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Application Research of AHP in Quantitative Evaluation of Urban Overpass Demolition Scheme

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Abstract

With the development of urban construction, some urban overpasses built in the early stage gradually cannot meet the needs of urban traffic due to various reasons, and the demolition of urban overpasses is gradually concerned by urban management departments, construction enterprises and relevant experts and scholars. Aiming at the evaluation problem of urban overpass demolition scheme, this paper establishes a quantitative evaluation model of urban overpass demolition scheme by AHP. The model contains 5 standards and 15 evaluation indexes, and carries out systematic quantitative evaluation of urban overpass demolition scheme from the aspects of safety, schedule, cost, technology and circular degree. Three alternative schemes of overpass demolition in a city are mechanical demolition scheme, static demolition scheme and blasting demolition scheme. The scheme with the highest score is selected through quantitative evaluation of the scheme. The validity of the method is verified. It provides effective suggestions for the following urban overpass demolition project.

Keywords: Urban overpass; demolition scheme; quantitative evaluation; Analytic hierarchy process(AHP); pairwise comparisons; Expert score

1 Introduction

In recent years, urban transportation construction in mainland China is undergoing revolutionary changes. In the 1980s, the construction of overpasses began to rise gradually in major cities. With the development of the city, some overpasses built early can not meet the needs of urban traffic. Some urban overpasses are damaged by floods, earthquakessand other natural disasters due to the low planning and construction standards in the early stage, and some urban overpasses cannot continue to be used after the reasonable use period expires, and so on.

An Overpasses is located in the north ring section of the city Third Ring Road. It was built in 1994, but now the city municipal government has decided to demolish it. The demolition of urban overpasses has been gradually concerned by government departments, enterprises and scholars.

The demolition of urban overpass is first to interrupt its related traffic for a period of time. The important function of urban overpass in traffic determines the impact of its demolition on traffic. The larger the scale of urban overpass is, the longer the demolition time is generally required. The demolition of urban overpass will also affect the normal operation of above-ground and underground buildings and structures such as rain sewage pipes, communication cables, heating pipes, tap water, natural gas pipelines, pumping stations and so on, and then affect the lives of surrounding residents, and even bring disaster to the surrounding residents.

Secondly, dust, noise and sewage produced in the process of removing urban overpass will have a serious impact on the surrounding environment. The demolition of urban overpasses is generally an open-air operation, which requires the investment of a lot of large machinery and even the use of blasting. For the demolition of urban overpasses, manpower should be invested to build temporary facilities for office and life. Dust, noise, sewage and other pollutants will inevitably occur in the demolition of urban overpass for human, mechanical and blasting operations.

Demolishing urban overpasses again can cost hundreds of millions of dollars. Urban overpass demolition use large machinery, the use of manpower, the demolition cycle is long, but also need to go through all kinds of administrative approval procedures, take all kinds of temporary dust control, noise reduction, emission reduction, protection measures, as well as the demolition of urban overpass generated by a large amount of garbage needs to be absorbed, the demolition of the establishment of overpass need a lot of capital is inevitable.

There are demolition of urban overpass construction and mining, chemical hazards similar. Large machinery and explosives used to demolish urban overpasses are major hazard sources. The operation of large machinery and the use of explosives are special operations in the field of safety management, and the users of special operations are also major hazard sources. The dismantlement process requires the cooperation of personnel and machinery, and the management process is also full of challenges, requiring professionally trained and experienced personnel to undertake.

The problem of garbage consumption caused by the removal of urban overpasses has become one of the world's difficult problems troubling human existence. The garbage generated by the demolition of urban overpass is mainly concrete and reinforced concrete, and a small amount of steel. It is difficult to reuse the concrete, reinforced concrete and steel generated by the demolition of urban overpass, and transportation and consumption are difficult problems.

Therefore, it is necessary to study a systematic selection process of urban overpass demolition scheme, determine the evaluation standard and priority of urban overpass demolition scheme, and evaluate the urban overpass demolition scheme in safety, cost, environmental protection, technology, cycle and other aspects. The evaluation method of urban overpass demolition scheme should also reduce the time of evaluation scheme and reach consensus.

Zhang Yongling, Zhao Wan et al suggested using analytic Hierarchy Process (AHP) to solve the demolition scheme evaluation problem. They proposed analytic hierarchy process mainly because of its inherent ability to deal with qualitative and quantitative criteria used in the evaluation of demolition options. Moreover, it is easy for managers to understand and apply. At the same time, analytic hierarchy process can help improve the decision-making process. The hierarchy used in building the AHP model enables all members of the evaluation team to systematically visualize problems against relevant criteria and sub-criteria. If necessary, the team can also provide input to modify the hierarchy through additional standards. In addition, using analytic hierarchy process, evaluation teams can systematically compare and prioritize standards and substandards. Based on this information, the team can compare several demolition options and choose the best one for the urban overpass.

Taking a Bridge in a city as the research object, this paper discusses the feasibility of applying ahp to the evaluation of urban overpass demolition scheme, so as to make the project decision more logical and systematic. First of all, in section 2, we determine the key success factors of urban overpass demolition scheme evaluation, and the key evaluation factors will constitute the determination of important standards and sub-standards. In Section 3, these factors will be used to construct an AHP model to express the evaluation problem of urban overpass demolition scheme. In section 4, AHP model will be applied to the evaluation of rainbow Bridge demolition scheme in Zhengzhou to conduct a case study to demonstrate its application and test its effectiveness. The advantages of using the model presented in this article are also discussed in Section 4. Section 5 is the conclusion.

In order to determine the criteria and sub-criteria for the evaluation of urban overpass removal options, we conducted a survey, as described in Section 2. The purpose of this survey is to enumerate the key evaluation factors, which will constitute the basis for determining the evaluation criteria and sub-criteria of the urban overpass demolition scheme, in order to develop the AHP model. It is not used to determine the priority weights of criteria and sub-criteria, which is the main purpose of analytic hierarchy process.

2 Determine Standards and Sub-standards

Liu Xinzhong, Wang Senlin(2019) et al. determined four criteria for the evaluation of urban overpass demolition scheme, namely, safety, economy, degree of traffic impact, traffic impact time and construction period. According to the research of Fu Guangming and Ren Caiqing(2011) et al., the influencing factors for the evaluation of material blasting demolition scheme should mainly include: directional design scheme, blasting parameters, safety check and protection, initiation equipment and network, etc. In addition, zhang Yongling, Zhao Wan(2018) et al argued that the evaluation factors of the dismantling scheme of nuclear facilities include safety factors, waste amount, decommissioning funds, decommissioning cycle, technical factors, public recognition and other aspects. Their research can also be applied to the evaluation of urban overpass demolition scheme. These factors can be roughly divided into five categories: safety, cycle, technology, cost and environmental protection. Safety factors include equipment safety, personnel safety and construction process safety. Cycle factors include preparation cycle, construction cycle and recovery cycle; Technical factors include originality, applicability, maturity and contribution; Expenses include relocation expenses, demolition expenses, temporary facilities expenses, office expenses and consumption expenses. Environmental protection includes dust, noise, sewage, light pollution, etc.

We conducted a survey of 20 people, including leaders of government departments, industry experts and scholars from universities and research institutions, who were directly involved in the evaluation of the demolition scheme. As mentioned in Section 1, the purpose of this survey is to evaluate and determine the above-mentioned safety, cycle, technology, cost and environmental protection factors as relevant standards and sub-standards for formulating AHP model. A questionnaire containing these factors was designed for the survey. Before conducting the survey, we conducted a pilot test with two industry experts. Based on the comments received, the questionnaire was adjusted and some additional criteria were added. The new questionnaire was sent to randomly selected respondents. To determine the relevant criteria, respondents were asked to evaluate each factor on a three-point scale of “not important,” “somewhat important,” and “very important" when choosing an urban overpass demolition option. The survey results are summarized in Figure 1, where the average for each factor is determined by multiplying the percentage of respondents by the values of 1, 2, and 3 related to "unimportant," "somewhat important," and "very important," respectively, plus the resulting data. The criteria are listed in descending order of their average, using 2.3 as the threshold and identifying those factors with an average greater than or equal to 2.4 as the relevant criteria. As can be seen from Figure 1, the value of 2.4 seems to be the natural turning point, since it is the average of the highest (2.9, see Figure 1) and lowest (1.9, see Figure 1) average rating values for all factors in the survey. The existence of too many standards leads to a huge amount of work in evaluating the construction scheme of urban overpass demolition by pair comparison. As explained in Section 3.1 and 5, this may also lead to the evaluation deviation of the evaluator. To overcome these problems, a threshold approach is needed to reduce the number of standards. Fifteen criteria were selected to construct the analytic hierarchy Process model.

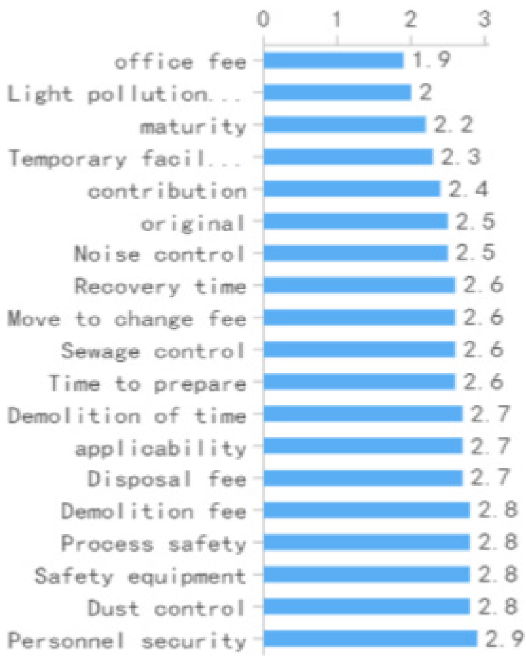

Figure. 1.Factorsaffecting the selectiong of urban overpass demolition scheme

3 Analytic Hierarchy Process Model

The modeling process of analytic hierarchy process includes the following stages: the construction of decision problem, measurement and data collection, determination of normalized weight and comprehensive solution of the problem. Using this method, we first developed an AHP model for quantitative evaluation of urban overpass removal scheme in this section, which can be applied to quantitative evaluation of any urban overpass removal scheme.

3.1 Evaluation of Urban Interchange Demolition Scheme

This stage involves an appropriate hierarchy of the analytic hierarchy model, which consists of objectives, criteria and sub-criteria, and alternatives. The goal of our question is to select an urban overpass demolition scheme, which must meet the requirements of relevant government departments and bring profits to enterprises. This goal is placed at the first level of the hierarchy, as shown in Figure 2. The second level of the hierarchy is safety, cycle, technology, cost and environmental protection. The third tier consists of 15 sub-standards, identified in Section 2 above, and combined with the criteria occupying the second tier, as shown in Figure 2.

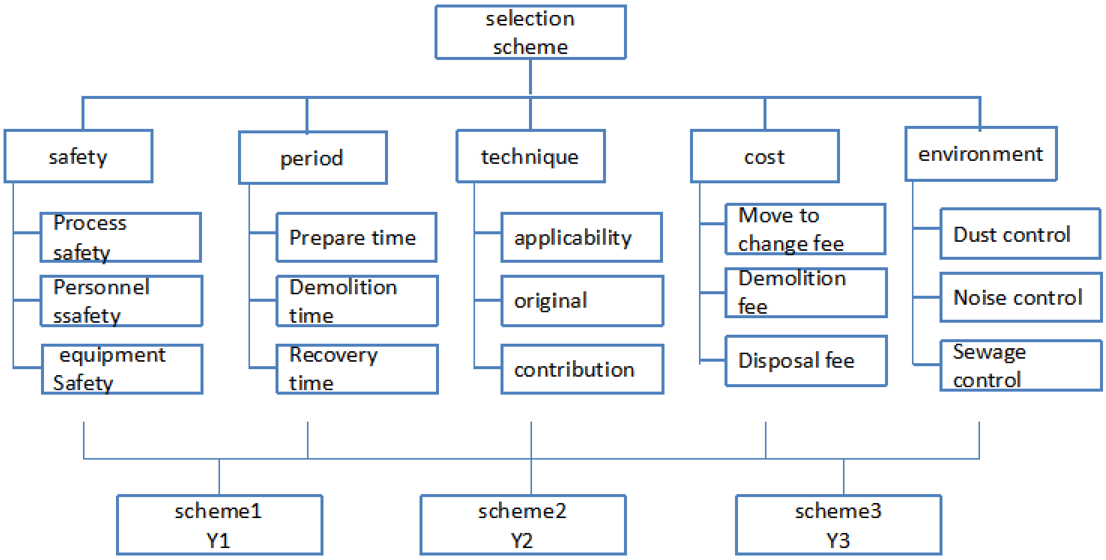

Figure. 2.AHP model for quantitative evaluation of urban overpass demolition scheme

For the convenience of description, each factor is numbered in Table 1.

