism (C2)	0.4	0.6	0	0	0
Material entry control (C3)	0.5	0.4	0.1	0	0
Material inspection and proportioning (C4)	0.4	0.5	0.1	0	0
Equipment leasing and procurement (C5)	0.5	0.5	0	0	0
Operation training (C6)	0.5	0.5	0	0	0
Maintenance and iteration of equipment (C7)	0.5	0.3	0.2	0	0
Construction organization (C8)	0.3	0.7	0	0	0
Process control (C9)	0.5	0.5	0	0	0
Quality inspection (C10)	0.5	0.4	0.1	0	0
Measurement accuracy (C11)	0.4	0.6	0	0	0
Guidelines for the use of measuring tools (C12)	0.5	0.5	0	0	0
Maintenance and repair (C13)	0.5	0.4	0.1	0	0
Natural construction environment (C14)	0.5	0.5	0	0	0
Finished product environmental protection (C15)	0.4	0.6	0	0	0

Table 12. FCE of quality management

First level indicator	First level indicator score	Evaluation level
Personnel (B1)	7.936	II
Material (B2)	7.824	II
Mechanical (B3)	8.014	I
Method (B4)	7.728	II
Measurement (B5)	7.938	II
Environment (B6)	7.826	II
Overall quality score	7.605	II

4. Discussion

The study's core finding is that, in a comprehensive weighted assessment, Method, Machine, and Measurement are identified as the most critical dimensions influencing the quality of municipal road projects. This result contrasts interestingly with the focus of some traditional research. Many existing studies examining construction quality focus primarily on the traditional elements of Personnel and Material, emphasizing that human skills and raw material quality are the cornerstones of quality control (Bashir et al., 2024). The findings of this study are not intended to diminish the importance of these factors. On the contrary, quantitative analysis shows that in modern complex urban infrastructure projects, the construction process of the system, the advancement and maintenance of technical equipment, and the accuracy of measurement systems are increasingly becoming key determinants of project success. This finding aligns with the broader trend in the construction industry toward lean construction and digitalization, which also emphasizes the importance of process optimization and technology integration (Prasetijo et al. 2023).

Furthermore, the environment component of the traditional 5M1E model is often limited to physical construction conditions (Lyu et al., 2025). By incorporating indicators such as climate, community impact, and the integration of green facilities, the proposed model provides quantitative empirical support for environmental and social impact assessment and green infrastructure. In the past, these concepts mainly were qualitatively discussed at the policy and planning levels. However, the model proposed in this study demonstrated how to incorporate it into the comprehensive quality performance evaluation of projects to ensure the implementation of these macro sustainable development concepts. The EW-AHP used in the study has significant advantages compared to the individual evaluation method proposed by (Bozanic et al., 2023). The traditional AHP relies on subjective judgments from experts to construct judgment matrices, which can easily lead to weight deviations from reality due to cognitive biases. The combination weighting method used in the study not only retains experts empirical judgments on key elements of the industry but also corrects subjective biases through objective data.

5. Conclusion

To achieve QME of MRC projects, this study constructed the MRC project QIF system based on the 5M1E theory, and used the FCE method, combined with EW-AHP, to determine the subjective and objective combination weights, to conduct QME of the Z Avenue project. In the experiment, the dimension with the highest combination weight of primary indicators was “method,” with a weight value of up to 0.2256. The next was ”mechanical”, with a combined weight of 0.2223. The combined weight of the measurement dimensions was 0.1856. All three were the core of quality management for MRC projects. The combination weight of the environmental dimension was the lowest, only 0.1189. In the secondary indicators, the combination weights of man professionalism (0.6655), construction organization (0.5110), material entry control (0.5835), and finished product environmental protection (0.5845) ranked high, reflecting the importance of technical personnel skills, construction plan design, raw material source control, and finished product protection. In FCE, the comprehensive score of construction quality for Z Avenue was 7.605 points, with a level of II. Among them, the mechanical dimension performed the best, with a score of 8.014 points and a level of I. This indicates that the 5M1E theory applies to the QIF analysis of MRC, and the FCE method can effectively achieve quantitative evaluation of quality. During the construction of Z Avenue, the management of equipment leasing, procurement, and operation training is very standardized, but the systematic maintenance of equipment is insufficient. The measurement accuracy and tool usage standards are well implemented, but tool maintenance and repair need to be strengthened. In addition, the construction unit has taken effective protective measures in complex environments, but the protection of finished products still needs to be strengthened. From a practical management perspective, the results of the research will prompt project managers to fundamentally adjust their decision-making process from three key aspects. Firstly, in terms of resource allocation, managers will shift from traditional over reliance on material and personnel control to prioritizing the optimization of construction methods and measurement system accuracy. Secondly, in terms of equipment management, decision-makers will shift their focus from procurement and operations to implementing proactive and systematic maintenance plans to prevent quality degradation caused by equipment fatigue under compressed project schedules. Finally, in quality assessment, managers will transition from experience based judgments to adopting data-driven hybrid evaluation models to reduce subjective biases and achieve more accurate quality control. Although the current indicator system covers the main factors throughout the construction process, emerging variables are increasingly becoming the key factors affecting quality. Future research should focus on incorporating emerging technological variables such as intelligent construction equipment, building information modeling technology application level, and Internet of Things data integration into the evaluation framework, further enhancing adaptability to future smart construction sites.

Meanwhile, in the future, the application of combination evaluation models (such as FCE-TOPSIS) in complex projects can be explored. In addition, although the study considered environmental changes during the construction period, the combination weights did not reflect stage differences. Subsequent research will introduce time series weight adjustment, dividing construction into roadbed, pavement, and ancillary facility periods, and dynamically adjusting the weights of core indicators in each stage.

Author Contributions

Chen Huang contributes to conceptualization, methodology, software, validation, analysis, investigation, data collection, draft preparation, manuscript editing, visualization, supervision, project administration, and funding acquisition. Wenwen Zhou contributes to conceptualization, methodology, software, validation, analysis, investigation, data collection, draft preparation, manuscript editing, visualization, supervision, project administration, and funding acquisition. All authors have read and agreed with the manuscript before its submission and publication.

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Institutional Review Board Statement

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Declaration of Artificial Intelligence (AI) Tools

The authors used Grammarly Premium solely for language editing and readability improvement. The authors reviewed and verified all content and take full responsibility for the accuracy and integrity of the manuscript.

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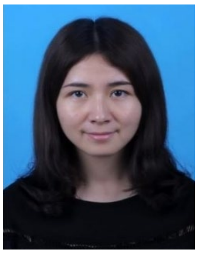

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