Table 1: The code of criterion

Code	Meaning	Code	Meaning
X1	Safety	X11	Process safety
		X12	Personnelsafety
		X13	Equipment safety
X2	Period	X21	Prepare time
		X22	Demolition time
		X23	Recovery time
X3	Technique	X31	Applicabiltiy
		X32	Original
		X33	Contribution
X4	Cost	X41	Move to change fee
		X42	Demolition fee
		X43	Disposal fee

The criteria and sub-criteria used in these two levels of the AHP hierarchy can be evaluated using the basic AHP method, where elements in each level are compared in pairs with each parent element located above one level. You can then determine a set of global priority weights for each child standard by multiplying the local weights of the child standard by the weights of all the parent nodes above.

Saaty et al. suggested quoting numbers 1-9 and their reciprocal as scales, as shown in Table 2.

Interpolated 9-point rating tables of equal importance, slightly important, obviously important, much more important and absolutely important and their adjacent judgments were used. The priority weights of these ratings can be determined by pairwise comparison in Section 3.3 below. A potential complication can be reduced when using a 9-point rating system to assign rating scales. For example, the relative ratings of “equally important” and “slightly important” may vary according to different criteria. Interpolation 2 of 1 and 3 can be selected in the judgment. Use them to determine local and global priority weights, as described in sections 3.3 and 3.5 below

Table 2: Quoting numbers 1-9 and their reciprocal as scales

Scale	Meaning
1	Indicates that two factors are of equal importance when compared
3	Refers to the comparison of two factors, one of which is slightly more important than the other
5	When two factors are compared, one is significantly more important than the other
7	When two factors are compared, one is much more important than the other
9	When two factors are compared, one is absolutely more important than the other
2、4、6、8	As the median value of the adjacent judgment above
Reciprocal of the numbers above	The inverse ratio of another factor to the original factor

Interpolated 9-point rating tables of equal importance, slightly important, obviously important, much more important and absolutely important and their adjacent judgments were used. The priority weights of these ratings can be determined by pairwise comparison in Section 3.3 below. A potential complication can be reduced when using a 9-point rating system to assign rating scales. For example, the relative ratings of "equally important" and "slightly important" may vary according to different criteria. Interpolation 2 of 1 and 3 can be selected in the judgment. Use them to determine local and global priority weights, as described in sections 3.3 and 3.5 below

The lowest level of the hierarchy includes alternatives, which are the evaluation of different demolition options in order to select the best option for urban overpass removal. As shown in Figure 2, we use three demolition scenarios to represent any three scenarios we wish to evaluate. The AHP model shown in Figure 2 is generally applicable to issues where the team wishes to evaluate options for urban overpass removal, as it covers key criteria and sub-criteria. Therefore, when the team needs to choose a demolition plan, it can evaluate the demolition plan through the rating plan described above and determine the priority weight of the demolition plan to select the best demolition plan. As explained earlier in Section 1, the model provides the feasibility of including any specific criteria, as well as goals and criteria that the team may wish to consider in any other situation.

3.2 Measurement and Data Collection

After building the AHP hierarchy, the next stage is measurement and data collection, which involves forming team assessments and assigning criteria and sub-criteria for comparison in pairs, as explained above. Saaty's 9-point scale was used to pairwise compare all elements at each level of the hierarchy. Typically each member assigns his or her pairwise comparison, which is translated into the corresponding pairwise comparison judgment matrix (PCJMs). To simplify the calculation, we used arithmetic to get the consensus PCMs of the whole team, or we could use geometric averaging to combine individual PCJMs to get a more accurate consensus PCMs of the whole team.

With this approach, it is important to establish assessment groups. Assessment team members should have experience in the evaluation of urban interchange demolition options. Two of the evaluators were senior engineers in the engineering industry, each with more than five years of experience. The other two were from universities and research institutions. One of them has been engaged in relevant teaching work for more than 20 years, and the other has been engaged in demolition construction related research for more than 20 years. The final evaluator is the operational head of the construction authority responsible for safety and technical supervision. Therefore, the evaluator has long experience in the evaluation of urban overpass demolition scheme, and is therefore qualified to assign pairwise comparison judgment.

We designed a questionnaire consisting of all criteria and sub-criteria at both levels of the AHP model to collect pair comparative judgments from all evaluation team members. This method has been found useful in collecting data. According to the attributes of a higher layer in the hierarchy, from the standard level to the sub-standard level, compare and judge the attributes of a layer in the hierarchy. The results collected from the questionnaire were used to form the corresponding pair comparison judgment matrix (PCJMs) to determine standardized weights, as described in the following section.

3.3 Determine the Weights

As mentioned above, the pair comparison judgment matrices obtained by five evaluators in the measurement and data acquisition stages are combined by arithmetic mean method at each level to obtain corresponding consistent pair comparison judgment matrices. Then, each matrix is transformed into the corresponding maximum eigenvalue problem, and the normalized and unique priority weight of each criterion is calculated, as shown in Table 3-8. Software systems are used to determine normalized priority weights. The consistency ratio (CR) of each PCJM is also shown under each matrix. It can be seen that the consistency of all PCJM is ≤ 0.1 empirical value. This obviously means that evaluators are consistent in assigning pairwise comparison judgments.

Table 3: Pairwise comparison judgment matrices of quantitative evaluation of demolition scheme

A	X1	X2	X3	X4	X5	Weights
X1	1	7	3	8	8	0.564
X2	1/7	1	1/4	3	2	0.098
X3	1/3	4	1	3	3	0.219
X4	1/8	1/3	1/3	1	2	0.065
X5	1/8	1/2	1/3	1/2	1	0.054
CI	0.068					
RI	1.12					
CR	0.061					

CR=0.061<0.1 It passes the consistency test

X1	X11	X12	X13	Weights
X11	1	1/2	1	0.232
X12	2	1	4	0.584
X13	1	1/4	1	0.184
CI	0.027			
RI	0.58			
CR	0.047			

CR=0.047<0.1 It passes the consistency test

X2	X21	X22	X23	Weights
X21	1	1/2	1	0.24
X22	2	1	3	0.55
X23	1	1/3	1	0.21
CI	0.009			
RI	0.58			
CR	0.016			

CR=0.016<0.1 It passes the consistency test

X3	X31	X32	X33	Weights
X31	1	3	3	0.6
X32	1/3	1	1	0.2
X33	1/3	1	1	0.2
CI	0			
RI	0.58			
CR	0			

CR=0<0.1 It passes the consistency test

X4	X41	X42	X43	Weights
X41	1	1/4	2	0.2
X42	4	1	5	0.683
X43	1/2	1/5	1	0.117
CI	0.012			
RI	0.58			
CR	0.021			

CR=0.021<0.1 It passes the consistency test

X5	X51	X52	X53	Weights
X51	1	1	2	0.4
X52	1	1	2	0.4
X53	1/2	1/2	1	0.2
CI	0			
RI	0.58			
CR	0			

CR=0<0.1 It passes the consistency test

3.4 Solutions to Problems

After calculating the normalized priority weight of each PCJM in the AHP hierarchy, the next stage is the solution of the comprehensive problem. Criteria for standardized local priority weights The sub-criteria obtained from the third stage are combined with all successive levels to obtain the global composite priority weights for all the sub-criteria used in the third level of the AHP model. As mentioned earlier, expert selection software systems are used to determine these global priority weights, as shown in table4.

Table 4: Composite priority weights for critical success factors

Criteria	Local Weights	Subcriteria	Local Weights	Globle Weights
A-X1	0.564	X1-X11	0.232	0.131
		X1-X12	0.584	0.329
		X1-X13	0.184	0.104
A-X2	0.098	X2-X21	0.24	0.024
		X2-X22	0.55	0.054
		X2-X23	0.21	0.021
A-X3	0.219	X3-X31	0.6	0.131
		X3-X32	0.2	0.043
		X3-X33	0.2	0.043
A-X4	0.065	X4-X41	0.2	0.013
		X4-X42	0.683	0.044
		X4-X43	0.117	0.007
A-X5	0.054	X5-X51	0.4	0.021
		X5-X52	0.4	0.021
		X5-X53	0.2	0.011

After calculating the global weights of each sub-criterion at level 2, see Table 5. It can be seen from the figure that the top two factors are safety and technology, human safety is the most important factor of safety, and applicability of technology is the most important factor of technology.

Table 5: Ranking of critical success factors

Rank	Subcriteria	Globle Weights
1	X1-X12	0.329
2	X1-X11	0.131
3	X3-X31	0.131
4	X1-X13	0.104
5	X2-X22	0.054
6	X4-X42	0.044
7	X3-X32	0.043
8	X3-X33	0.043
9	X2-X21	0.024
10	X2-X23	0.021
11	X5-X51	0.021
12	X5-X52	0.021
13	X4-X41	0.013
14	X5-X53	0.011
15	X4-X43	0.007
	total	1.000

As mentioned above, the AHP model of the design criteria and sub-criteria, as well as their global priority weights, can be applied to any specific urban overpass demolition scheme selection problem. In section 4 below, we consider the selection of scheme provider for the removal of overpasses in three cities and show how to apply the model to select the best scheme for the removal of overpasses in cities.

4 AHP Model Is Applied to Solve the Problem of Choosing the Demolition Scheme of Rainbow Bridge in Zhengzhou

4.1 Scheme Evaluation

After the demolition of Zhengzhou Rainbow Bridge was confirmed by the competent government department, the relevant engineering company provided three demolition schemes, namely mechanical demolition scheme, static demolition scheme and blasting demolition scheme. Each of these three schemes has its own advantages and disadvantages, and the owner, supervision company and dismantling enterprise are not in agreement. The owner unit, the supervision company and the dismantling enterprise decide to use AHP method to choose the dismantling scheme through consultation. The owner unit and the supervision company shall each send two experts, and the dismantling enterprise shall send one expert to form the decision-making group. The decision-making group evaluated the three schemes with the nine-point evaluation method, and summarized the scores of the five experts with the arithmetic mean method. The summary results are shown in Table 6.

Table 6: Expert score summary

X11	Y1	Y2	Y3
Y1	1	3	1/3
Y2	1/3	1	3
Y3	3	1/3	1
X12	Y1	Y2	Y3

Y1	1	3	7
Y2	1/3	1	5
Y3	1/7	1/5	1
X13	Y1	Y2	Y3
Y1	1	3	7
Y2	1/3	1	3
Y3	1/7	1/3	1
X21	Y1	Y2	Y3
Y1	1	1/3	1/7
Y2	3	1	1/4
Y3	7	4	1
X22	Y1	Y2	Y3
Y1	1	3	7
Y2	1/3	1	3
Y3	1/7	1/3	1
X23	Y1	Y2	Y3
Y1	1	1	1
Y2	1	1	1
Y3	1	1	1
X31	Y1	Y2	Y3
Y1	1	1/3	1/5
Y2	3	1	1/4
Y3	5	4	1
X32	Y1	Y2	Y3
Y1	1	3	1/5
Y2	1/3	1	1/4
Y3	5	4	1
X33	Y1	Y2	Y3
Y1	1	1/3	1/5
Y2	3	1	1/3
Y3	5	3	1
X41	Y1	Y2	Y3
Y1	1	1/3	1/5
Y2	3	1	1/3
Y3	5	3	1
X42	Y1	Y2	Y3
Y1	1	1/3	1/7
Y2	3	1	1/3
Y3	7	3	1
X43	Y1	Y2	Y3
Y1	1	1	8/9
Y2	1	1	1
Y3	1	1	1
X51	Y1	Y2	Y3
Y1	1	1	1/5
Y2	1	1	1/3
Y3	5	3	1
X52	Y1	Y2	Y3
Y1	1	3	1/5
Y2	1/3	1	1/3
Y3	5	3	1
X53	Y1	Y2	Y3
Y1	1	1/3	1

Y2	3	1	1
Y3	1	1	1

4.2 Calculation and Analysis of Evaluation Results

Table 8 Combined with the analysis in Section 3 of the article, the evaluation results are calculated: Y1 total score =0.416; Y2 total score =0.230; Y3 total score =0.354. The calculation process is shown in Table 7.

Table 7: Application of the AHP model

Layer 1	Layer 2	Scheme					
Criteria	Local Weights	Subcrite-ria	Local Weights	Globle Weights	Y1	Y2	Y3
A-X1	0.564	X1-X11	0.232	0.131	0.33	0.14	0.528
		X1-X12	0.584	0.329	0.649	0.279	0.072
		X1-X13	0.184	0.104	0.669	0.243	0.088
A-X2	0.098	X2-X21	0.24	0.024	0.084	0.211	0.705
		X2-X22	0.55	0.054	0.669	0.243	0.008
		X2-X23	0.21	0.021	0.333	0.333	0.333
A-X3	0.219	X3-X31	0.6	0.131	0.101	0.226	0.674
		X3-X32	0.2	0.043	0.188	0.081	0.731
		X3-X33	0.2	0.043	0.105	0.258	0.637
A-X4	0.065	X4-X41	0.2	0.013	0.105	0.258	0.637
		X4-X42	0.683	0.044	0.088	0.243	0.669
		X4-X43	0.117	0.007	0.333	0.333	0.333
A-X5	0.054	X5-X51	0.4	0.021	0.156	0.185	0.669
		X5-X52	0.4	0.021	0.188	0.081	0.731
		X5-X53	0.2	0.011	0.333	0.333	0.333
Total score	0.416	0.230	0.354				

The weight of criterion layer 1, criterion layer 2 and three weights of scheme layer are obtained by judgment matrix. The node weight of criterion layer 2 is the weight of criterion 1 multiplied by the link weight of criterion 2. The total score is obtained by multiplying the node weights of criterion 2 by each scheme weight.

Plan 1 is better

4.3 Overall Consistency Test

The consistency test of each judgment matrix has been carried out in the preceding paragraph, that is, the CR value of each judgment matrix has been calculated. The overall conformance test calculates the cumulative CR value (top to bottom) to see if the CR3 value is less than 0.1

CI1=0.068 RI1=1.12 CR1=0.061

CI2=0.564*0.027+0.098*0.009+0.219*0+0.065*0.012+0.054*0=0.0016

RI2=0.564*0.58+0.098*0.58+0.219*0.58+0.065*0.58+0.054*0.58=0.58

CR2=CR1+CI2/RI2=0.0637

CI3=0.131*0.027+0.329*0.032+0.104*0.004+0.0204*0.016+0.054*0.004+0.021*0+0.131*0.043+0.043*0.032+0.043*0.019+0.013*0.019+0.044*0.004+0.007*0+0.021*0.015+0.021*0.032+0.011*0=0.01

RI3=0.58

CR3=CR2+CI3/RI3=0.0637+0.017=0.0807<0.1

CR3<0.1generally passed the consistency test.

5 Conclusions

The modeling process of analitc hierarchy process includes the following stages: the construction of decision problem, measurement and data collection, determination of normalized weight and comprehensive solution of the problem. Using this method, we first developed an AHP model for quantitative evaluation of urban overpass removal scheme in this section, which can be applied to quantitative evaluation of any urban overpass removal scheme.

From the results of the case study, it can be concluded that it is desirable to apply AHP to the selection of urban overpass demolition scheme to improve the team decision-making process. The AHP model established in this paper can be used as the basis of urban overpass demolition scheme selection.

It should be noted, however, that data collection and calculation problems will increase as the number of criteria and sub-criteria increases and as the number of urban overpass removal options are considered in the selection. This is one of the reasons why we suggest first listing the number of urban overpass removal schemes and then applying the AHP model. Again, as shown here, the number of success factors can be grouped to minimize the number of criteria and sub-criteria used to build an AHP model. The number of assessors can be increased to collect more data. In fact, we can increase the number of evaluators and collect data and set priorities to check if they change. In this way, we can perform sensitivity analysis and determine the best number of evaluators to use to collect data. However, several case studies using AHP in the literature indicate that between three and seven evaluators were used. In this way, the evaluator's bias in evaluating pairwise comparisons can be reduced.

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Life-cycle Carbon Emission Calculation and Reduction Strategies for Glass Curtain Wall Hotels

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Abstract

Based on the whole-life-cycle theory of building carbon emissions, this study takes a glass-curtain-wall hotel in Ganzhou City as an example, divides the hotel's life-cycle carbon emissions into five stages—material production, transportation, construction, operation and demolition—according to its material and mechanical consumption, and conducts corresponding carbon-reduction strategy research. The results show that the material production and operation stages contribute the most to the building's life-cycle carbon emissions. As the primary targets for carbon reduction, these stages can be addressed by extending the building's service life, improving the thermal performance of the envelope, and adopting low-carbon elevators, among other measures, to achieve emission reduction goals.

Keywords: Building carbon emissions; Whole life cycle; Carbon reduction; Hotel construction project; Carbon emission calculation

1 Introduction

In recent years, significant global climate change has drawn widespread international attention to greenhouse gas emissions and their control, making low-carbon development a new strategic goal across industries. In response, China proposed at the 75th UN General Assembly the key objectives of "striving to peak carbon emissions before 2030 and achieve carbon neutrality before 2060" . Research indicates that in 2021, China's total building lifecycle carbon emissions reached 4.07 billion tCO_2, accounting for 38.2% of energy-related carbon emissions . Therefore, achieving low-carbon development in the building sector is crucial for China's dual-carbon goals, with energy-intensive hotel buildings representing a key focus for energy conservation and emission reduction. Conducting research on lifecycle carbon emission calculation and reduction strategies for hotel buildings holds significant importance for advancing low-carbon development in the construction industry.

Carbon emission calculation and analysis serve as the foundation for studying whole-life-cycle carbon reduction in buildings, which not only helps accurately identify key emission phases and critical reduction factors at each stage, but also effectively guides low-carbon development throughout hotel construction phases including material production, transportation, construction, demolition, and operation. Since the Paris Climate Agreement, research on carbon emissions has intensified, with the construction sector as a key focus area, prompting numerous scholars to conduct micro-level studies on building carbon reduction. Domestically, Sun established three carbon-reduction calculation models (raw material utilization, enterprise production process, and material application) that conclusively demonstrate green building materials' contributions and potential for emission reduction. Zhang et al. conducted building carbon accounting through input-output analysis, revealing construction's significant driving effect on other sectors' emissions, and proposed that guiding material selection could reduce indirect emissions and achieve low-carbon material choices. Guo et al. developed a calculation formula for retrofit buildings' life-cycle emissions, providing theoretical support for low-carbon renovation projects. Li et al. simulated building energy-saving pathways under various policy scenarios using a Stars/Building comprehensive evaluation model, concluding that renewable energy utilization and heating system optimization significantly contribute to emission reduction.

Concurrently, international scholars have also conducted relevant research on building carbon emissions. Kou et al. proposed a novel passive solar house integrated with gravity heat pipes, achieving an envelope with variable thermal performance that efficiently utilizes solar energy for zero-carbon heating, thereby reducing building emissions. Jia et al. investigated SiO_2 aerogel-based low-carbon building materials utilizing CO_2 adsorption properties and carbonization technology, discovering that amino-modified aerogels significantly enhance carbon adsorption capacity, which can partially reduce emissions during building material production. Eum et al. implemented electricity-centric energy sharing systems (incorporating photovoltaics, battery storage, and energy management systems) in two Korean communities, enabling surplus energy trading and renewable energy utilization between communities and buildings, consequently reducing building emissions.

Current research on building decarbonization primarily focuses on conventional building typologies including office, cultural-educational, exhibition, and medical facilities, given their substantial societal prevalence and well-established energy/carbon emission patterns, making them representative models for building carbon emission studies. However, hotel buildings - as mixed-use commercial structures (integrating guest accommodations, entertainment, and food services) - remain under-investigated. This study addresses this gap by examining a glass curtain-walled hotel in Ganzhou City, conducting a comprehensive whole-life carbon assessment to identify critical emission drivers, develop tailored decarbonization strategies, and establish a methodological framework for future hotel carbon research.

2 Overview of Carbon Emission Calculation

2.1 Research Scope and Calculation Methodology for Carbon Emissions

The carbon emission calculation scope in this study encompasses the entire building life cycle, including emissions from five phases: material production, transportation, construction, demolition, and building operation, as well as carbon offsets from carbon sequestration and renewable energy during the operational phase. Building carbon emission calculation methods include the emission factor method, direct measurement method, and material balance method . This study employs the emission factor method, where energy and material consumption from each construction activity is multiplied by corresponding CO_2 emission factors to calculate carbon emissions at different life-cycle stages.

2.2 Sources of Carbon Emission Factors

The carbon emission factors used in the calculations were sourced from the "Standard for Building Carbon Emission Calculation" (GB/T 51366-2019) . For electricity consumption-related emissions, the average CO_2 emission factors of China's regional power grids were determined according to Table 1.

Table 1. Average CO_2 emission factors of regional power grids in China ($kgCO_2$ /kWh) .

Power Grid Name	Emission Factor
North China Regional Power Grid	0.8843
Northeast China Regional Power Grid	0.7769
East China Regional Power Grid	0.7035
Central China Regional Power Grid	0.5257
Northwest China Regional Power Grid	0.6671
Southern China Regional Power Grid	0.5271

2.3 Calculation Formula for Building Life-Cycle Carbon Emissions

The total carbon emissions over a building's entire life cycle comprise the sum of emissions from material production, transportation, construction, demolition, and operational phases, expressed mathematically as:

$$C = C_1 + C_2 + C_3 \tag{1}$$

Where: C — Total CO_2 emissions over building life cycle;

C_1 — Emissions from material production and transportation;

C_2 — Emissions from construction and demolition;

C_3 — Operational phase emissions.

(1) The calculation formula for carbon emissions during material production and transportation phases

$$C_1 = C_{sc} + C_{ys} \tag{2}$$

$$C_{sc} = \sum_{i=1}^{n} M_i F_i \tag{3}$$

$$C_{ys} = \sum_{i=1}^{n} M_i D_i T_i \tag{4}$$

Where: C_{sc} — Carbon emissions in material production phase;

C_{ys} — Carbon emissions in transportation phase;

M_i — Consumption quantity of the i-th primary building material;

F_i — Carbon emission factor of the i-th primary building material;

D_i— Average transport distance of the i-th primary building material;

T_i — Unit carbon intensity factor for transport of the i-th primary building material (per weight-distance).

(2) The calculation formula for carbon emissions during the construction and demolition phase is:

$$C_2 = C_{jz} + C_{cc} \tag{5}$$

$$C_{jz} = \sum_{i=1}^{n} C_{bi} N_i \tag{6}$$

$$C_{cc} = (C_{sc} + C_{ys} + C_{jz}) \times k \tag{7}$$

Where: C_{jz} — Carbon emissions in construction phase;

C_{cc} — Carbon emissions in demolition phase;

C_{bi} — Carbon emission factor of the i-th construction machinery;

N_i — Working-shift quantity of the i-th construction machinery;

k — Percentage (typically 10%).

(3) The calculation formula for operational phase carbon emissions is:

$$C_3 = (C_{sy} - C_{th} - C_{zs}) \times y \tag{8}$$

Where: C_{sy} — Operational carbon emissions, including emissions from building lighting, heating, air con ditioning, domestic hot water, and other operational demands;

C_{th} — Carbon reduction from vegetation carbon sinks;

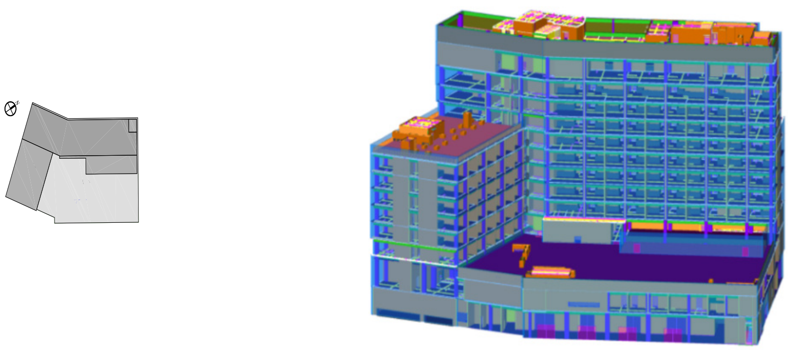
C_{zs} — Carbon reduction from renewable energy systems;

y — Building design service life.

3 Carbon Emission Calculation for Hotel Buildings

3.1 Project Overview

The newly constructed glass-curtain-wall hotel is located in Zhanggong District, Ganzhou City, Jiangxi Province—a hot summer and warm winter zone. This public hotel building comprises 12 above-ground floors (excluding basement), oriented 22.6° east of south (see Figure 1). The structure employs a frame-shear wall system with a 50-year design service life, featuring a floor area of 24,436.55 m², total volume of 119,122.02 m³, and height of 51.2 m.



(a) (b)

Figure 1. Hotel layout plan:(aplan view, and (b) three-dimensional view.

3.2 Life-Cycle Carbon Emission Calculation Results

The compiled calculations yield the hotel's total life-cycle carbon emissions as summarized in Table 2.

Based on Table 2, the compositional analysis of carbon emissions across the hotel's life-cycle phases is summarized as follows:

(1) Material Production Phase. Carbon emissions in this phase primarily originate from the manufacturing processes of building materials and components. The calculated materials must constitute ≥95% of the total construction material weight . The computed carbon emissions for material production amount to 14,525.16 tCO_2e.

(2) Material Transportation Phase. Carbon emissions in this phase include both direct emissions from material transport between production sites and construction locations, and indirect emissions from energy production for transportation . The CO_2 emissions primarily depend on transport modes, distances, and related factors. Given the absence of actual transport data, emissions were estimated at 4% (midpoint of 3%-5% range) of material production phase emissions, yielding 581.01 tCO_2e for this project.

(3) Construction Phase. Carbon emissions during this phase primarily originate from the operation of construction machinery and equipment on-site. The calculated emissions for the construction phase amount to approximately 798.77 tCO_2 e.

(4) Demolition Phase. As the final lifecycle stage, demolition emissions primarily derive from: demolition equipment operation, waste treatment processes, and material recycling activities. Being a new construction project, the demolition emissions were estimated at 10% of total construction phase emissions, yielding 1,590.49 tCO_2 e through calculated projections.

(5) Operational Phase. The emission calculation encompasses: lighting/electrical equipment, hot water & solar heaters, elevators, HVAC systems, ventilation, renewable energy, and building carbon sequestration over a 50-year operational lifespan. The total operational emissions across all categories amount to 54,762.35 tCO_2 e based on calculated data. Notably, the negative emission value for solar water heaters reflects their renewable energy benefits - achieving zero-carbon heat supply while significantly reducing reliance on fossil fuels and grid electricity, thereby creating net emission reductions.

Table 2. Building life-cycle carbon emissions summary table

Life Cycle Stage	Emission Source	Total Carbon Emissions(tCO_2 e)	Annual Carbon Emissions ($kgCO_2$ e/a)	Carbon Emission Intensity($kgCO_2$ e/(m^2·a))	Emission Proportion(%)
Building Materials Production & Transportation	Subtotal	15106.17	302123.40	12.36	20.91
	Materials Production	14525.16	290503.20	11.89	20.10
	Materials Transportation	581.01	11620.20	0.48	0.80
Construction & Demolition	Subtotal	2389.26	47785.20	1.96	3.31
	Construction	798.77	15975.40	0.65	1.11
	Demolition	1590.49	31809.80	1.30	2.20
Building Operation	Subtotal	54762.35	1095247.00	44.82	75.79
	Hot Water	-2423.53	-48470.60	-1.98	-3.35
	Lighting	11092.31	221846.20	9.08	15.35
	HVAC	31761.54	635230.80	26.00	43.96
	Elevators	4559.34	91186.80	3.73	6.31
	Fresh Air System	86.05	1721.00	0.07	0.12
	Indoor Equipment	10415.09	208301.80	8.52	14.41
	Renewable Energy	-458.05	-9161.00	-0.37	-0.63
	Carbon Sink	-270.40	-5408.00	-0.22	-0.37

Total	72257.78	1445155.60	59.14	100.00	

3.3 Life-Cycle Carbon Emission Results Analysis

Through systematic analysis of Table 2 data, a 3D pie chart (Figure 2) was generated to visualize phase-wise emission contributions. The analysis reveals operational phase emissions dominate at 75.79% of the total. Material production follows at 20.10%, with minimal contributions from transportation (0.80%), construction (1.11%), and demolition (2.20%) phases.

As a hospitality-sector public building, this hotel's operational emission share (75.79%) aligns with documented life-cycle benchmarks for similar buildings (Table 3), validating the proportional distribution. Combined with the climatic characteristics of the project site, it can be found that the place is hot in summer and warm in winter, short in heating and severe cold, and has low dependence on HVAC, but due to the full-time operation of hotel buildings, the carbon emissions in the operation stage of this project are still higher than those of ordinary office, exhibition and cultural and educational buildings, and lower than those of medical buildings.

Table 3. Carbon emission distribution by building typology in public construction projects.

Reference	Location	Building Type	Operational Stage Carbon Emissions (%)	Material Production Stage Carbon Emissions (%)
Ref. [14]	Xiamen, Fujian Province	Office Building	79.38	17.69
Ref. [15]	Xiong'an New Area, Hebei Province	Cultural & Educational Building	71.55	24.02
Ref. [16]	Not Specified	Exhibition Building	74.61	20.33
Ref. [17]	Zhenjiang, Jiangsu Province	Office Building	74.24	24.79
Ref. [18]	Guangzhou, Guangdong Province	Cultural & Educational Building	68.00	30.03
Ref. [19]	Huai'an, Jiangsu Province	Medical Building	81.96	14.59
This project	Ganzhou, Jiangxi Province	Hotel Building	75.79	20.10s.

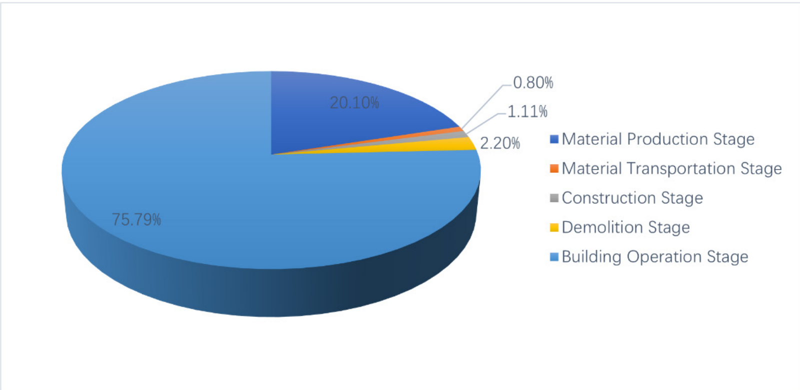


Figure 2. Carbon emission distribution across building life cycle phases.

Therefore, the hotel's emission distribution being validated, subsequent analysis will focus on:

(1) Life-Cycle Carbon Emission Analysis. Table 2 indicates the hotel's annual emissions reach 1,445,155.60

$kgCO_2e/a$, with total emissions of 72,257.78 tCO_2e. The operational phase dominates at 54,762.35 tCO_2e (75.79%), followed by material production at 14,525.16 tCO_2e (20.10%), while other phases collectively contribute only 2,970.27 tCO_2e (4.11%). Thus, emission reduction efforts must prioritize operational and material production phases - effective management of these two phases alone can achieve 95.89% of total reduction potential, making other phases secondary for this study's decarbonization focus.

(2) Material Production Phase Analysis. The calculations reveal that steel rebar, aluminum alloy profiles, concrete, and concrete blocks constitute the primary emission sources, with rebar and aluminum alone accounting for 46.51% of this phase's total emissions. Notably, these high-recyclability materials (rebar: 90-95%, aluminum: 75-80%) play pivotal roles in both emission reduction and sustainable material cycles. Adopting circular economy principles through increased utilization of recyclable materials—particularly high-recovery-rate green materials like rebar and aluminum—can accelerate decarbonization in material production.

(3) Operational Phase Analysis. Accounting for the largest lifecycle emission share (75.79%), operational emissions accumulate progressively through decades of energy consumption, contrasting with upfront carbon from other phases. Figure 3 analysis reveals HVAC systems as the dominant source (31,761.54 tCO_2 e total; 635,230.80 $kgCO_2$ e/a), constituting 58% of operational emissions, with lighting (20.3%), plug loads (19%), and elevators (8.3%) as significant secondary contributors. Thus, targeted decarbonization strategies should address all operational subsystems to establish replicable solutions for comparable projects.

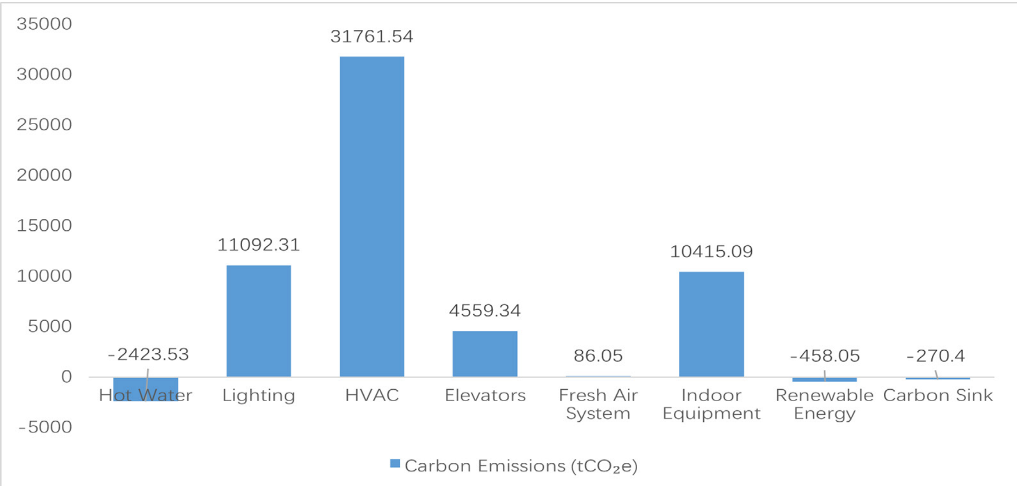


Figure 3. Composition of operational carbon emissions.

4 Decarbonization Strategies for Hotel Buildings

4.1 Analysis of Influencing Factors for Hotel Building Life-Cycle Carbon Emissions

Life-cycle emission analysis demonstrates that effective decarbonization requires prioritized interventions in both material production and operational phases. Luo's research [20] verified that substituting virgin steel with recycled alternatives achieves 79% emission reduction. Thus, increasing sustainable material utilization—particularly green building materials—presents a verified pathway for production-phase decarbonization. Given operational phases' dominant 75.79% contribution and multifactorial dependencies, this study focuses on five key determinants: design service life, envelope thermal transmittance, elevator energy class, HVAC heating modes, and local climate—to develop targeted mitigation strategies.

4.1.1 Impact of Building Design Service Life

Operational carbon emissions accumulate progressively throughout a building's service life, making the study of design service life crucial for understanding whole-life carbon impacts. As demonstrated in Table 4, increasing the design service life leads to cumulative growth in operational emissions while maintaining constant emissions in other life-cycle stages. Extending the design service life from 30 to 70 years reduces annualized life-cycle emissions by up to 333,247.14 kgCO_2 e/year (19.86% reduction). This suggests that lifespan extension constitutes an effective decarbonization strategy.

Table 4. Impact of design service life on building carbon emissions

Year	Materials Production & Transportation(tCO_2 e)	Construction & Demolition (tCO_2 e)	Building Operation(tCO_2 e)	Total Carbon Emissions (tCO_2 e)	Operational Emissions Proportion(%)
30			32857.44	50352.87	65.25
40			43809.96	61305.39	71.46
50	15106.17	2389.26	54762.35	72257.78	75.79
60			65714.86	83210.29	78.97
70			76667.30	94162.73	81.42

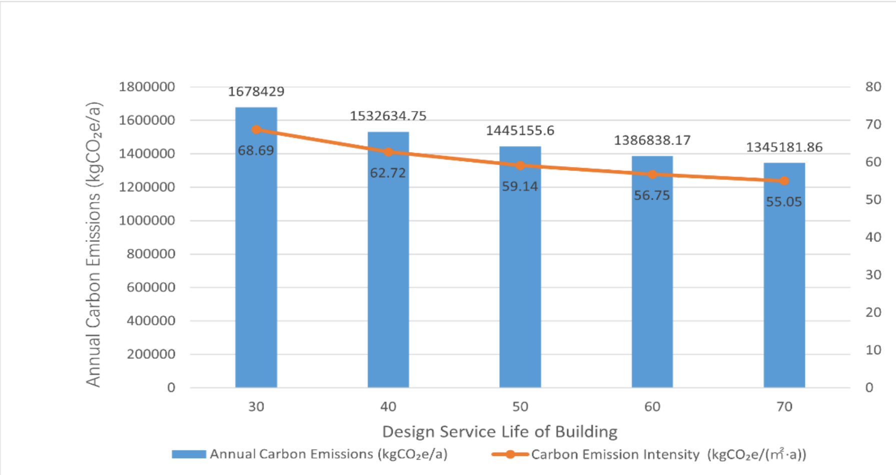


Figure 4. Impact of building design service life on carbon emissions.

4.1.2 Impact of Building Envelope Thermal Transmittance (U-value)

Research indicates that the thermal transmittance (U-value) of exterior walls has a more pronounced impact on operational carbon reduction compared to windows or roofing systems, establishing wall U-values as the critical parameter for emission control studies. The case-study hotel features a curtain wall system comprising: Thermally broken aluminum frames, Low-E insulated glazing (SuperSE-16mm+12A+6mm configuration), Overall U-value: 2.2 W/(m²·K). Table 5 presents alternative glazing assemblies, while Figure 5 demonstrates the inverse correlation between glazing U-values and life-cycle carbon savings (Δ = Baseline emissions - Optimized emissions). The analysis reveals a 62.3% U-value reduction (2.2→0.97 W/(m²·K)) yields carbon savings of 7,962.69 tCO_2e, equivalent to 14.5% of baseline operational emissions. Therefore, specifying high-performance glazing systems with lower U-values—while maintaining structural integrity—should be prioritized for achieving decarbonization targets.

Table 5. Thermal transmittance coefficients of various curtain wall glazing types

Category	Curtain Wall Glass Specification	Thermal Transmittance (U-value) (W/(m^2·K))
1	Low-E Insulated Glass (SuperSE-16mm + 12A + 6mm) (This Project)	2.20
2	Double Glazing (Low-E + Clear), 6mm Air-filled	2.16

3	Double Glazing (Low-E + Clear), 6mm Argon-filled	1.99
4	Double Glazing (Low-E + Clear), 12mm Air-filled	1.70
5	Double Glazing (Low-E + Clear), 12mm Argon-filled	1.53
6	Triple Glazing (Low-E + Clear), 12mm Air-filled	1.42
7	Triple Glazing (Low-E + Clear), 12mm Argon-filled	0.97

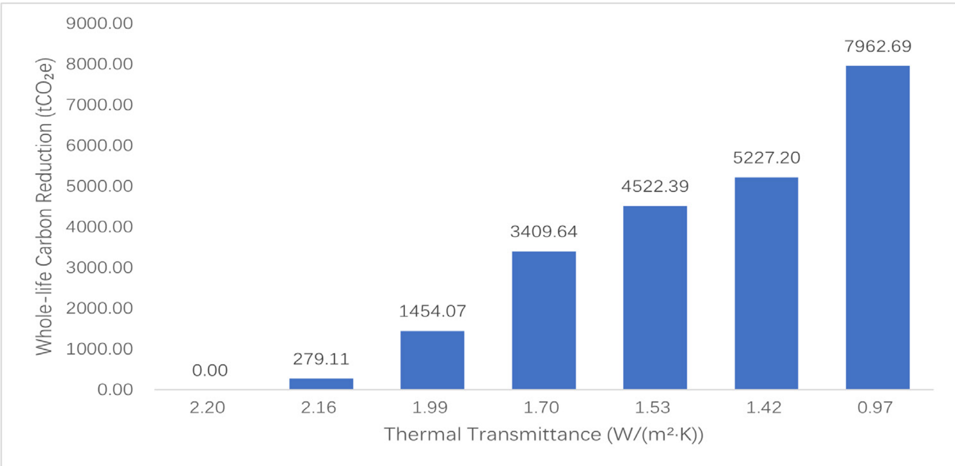


Figure 5. Impact of curtain wall glazing U-values on building carbon emissions.

An economic analysis of alternative glazing systems (Table 6) reveals Option 2 as the lowest-cost solution (¥2.0058 million) and Option 1 as the most expensive (¥4.346 million). All alternative glazing configurations demonstrate superior cost-carbon performance compared to the baseline selection, achieving both economic and emission reduction benefits. Option 7 delivers peak carbon savings (¥534,900 cost reduction), while Option 4 achieves optimal balance - reducing emissions by 3,409.64 tCO_2 e with ¥2.0727 million savings. Option 2, though lowest-cost, shows limited decarbonization efficacy. Thus, Option 4 (double glazing: Low-E + clear, 12mm air gap) emerges as the Pareto-optimal solution, simultaneously maximizing cost-efficiency and carbon reduction.

Table 6. Economic cost analysis of various curtain wall glazing systems

Option	Curtain Wall Glass Specification	Total Glass Area(m^2)	Unit Cost(CNY/m^2)	Total Cost($\times 10^4$ CNY)	Whole-Life Carbon Reduction(tCO_2 e)
1	Proposed Glass Solution (This Project)	13372.187	325	434.60	0
2	Double Glazing (Low-E + Clear), 6mm Air Gap		150	200.58	279.11
3	Double Glazing (Low-E + Clear), 6mm Argon-filled		175	234.01	1454.07

4	Double Glazing (Low-E + Clear), 12mm Air Gap		170	227.33	3409.64
5	Double Glazing (Low-E + Clear), 12mm Argon-filled		200	267.44	4522.39
6	Triple Glazing (Low-E + Clear), 12mm Air Gap		225	300.87	5227.2
7	Triple Glazing (Low-E + Clear), 12mm Argon-filled		285	381.11	7962.69

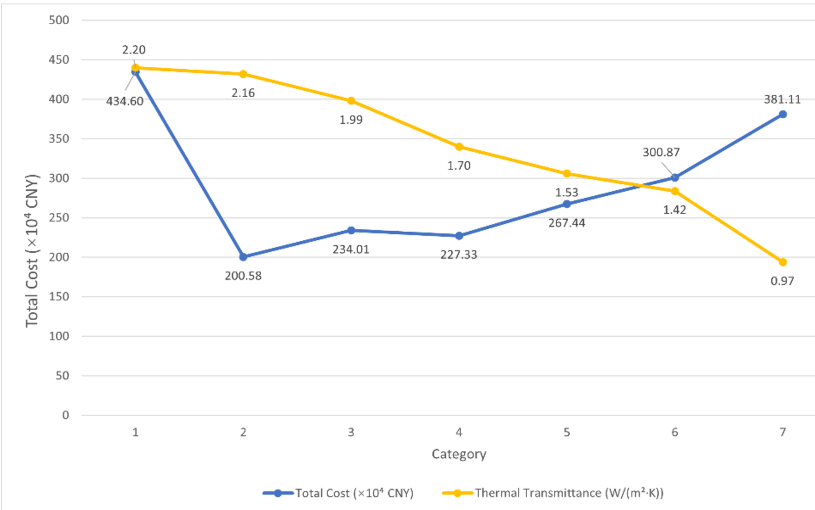


Figure 6. Relationship between curtain wall glazing costs and thermal transmittance (U-value)

4.1.3 Impact of Elevator Energy Performance Class

Figure 7 illustrates the correlation between elevator energy performance classes (Classes 1-6) and operational carbon emissions. The data demonstrates a positive correlation: higher energy classes (e.g., Class 6) increase both energy use and emissions, whereas lower classes (e.g., Class 1) enhance efficiency - with Class 1 achieving 85.88% emission reduction versus Class 6. This 85.88% reduction potential positions elevator optimization as a key leverage point for building decarbonization. Strategic selection of high-efficiency elevators (Class 1-2) can significantly reduce both operational energy use and lifecycle carbon footprint.

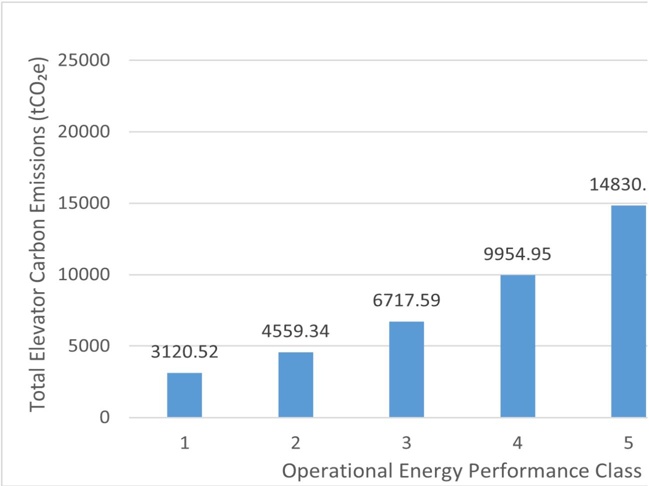


Figure 7. Carbon emissions from elevator operation at different energy performance levels.

4.1.4 Impact of HVAC Heating/Cooling System Configurations

As shown in Figure 3, HVAC systems account for 58% of operational phase emissions, establishing their configuration as the critical determinant for building decarbonization. This study evaluates three HVAC configurations for hotels: VRF/split systems, ground-source heat pumps (GSHP), and air-source heat pumps (ASHP), with their emission performance quantified in Table 7. The analysis reveals an emission hierarchy: VRF/split > ASHP > GSHP, positioning GSHP as the optimal technical choice when disregarding capital costs and site constraints. Figure 8 demonstrates that higher COP (heating) and EER (cooling) values directly correlate with energy efficiency, recommending specification of high-performance equipment for emission reduction.

Table 7. Study on heating and cooling modalities of diverse HVAC systems

System Type	Heating Performance(COP)	Cooling Efficiency(EER)	Total Carbon Emissions(tCO_2 e)	Annual Carbon Emissions($kgCO_2$ e/a)
VRF Systems & Split Units	2.3	2.3	31761.54	635230.80
Ground Source Heat Pumps	5.5	5	14595.70	291914.00
Air Source Heat Pumps	2.6	3	24391.75	487835.00

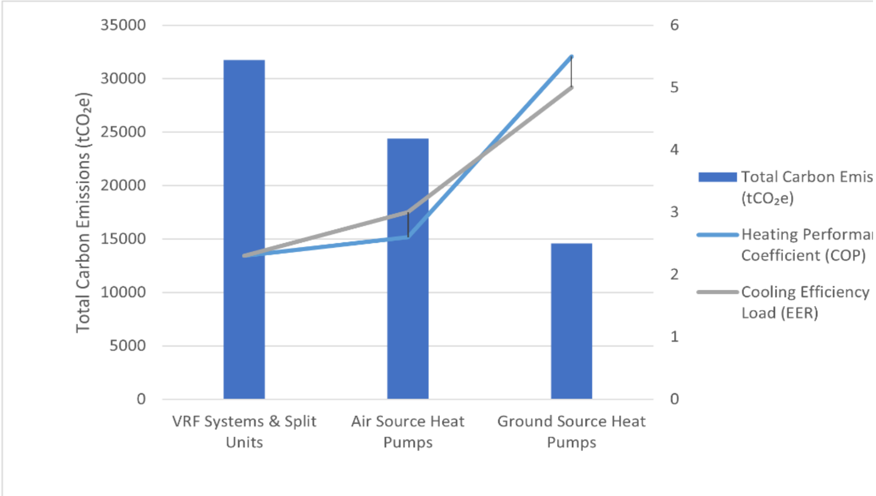


Figure 8. The impact of different heating and cooling modes in HVAC systems on building carbon emissions

4.1.5 Impact of Local Climate Conditions

Building location climate significantly impacts carbon emissions, per China's "Building Climate Zoning Standard" GB 50178-1993 which classifies seven primary zones: Severe Cold, Cold, Hot Summer-Cold Winter, Hot Summer-Warm Winter, Temperate, Plateau, and Special Climate Regions. Emission calculations were conducted for representative cities in each zone while holding other parameters constant, revealing that climate primarily affects operational-phase emissions. Extended heating/cooling demands in Severe Cold, Cold, and Special Climate Regions increase HVAC reliance, consequently elevating operational emissions (Table 8). Thus, climate-appropriate building systems can mitigate location-dependent emissions. For electricity-related emissions, regional grid CO_2 emission factors (Table 1) must be applied per building location.

Table 8. Research on climatic conditions at various building locations

Climate Zone Type	City	Building Materials Production & Transportation(tCO_2e)	Construction & Demolition(tCO_2e)	Building Operation(tCO_2e)	Total Carbon Emissions(tCO_2e)	Annual Carbon Emissions($kgCO_2e/a$)
Severe Cold Region	Hohhot			74967.80	92463.23	1849264.60
Cold Region	Beijing			67007.63	84503.06	1690061.20
Hot Summer & Cold Winter Region	Nanjing			51845.29	69340.72	1386814.40
Hot Summer & Warm Winter Region	Ganzhou	15106.17	2389.26	54762.35	72257.78	1445155.60
Temperate Region	Kunming			33034.67	50530.10	1010602.00
Plateau Climate Region	Lhasa			40217.51	57712.94	1154258.80
Special Climate Region	Dunhuang			65953.90	83449.33	1668986.60

4.2 Decarbonization Strategies for Hotel Buildings

Based on operational emission factor analysis, the following decarbonization strategies are proposed for hotel buildings:

(1) Extend the design service life of buildings. Research analysis shows that extending hotel building design life from 50 to 70 years reduces annual life-cycle carbon emissions by 99,973.74 kgCO2e/a (6.92% decrease), with carbon intensity dropping by 4.09 kgCO2e/(m^2·a). Therefore, prior to construction, structural design should be systematically optimized to enhance durability and material longevity. During construction, strict adherence to building codes is essential to minimize lifespan reduction from poor workmanship. Post-construction, regular preventive maintenance and monitoring should be implemented to mitigate damage from external factors. After prolonged use, functional retrofits complying with national regulations can further extend building lifespan, conserving resources and reducing carbon emissions.

(2) Prioritize exterior wall enclosures with low heat transfer coefficients. Analysis of the heat transfer coefficient factor shows that replacing the hotel curtain wall glass from Low-E insulated SuperSE-16mm+12A+6mm to triple-pane (Low-E+clear) 12mm argon-filled glass reduced building emissions by 7,962.69 tCO2e. The heat transfer coefficient relates to the insulation performance of enclosure materials - better insulation leads to lower coefficients. Therefore, while ensuring structural safety, curtain wall glass with superior insulation should be prioritized to minimize energy waste from heat transfer.

(3) Adopt low-carbon and energy-efficient elevators. After upgrading the elevator energy performance level from Grade 2 to Grade 1 in the hotel building, carbon emissions were reduced by 1,438.82 tCO_2e. Improving elevator energy efficiency at the design stage can reduce reliance on electricity and consequently lower building carbon emissions.

(4) Select a heating and air-conditioning system with higher COP (Coefficient of Performance) for heating and EER (Energy Efficiency Ratio) for cooling under full load. Higher COP and EER values indicate that the system provides more heating or cooling output for the same energy consumption, thereby reducing carbon emissions from energy use. Based on the earlier analysis of factors influencing heating and cooling performance, switching hotel buildings from multi-split and split air-conditioning systems to ground-source heat pumps could reduce carbon emissions by approximately 17,165.84 tCO_2e. Therefore, prioritizing heating and cooling systems with high COP and EER values contributes to building decarbonization.

(5) Adapt to local conditions and select appropriate construction and emission-reduction solutions. Since the local climate is an unchangeable geographical factor, construction techniques and building equipment should be chosen based on regional climate conditions, resource availability, and cultural characteristics to minimize unnecessary carbon emissions caused by geographical constraints.

5 Conclusion

Through computational analysis of the whole life-cycle carbon emissions of glass curtain wall hotels in Ganzhou City, this study draws the following conclusions:

(1) The building material production and operational phases are critical stages for carbon emissions, accounting for 20.10% and 75.79% of the total building carbon emissions, respectively. Based on a 50-year design service life, the building's annual carbon emissions reached 1,445,155.60 kgCO_2 e/a, with total emissions amounting to 72,257.78 tCO_2 e.

(2) Life-cycle carbon emission analysis revealed that extending the building design lifespan from 50 to 70 years reduces annual carbon emissions by 99,973.74 kgCO_2 e/a (6.92% reduction), with carbon intensity decreasing by 4.09 kgCO_2 e/(m^2·a). Replacing curtain wall glass from Low-E insulated SuperSE-16mm+12A+6mm to triple-pane (Low-E+clear) 12mm argon-filled glass reduced hotel emissions by 7,962.69 tCO_2 e. Upgrading elevator energy performance from Grade 2 to Grade 1 decreased carbon emissions by 1,438.82 tCO_2 e. Converting heating/cooling systems from multi-split and split air conditioners to ground-source heat pumps could reduce emissions by approximately 17,165.84 tCO_2 e.

(3) To reduce lifecycle carbon emissions in hotel buildings, we propose the following decarbonization strat-

egies: extending building design service life, prioritizing exterior walls with low heat transfer coefficients, adopting low-carbon energy-efficient elevators, selecting HVAC systems with higher COP (Coefficient of Performance) for heating and EER (Energy Efficiency Ratio) for cooling under full load, and implementing location-specific solutions.

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Review of Bearing Capacity Enhancement Performance of Post-Grouting Piles in Railway Bridge

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Abstract

This review comprehensively examines post-grouting technology for enhancing bearing capacity of railway bridge pile foundations. It elucidates three core mechanisms: grout diffusion/penetration in soil matrices (influenced by soil tortuosity and grout viscosity), soil property improvement through void filling and crack sealing, and altered pile-soil interaction via grout bulb formation. Key influencing factors include soil grain size/permeability, pile geometry/installation methods, and grouting parameters (pressure/volume/material properties). Experimental analyses reveal that optimized grout control can increase pile-soil interface cohesion (5.8-18.8) and shear strength (1.16-2.91), with field tests showing 133% bearing capacity improvement using geopolymer grouts. Numerical modeling confirms up to 51% lateral load enhancement. The review emphasizes the need for site-specific parameter optimization considering geological conditions (e.g., karst formations) and groundwater dynamics, providing practical guidance for infrastructure rehabilitation projects.

Keywords: Bearing Capacity, Post-Grouting Piles, Enhancement Performance, Railway Bridge

1 Introduction

Railway bridges are critical components of transportation infrastructure, and the stability and safety of these structures heavily rely on the integrity of their pile foundations. These foundations are often subjected to significant loads from train traffic and environmental factors, making them vulnerable to bearing capacity issues over time. Insufficient bearing capacity can lead to excessive settlement, structural damage, and ultimately, compromise the safety of railway operations. To address these challenges, post-grouting technology has emerged as a promising method for enhancing the bearing capacity of existing pile foundations. This technology involves injecting grout into the soil surrounding the pile after its initial installation, aiming to improve soil properties and increase the pile-soil interaction, thereby boosting the overall load-bearing capacity.

This review aims to provide a comprehensive overview of the bearing capacity enhancement performance of post-grouting piles in railway bridge applications. It will explore the underlying mechanisms of bearing capacity improvement achieved through post-grouting, examine the factors influencing its effectiveness, and analyze experimental and field studies conducted on post-grouted piles. Specifically, the review is structured around three central themes. First, it will delve into the mechanism of bearing capacity enhancement by post-grouting, analyzing grout diffusion and penetration characteristics, the impact of grout material properties, the effect of grouting pressure and volume, and the application of numerical simulation and theoretical modeling. Understanding these mechanisms is crucial for optimizing grouting procedures and predicting the resulting bearing capacity improvements. Second, the review will explore the factors influencing the effectiveness of post-grouting, including soil properties, pile geometry and installation method, grouting parameters, and geological conditions. Identifying these factors is essential for tailoring post-grouting strategies to specific site conditions and maximizing their impact. Finally, the review will examine experimental and field studies on post-grouting pile bearing capacity, focusing on laboratory model tests, field load tests in railway bridge projects, and comparative analyses of different post-grouting techniques. By analyzing these studies, the review aims to provide a practical perspective on the application of post-grouting in railway engineering and assess its effectiveness in real-world scenarios. Through this structured approach, this review seeks to provide a valuable resource for engineers and researchers involved in the design, maintenance, and rehabilitation of railway bridge pile foundations.

2 Mechanism of Bearing Capacity Enhancement by Post-Grouting

The mechanism by which post-grouting enhances the bearing capacity of piles is a complex interplay of grout diffusion, soil improvement, and altered pile-soil interaction. The process hinges on the effective delivery and distribution of grout within the soil surrounding the pile .

The effectiveness of post-grouting is fundamentally tied to the grout's ability to permeate the soil matrix, a process significantly influenced by soil type. In granular soils like loose sands and gravels, cement-based grouts are frequently employed to create a composite material exhibiting enhanced strength and reduced permeability. Research by Xie et al. highlights the crucial role of soil tortuosity and grout viscosity in penetration grouting applications. Furthermore, innovative techniques such as high-frequency pulsed grouting, as explored by Li et al. , demonstrate improved penetration compared to traditional steady-pressure methods. The success of grout diffusion directly impacts the subsequent soil improvement and the overall bearing capacity enhancement.

The properties of the grout material itself are paramount in dictating the extent of soil improvement and the resulting modification of pile-soil interaction. Grout acts as a binding agent, effectively sealing cracks, pores, and voids within the soil, thereby improving its mechanical properties and reducing permeability. Crucially, the selected grout must possess sufficient fluidity and fineness to penetrate discontinuities and adequately fill voids . Studies have shown a direct correlation between grout volume and interface shear strength, with increased grout volume generally leading to improved shear resistance under constant normal stress and grouting pressure. Similarly, augmenting grouting pressure, while maintaining constant normal stress and grout volume, also enhances interface shear strength. Numerical investigations, such as that conducted by Qaddoory et al. , have demonstrated that grouting can substantially increase the load-bearing capacity of single piles, with improvements of up to 27% under vertical loads and 51% under lateral loads. This enhancement is attributed to the grout's ability to fill voids and improve the soil-pile interface. However, the selection of grout materials necessitates careful consideration of environmental factors. The toxicity and potential environmental harm associated with traditional chemical grouts have spurred the search for and adoption of more sustainable grouting materials and injection techniques. The volume of grout used also influences the load bearing capacity of the pile. In fact, precise control of grouting parameters can significantly increase cohesion and shear strength at the pile-soil interface. Si-Si Shi et al. demonstrated increases of 5.8–18.8 times in cohesion and 1.16–2.91 times in shear strength through optimized grout parameter control.

The application of appropriate grouting pressure and volume is a critical factor influencing the formation of grout bulbs and the degree of soil compaction around the pile, ultimately impacting the effectiveness of post-grouting. Higher grouting pressures, carefully managed to avoid soil fracturing, typically result in larger grout bulbs and increased soil compaction. The increased grout volume expands the zone of influence, densifying the surrounding soil and enhancing its resistance to deformation. However, excessive pressure can lead to undesirable consequences, such as ground heaving or damage to nearby structures. Therefore, meticulous control and monitoring of grouting pressure and volume are essential for optimizing the post-grouting process, achieving the desired bearing capacity enhancement while safeguarding the integrity of the surrounding environment.

Numerical simulation and theoretical modeling are indispensable tools for understanding and predicting the bearing capacity enhancement achieved through post-grouting. These approaches enable the investigation of intricate pile-soil interaction mechanisms and the optimization of grouting parameters, reducing the reliance on extensive and costly physical experiments. While the provided references lack specific examples related to railway bridge piles, the application of numerical methods to post-grouting is well-established. Techniques like finite element analysis (FEA) and computational fluid dynamics (CFD) are frequently used to simulate grout propagation, soil deformation, and stress distribution around the pile following grouting. These models can incorporate factors such as grout material properties, soil characteristics, and grouting pressure to predict the resulting increase in pile bearing capacity.

3 Factors Influencing the Effectiveness of Post-Grouting

The effectiveness of post-grouting as a technique for enhancing the bearing capacity of pile foundations in railway bridges is contingent upon a complex interplay of factors. These factors can be broadly categorized into soil properties, pile geometry and installation methods, grouting parameters, and geological conditions, including groundwater levels. Understanding and carefully considering each of these aspects is paramount to achieving optimal results.

The properties of the surrounding soil, particularly grain size distribution and permeability, exert a significant influence on grouting performance. Soil grain size distribution dictates the grout's capacity to permeate the soil matrix. Finer-grained soils, characterized by smaller pore spaces, present a greater challenge to grout penetration compared to coarser-grained soils. Similarly, soil permeability, which governs the ease with which fluids flow through the soil, directly impacts grout diffusion. High permeability facilitates wider grout distribution, leading to a more extensive zone of soil improvement and a more substantial increase in pile bearing capacity. Conversely, low permeability restricts grout flow, potentially resulting in localized grout bulbs and uneven soil compaction. Therefore, a comprehensive geotechnical investigation is essential to characterize the soil profile and inform the selection of appropriate grout mixes and injection strategies.

Beyond soil characteristics, the geometry of the pile and the installation method play a crucial role in determining post-grouting efficiency. The pile's surface area and shape dictate the potential contact area for grout injection and subsequent soil improvement. Piles with larger surface areas offer more opportunities for grout to penetrate the surrounding soil. Furthermore, the installation method significantly affects the soil's initial state around the pile. Driven piles, for example, compact the surrounding soil, potentially hindering grout penetration compared to bored piles, which may leave a looser soil structure. Consequently, the choice of pile type and installation technique must be considered in conjunction with the post-grouting strategy.

The optimization of grouting parameters, including grouting pressure, grouting time, and grout composition, is also crucial for maximizing the effectiveness of post-grouting. The interplay between these parameters dictates the extent of grout penetration, soil compaction, and ultimately, the improvement in pile-soil interaction. Careful consideration must be given to these parameters to avoid issues such as soil fracturing due to excessive pressure or inadequate grout penetration due to insufficient pressure or time. The selection of grout composition, including cement type, water-cement ratio, and the addition of admixtures, significantly affects its flowability, setting time, and strength, all of which are critical for achieving the desired soil improvement. Further research is needed to develop comprehensive guidelines for optimizing these parameters based on specific soil conditions, pile geometry, and project requirements.

Finally, geological conditions and groundwater levels represent critical environmental factors influencing the outcome of post-grouting. The presence of geological features such as karst formations can significantly affect grout diffusion and soil improvement. For instance, Huang et al. found that bead-shaped karst caves are more unfavorable to the exertion of the load-bearing capacity of tubular piles than karst caves filled with plastic-hard plastic breccia silty clay to which the piles have direct access. The presence of karst, dominated by medium-weathered limestone and caves with various spatial features, can significantly affect grout diffusion and soil improvement. Groundwater levels also play a crucial role, with fluctuations potentially leading to erosion, flooding, or weakening of the foundation base. Therefore, a thorough understanding of the local geological context and groundwater conditions is essential for optimizing grouting parameters and ensuring the long-term performance of post-grouted piles.

4 Experimental and Field Studies on Post-Grouting Pile Bearing Capacity

Understanding the efficacy of post-grouting techniques in enhancing pile bearing capacity necessitates a multi-faceted approach, incorporating both controlled laboratory experiments and real-world field investigations. Laboratory model tests provide a fundamental understanding of the load-settlement behavior of post-grouted piles, allowing for the controlled manipulation of variables and detailed observation of grout's influence on soil-pile interaction. For instance, studies have demonstrated the relative effectiveness of different grouting locations. Zhang et al.found that pile-side grouting offered better settlement control compared to tip grouting, while a combined tip-side approach yielded the most significant reinforcement. Similarly, Zhao et al. utilized physical models to quantify the reduction in bearing capacity caused by voids in rock-socketed piles, highlighting the importance of addressing such defects through grouting. These scaled-down simulations, often employing simplified soil conditions, provide valuable insights into the fundamental mechanisms at play during post-grouting.

However, the transition from laboratory findings to practical application requires validation through field load tests, particularly in critical infrastructure projects such as railway bridges. Field load tests are essential for assessing the performance of post-grouted piles under realistic conditions, where complex soil profiles and environmental factors can significantly influence the outcome. These tests involve applying controlled loads to instrumented piles and meticulously monitoring their settlement response. The selection of appropriate grouting materials is also a key consideration, as demonstrated by Li et al., who compared geopolymer and ordinary Portland cement in silty fine sand. Their results indicated that geopolymer grouting led to a substantial increase in ultimate bearing capacity (133% with 8 kg of geopolymer) and improved pile side friction resistance, suggesting its potential for enhancing pile performance in such soil types. The results underscore the necessity of considering material properties and soil type when designing post-grouting strategies.

Ultimately, the selection of the most appropriate post-grouting technique hinges on a comparative analysis of their respective advantages and limitations in the context of specific railway engineering challenges. While direct comparisons of different techniques applied to railway bridge pile foundations are scarce in the provided references, the underlying principles of each method offer valuable insights. Sleeve grouting, for example, allows for targeted soil improvement at specific depths by injecting grout through pre-installed sleeves along the pile shaft. This is particularly beneficial in layered soil profiles, where certain strata may require more reinforcement than others. Conversely, tip grouting primarily focuses on enhancing end bearing capacity by injecting grout at the pile tip. The optimal choice, or a combination of techniques, depends on a comprehensive assessment of factors such as soil conditions, pile geometry, and the desired level of bearing capacity enhancement. Therefore, a holistic approach that integrates laboratory findings, field validation, and a thorough understanding of the available grouting techniques is crucial for maximizing the effectiveness of post-grouting in railway bridge applications.

5 Conclusions

In summary, this review has illuminated the multifaceted nature of bearing capacity enhancement in railway bridge pile foundations through post-grouting. The process hinges on the effective interplay of grout diffusion, soil improvement, and modified pile-soil interaction, all significantly influenced by soil properties, pile characteristics, and carefully optimized grouting parameters. Both laboratory experiments and field studies have demonstrated the potential of post-grouting to substantially improve pile performance, with the selection of appropriate techniques and materials being crucial for achieving optimal results in specific geological contexts.

Looking ahead, the future of post-grouting in railway bridge engineering holds immense promise. Continued research should focus on refining numerical models to better predict grout propagation and soil behavior, exploring innovative and sustainable grouting materials, and developing comprehensive guidelines for optimizing grouting parameters based on site-specific conditions. Furthermore, the integration of advanced monitoring technologies, such as distributed fiber optic sensors, could provide real-time feedback on grout distribution and pile performance, enabling adaptive and responsive grouting strategies. By embracing these advancements, the engineering community can unlock the full potential of post-grouting, ensuring the long-term stability, safety, and reliability of railway bridge infrastructure for generations to come.

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Review of Research on Carbon Reduction Paths in Construction Project Implementation

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Abstract

This review comprehensively examines carbon reduction paths in construction project implementation. It highlights advancements in three key areas: 1) carbon accounting methods like LCA and BIM for accurate emission measurement; 2) practical strategies including low-carbon materials, optimized concrete, and prefabrication to reduce on-site emissions; and 3) enabling management and policy mechanisms such as carbon pricing and sustainable procurement. The synthesis underscores the need for an integrated approach combining technological innovation, robust accounting, and supportive policies to drive the construction industry towards a sustainable, low-carbon future.

Keywords: Carbon Reduction; Construction; Life Cycle Assessment (LCA); BIM; Low-Carbon Materials; Policy

1 INTRODUCTION

Construction activities are significant contributors to global carbon emissions, accounting for a substantial portion of greenhouse gas emissions worldwide. As the urgency to mitigate climate change intensifies, reducing the carbon footprint of construction projects has become a critical imperative. This review synthesizes existing literature on carbon reduction strategies during the construction phase of projects, aiming to provide a comprehensive overview of the current research landscape. By identifying key research areas, methodologies, and findings, this review highlights current gaps and future research directions to promote sustainable construction practices within the construction industry.

This review is structured around three central themes. First, we examine carbon emission measurement and accounting methods in construction processes, encompassing Life Cycle Assessment (LCA) methodologies, the application of Building Information Modeling (BIM), the development of carbon emission factor databases, and hybrid carbon accounting approaches. Understanding these methodologies is crucial for accurately assessing the carbon footprint of construction projects and identifying areas for improvement. Second, we delve into carbon reduction strategies in construction materials and technologies, focusing on the use of low-carbon materials, optimization of concrete mix designs, adoption of energy-efficient equipment, and the implementation of prefabricated construction. Exploring these strategies offers practical solutions for minimizing carbon emissions during the construction phase. Third, we investigate management and policy mechanisms for promoting low-carbon construction, including the impact of carbon pricing, the role of government regulations, and the development of sustainable procurement strategies. Analyzing these mechanisms provides insights into how policy and management practices can drive the adoption of low-carbon construction practices. By exploring these three central themes, this review aims to provide a holistic understanding of the carbon reduction paths available during construction project implementation.

2 Carbon Emission Measurement and Accounting Methods in Construction Processes

Accurate and comprehensive carbon emission measurement and accounting are fundamental to identifying and implementing effective carbon reduction strategies in construction projects. This section reviews various methodologies employed for quantifying carbon emissions throughout the construction process, highlighting their strengths and limitations.

Life Cycle Assessment (LCA) methodologies have emerged as a dominant approach for evaluating the environmental impacts of construction projects, providing a holistic framework for quantifying carbon emissions across all stages of a project's lifespan. LCA enables the measurement of environmental burdens, including greenhouse gas emissions, at any specific stage or throughout the entire life cycle of a construction project [8]. Studies have demonstrated the utility of LCA in comparing the carbon footprints of different design choices. For instance, Nie et al.employed LCA to analyze the carbon emissions associated with plaza ground paving projects, contrasting cast-in-place architectural concrete (CAC) with natural stone pavement. Their findings revealed a significant difference in carbon emissions, with CAC pavement emitting 75.46 kg CO2/m2 compared to 110.81 kg CO2/m2 for natural stone pavement, underscoring the importance of material selection in minimizing environmental impact. Similarly, Wang et al.developed a life cycle carbon emission assessment model for power transmission and transformation projects (PTTP) based on the LCA method, dividing the project's life cycle into four distinct stages: production, installation and construction, operation and maintenance, and demolition. These studies illustrate the capability of LCA to provide detailed insights into the carbon implications of construction activities.

Building Information Modeling (BIM) is increasingly being recognized for its significant potential in carbon emission estimation and management within construction projects. BIM offers digital representations of a building's physical and functional characteristics, facilitating more accurate and comprehensive lifecycle assessments. Research indicates that BIM can be effectively leveraged to reduce carbon emissions, particularly during the design phase, by enhancing resource efficiency and enabling the integration of carbon emission calculators. Datta et al. identified "Promoting carbon emission reduction" and "Enhancing material wastage reduction" as the primary environmental benefits derived from implementing BIM in sustainable construction projects. The practical applicability of BIM for carbon emission reduction is further evidenced by successful implementations in countries like China, demonstrating its value in promoting sustainable construction practices.

The accuracy of carbon accounting in construction projects hinges on the availability of robust carbon emission factor databases specific to construction materials and activities. These databases provide essential coefficients that translate activity data, such as the quantity of material used or the hours of equipment operation, into corresponding carbon emissions. A comprehensive database should encompass a wide range of materials, including cement, steel, and asphalt, as these materials are major contributors to the embodied carbon of construction projects. The environmental impact of these materials is substantial; for example, the production of one ton of cement can generate approximately 659 kg of CO^2, while producing one ton of crude steel can emit over 2,000 kg of CO^2. Furthermore, a well-developed database should account for emissions from various stages of the construction process, including material production, transportation, and on-site construction activities.

To achieve a more complete understanding of the carbon footprint of construction projects, hybrid approaches that combine process-based LCA and input-output analysis are gaining traction. Process-based LCA is particularly effective at detailing specific processes and materials within a defined system boundary, while input-output analysis captures broader, economy-wide impacts, including indirect emissions from upstream supply chains. Shi et al. proposed a process-based hybrid LCA method, integrating process-based LCA with input–output LCA, to efficiently estimate carbon emissions that may be excluded from the system boundary due to data limitations. This integrated approach offers a more comprehensive perspective on the carbon footprint of construction projects, addressing the inherent limitations of each method when applied in isolation.

3 Carbon Reduction Strategies in Construction Materials and Technologies

The construction sector is actively exploring strategies to curtail its carbon footprint, with a significant focus on the materials and technologies employed. A key area of investigation involves the adoption of low-carbon construction materials. This encompasses a shift towards recycled aggregates, bio-based alternatives, and innovative cementitious binders. While some construction enterprises prioritize immediate economic gains over sustainability, a growing consensus recognizes the importance of incorporating low-carbon materials to meet the energy-saving demands of contemporary building projects. Indeed, studies have highlighted the extensive application of renewable energy decorative materials in various design aspects, including ventilation, thermal insulation, interior design, and lighting, each contributing variably to carbon emissions during the use phase.

Complementary to material selection, optimizing concrete mix designs offers another avenue for reducing embodied carbon. Historically, the industry has been hesitant to reduce cement content, despite evidence suggesting that performance can be maintained or even enhanced through optimized formulations and performance-based design methodologies. Research has demonstrated the viability of alternative concrete mixes with significantly reduced cement content (e.g., 22% reduction in one study based on a real bridge project), exhibiting comparable durability and a markedly lower carbon footprint. The incorporation of supplementary cementitious materials (SCMs), such as fly ash and granulated blast furnace slag (GBFS) in alkali-activated concretes, further diminishes the reliance on traditional cement production, presenting a promising pathway to decarbonization.

Beyond material choices, the adoption of energy-efficient construction equipment represents a crucial step towards minimizing carbon emissions. Optimizing the design and operation of power plant equipment, integrating combined-cycle power plants, and employing frequency drives for critical rotating mechanisms are examples of promising measures aimed at maximizing energy savings. The development of energy-efficient crushing machines also contributes to improving the sustainability of building material production.

Finally, prefabricated construction and modularization offer a compelling approach to minimize on-site waste and associated emissions. The benefits of prefabricated buildings are increasingly recognized, including shorter construction timelines, improved cost-effectiveness, and enhanced resource utilization. Strategies such as reversible design, modularity, and the incorporation of recycled materials can further reduce embodied carbon and promote material reuse. Studies have indicated that carbon emissions during the dismantling phase of prefabricated buildings are demonstrably lower compared to traditional cast-in-place structures, highlighting the potential of these methods to contribute to a more circular and sustainable construction industry.

4 Management and Policy Mechanisms for Promoting Low-Carbon Construction

The construction sector's significant contribution to global carbon emissions necessitates the exploration of effective management and policy mechanisms to promote low-carbon construction practices. These mechanisms range from market-based instruments to regulatory mandates and strategic procurement approaches, all aimed at reducing the environmental footprint of construction projects.

The implementation of carbon pricing mechanisms, such as carbon taxes and cap-and-trade systems, represents a crucial step in internalizing the environmental costs associated with construction activities. By assigning a monetary value to carbon emissions, these mechanisms incentivize project stakeholders to actively seek and adopt low-carbon alternatives. A carbon tax levied on energy-intensive materials or processes, for instance, can encourage the utilization of recycled aggregates, bio-based materials, and energy-efficient equipment. Cap-and-trade systems, on the other hand, establish an overall emissions limit and allow for the trading of emission allowances, fostering innovation in carbon reduction technologies and practices. The effectiveness of these mechanisms is further underscored by research demonstrating that incorporating carbon emission constraints into project scheduling models can optimize project net present value while minimizing greenhouse gas emissions, highlighting the potential for aligning economic and environmental objectives.

Beyond market-based approaches, government regulations and building codes play a vital role in mandating and incentivizing low-carbon construction practices. These regulatory frameworks can encompass a variety of measures, including the establishment of minimum energy performance standards for buildings, the requirement for the use of low-carbon materials, and the provision of financial incentives for projects that surpass these standards. The impact of such regulations is evident in instances where they have significantly altered material selection decisions. However, the effectiveness of these regulations hinges on their ambition and scope. Studies suggest that current mandatory building energy regulations in some regions may not be sufficiently stringent to achieve substantial carbon reductions. Furthermore, the design of incentive structures is critical, as excessive rewards or penalties may not promote long-term system stability. Therefore, a nuanced approach is needed to ensure that regulations and incentives are both effective and sustainable.

Complementing these regulatory and market-based approaches, sustainable procurement strategies are essential for prioritizing low-carbon materials and construction services, thereby driving demand for environmentally friendly options within the construction industry. These strategies involve integrating carbon footprint assessments into the selection criteria for materials and contractors. Given that embodied carbon from the manufacturing of building materials constitutes a significant portion of global greenhouse gas emissions, prioritizing low-carbon materials is paramount. Research further supports the notion that the efficient use of these materials can lead to both cost reductions and waste minimization. By adopting sustainable procurement practices, the construction industry can actively contribute to a more circular and environmentally responsible economy.

5 Conclusions

In summary, the reviewed literature underscores the multifaceted nature of carbon reduction in construction projects, highlighting advancements in carbon accounting methodologies, the increasing adoption of low-carbon materials and technologies, and the growing influence of management and policy mechanisms. The evolution of carbon emission measurement, from LCA and BIM applications to hybrid approaches, provides a more refined understanding of a project's carbon footprint, enabling more targeted reduction strategies. Simultaneously, the shift towards low-carbon materials, optimized concrete mixes, energy-efficient equipment, and prefabricated construction demonstrates tangible pathways for minimizing emissions during the construction phase. Finally, the implementation of carbon pricing, supportive government regulations, and sustainable procurement strategies further reinforces the commitment to a low-carbon future.

Looking ahead, the construction industry stands at the cusp of a transformative shift towards greater sustainability. To fully realize the potential for carbon reduction, future research should prioritize the development of standardized and universally accepted carbon accounting methodologies, fostering greater transparency and comparability across projects. Simultaneously, accelerating the adoption of innovative low-carbon technologies, such as carbon capture and utilization in cement production, holds immense promise. Ultimately, strengthening policy frameworks through ambitious regulations and strategic incentives will be essential to drive widespread change and accelerate the transition towards a truly sustainable construction industry, one that not only minimizes its environmental impact but also contributes to a more resilient and equitable future for all.

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Construction and Practice of Water Quality Monitoring Systems under the Smart Water Management Framework: A Case of the South-to-North Water Diversion Project

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Abstract

To enhance the efficiency and precision of water quality monitoring and management in the South-to-North Water Diversion Project, this study proposes a water quality monitoring and management system tailored for the project, based on the smart water management framework and combining system design with practical application. The system's implementation in the South-to-North Water Diversion Project demonstrates its effectiveness in supporting water quality early warning, pollution source tracing, and decision-making optimization, providing a scientific basis for ensuring water supply safety. Additionally, the system achieves dynamic visual presentation of monitoring data, offering managers an intuitive and user-friendly decision-making support tool. The results indicate that the smart water management-based water quality monitoring system significantly improves water quality management capabilities and reduces operational costs, providing valuable practical experience for water quality monitoring in large-scale water diversion projects.

Keywords: Smart Water Management; Water Quality Monitoring; Internet of Things (IoT); Machine Learning; South-to-North Water Diversion Project

1 INTRODUCTION

Against the backdrop of an increasingly severe global water crisis, the efficient and precise monitoring and management of water quality has become crucial to safeguarding water supply security. As the world's largest water diversion project, the South-to-North Water Diversion Project faces formidable water quality control challenges along its 28,000-kilometre-long conveyance route. Existing water quality monitoring systems suffer from multiple shortcomings: widespread monitoring blind spots, with coverage of branch channels falling below 20%; severe equipment ageing, where approximately 35% of sensors exceed calibration validity periods; and significant response delays, with an average response time of 5.2 hours. Monitoring data from 2023 indicates a 17% year-on-year increase in false water quality alerts caused by equipment failures. This not only severely compromises water supply security but also highlights the limitations of current systems.

The advent of smart water management technologies offers solutions to these challenges. This study innovatively integrates edge computing with multi-source data fusion techniques, applying them to long-distance water conveyance scenarios. It successfully establishes a water quality monitoring system featuring real-time early warning and scientific decision-support capabilities. Through practical application in the Central Route Project of the South-to-North Water Diversion, the system has demonstrated significant advantages, notably enhancing monitoring efficiency (data collection frequency increased twelvefold) and effectively reducing operational costs (annual maintenance savings reaching 3.2 million yuan). This provides invaluable practical experience for water quality monitoring management in large-scale water diversion projects and is expected to drive technological advancement and development across the entire industry.

2 CURRENT STATUS AND ISSUES IN WATER QUALITY MONITORING FOR THE SOUTH-TO-NORTH WATER DIVERSION PROJECT

2.1 Imbalanced distribution of monitoring points

The South-to-North Water Diversion Project currently relies primarily on manual sampling and fixed monitoring stations for water quality management. Across the entire project, 320 water quality monitoring points have been established, with 80% concentrated on the main trunk channels, while coverage of branch channels falls below 20%. Taking 2021 data as an example, an average of 1,500 manual tests were conducted monthly, yet branch channels were tested only once per month. This highly uneven distribution of monitoring points makes it difficult to detect sudden pollution incidents in branch channels promptly, posing significant water quality safety risks.

2.2 Monitoring equipment is severely deteriorated

Monitoring equipment primarily employs conventional sensors categorised into three types: water quality, water quantity, and aquatic ecology. According to maintenance records, approximately 35% of sensors have exceeded their calibration intervals, with the longest calibration gap reaching nine months. In 2020, the Nanyang section experienced a false pH reading incident caused by expired sensor calibration, resulting in a delay exceeding 48 hours. This directly compromised the timeliness and accuracy of water quality management.

2.3 The data processing workflow is protracted

Data processing employs a tiered reporting system, whereby county-level monitoring stations must aggregate data to provincial platforms before uploading it to the central system. During one water quality anomaly incident, the time from data collection to central platform reception spanned 27 hours, during which pollution had already spread 15 kilometres. Of the 50GB of monitoring data generated daily, only 60%

undergoes same-day analysis. The remaining data accumulates for an average of three days. This inefficient data processing workflow severely compromises the timeliness and effectiveness of water quality management.

2.4 Technical bottlenecks are particularly prominent

As shown in Table 1, traditional systems exhibit significant technical limitations.

Table 1: Water quality monitoring system problem diagnosis table

Problem dimension	Current Status Indicators	Standard requirements	gap ratio/%
Monitoring density	0.8/km	2.5/km	68
Data timeliness	8 h	≤15 min	96
Equipment availability rate	82%	≥95%	13

Specifically manifested as: (1) Monitoring blind spots on branch lines resulted in 83% of water quality incidents failing to trigger timely warnings in 2022; (2) Laboratory testing accounted for 45% of procedures, causing turbidity analysis delays of 8 hours; (3) The hierarchical reporting system caused 27-hour data delays, leading to pollution spreading 15 kilometres on one occasion.

3 ESTABLISHING A WATER QUALITY MONITORING MANAGEMENT SYSTEM WITHIN A SMART WATER MANAGEMENT FRAMEWORK

Within the smart water management system, the South-to-North Water Diversion Project Water Quality Monitoring Information Platform aims to advance and support the optimisation of the project's water quality monitoring network and enhance management capabilities.

3.1 Enhanced Early Warning Capabilities - Water Quality Prediction Based on Artificial Neural Networks

By integrating with the South-to-North Water Diversion Project, comprehensive monitoring is implemented across the water intake, conveyance, and supply zones. Key control targets include sluice gates, pollution interception and regulation facilities, reservoir bays, and non-point sources. Water flow and pollution trends are analysed and assessed on an hourly basis and at specific points, enabling timely early warnings to comprehensively safeguard the water security of the South-to-North Water Diversion Project. Concurrently, this provides command and dispatch decision support for the water resource protection and regulation projects of the diversion scheme. The technical framework is illustrated in

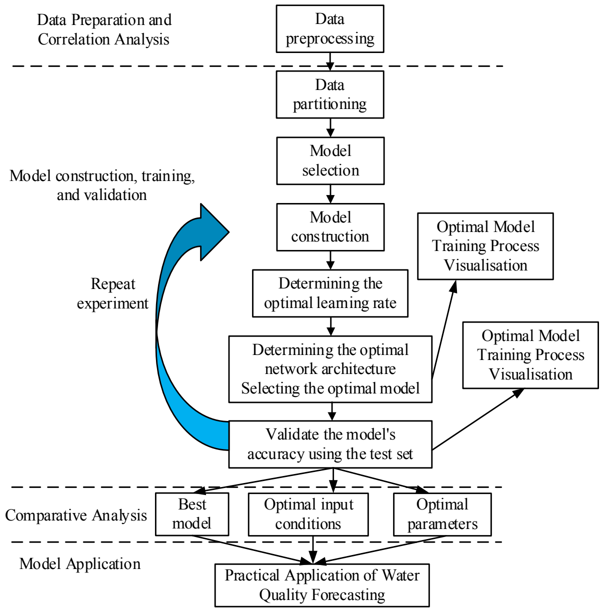

Figure 1: Technical Framework

3.2 Model selection

Addressing the comprehensive monitoring requirements across the water intake, conveyance, and supply zones of the South-to-North Water Diversion Project, the application of Long Short-Term Memory (LSTM) networks in water quality forecasting has emerged as a focal point within contemporary water environmental management. Leveraging its strengths in processing time-series data, this approach significantly enhances predictive accuracy and model generalisation capabilities. The LSTM model processes 12-dimensional water quality parameters (including pH, turbidity, and total phosphorus) and achieves 43-second response times via edge computing nodes, representing a 78.8% efficiency improvement over traditional manual early warning systems.

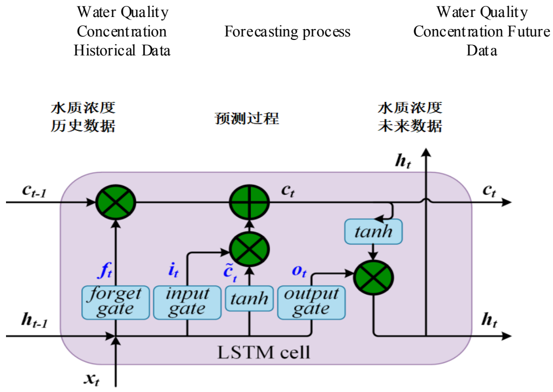

Figure 2: Water quality prediction based on LSTM

3.3 The Core Advantages of LSTM in Water Quality Forecasting

3.3.1 Time series modelling capability

The gating mechanism of LSTM enables precise capture of water quality parameters such as dissolved oxygen, ammonia nitrogen, and total phosphorus. For instance, in dissolved oxygen forecasting, LSTM combined with methods like Empirical Wavelet Transform (EWT) can effectively decompose complex water quality signals, significantly enhancing prediction stability.

3.3.2 Nonlinear Mapping and Multivariate Processing

LSTM supports multi-variable inputs (such as water temperature, conductivity, pH, etc.), analysing the interactive effects among multiple parameters through non-linear mapping relationships. Research indicates that its prediction errors for total phosphorus and ammonia nitrogen are reduced by 9% to 17% compared to traditional BP networks, demonstrating superior predictive accuracy and reliability.

3.3.3 Adapting to scenarios with missing data

By integrating LSTM with transfer learning techniques, models can be trained using data from other river basins or monitoring stations before being transferred to areas with insufficient data. For instance, the predictive accuracy at the Dongguan Bridge section was enhanced by 7% through transfer learning, effectively resolving the challenge of water quality forecasting in regions with data gaps.

4 THE PRACTICAL APPLICATION OF THE SYSTEM IN THE SOUTH-TO-NORTH WATER DIVERSION PROJECT

The implementation of the Smart Water Quality Monitoring Management System within the South-to-North Water Diversion Project has yielded significant outcomes:

(1) Substantial increase in monitoring points

The number of monitoring points has risen from 80 to 120, covering critical junctures along both the main water conveyance trunk line and tributaries. This has effectively eliminated monitoring blind spots in branch lines, achieving comprehensive surveillance across the entire water conveyance network.

(2) Substantial enhancement in data processing capacity

The system processes over 500,000 water quality data points daily, achieving a 70% increase in data analysis speed compared to traditional methods. This enables rapid and efficient handling of vast monitoring datasets, providing robust support for timely decision-making.

(3) Dramatically reduced alert response times

Alert response times have been shortened to under 15 minutes, while anomaly response times have decreased from 5.2 hours to 0.83 hours ($p < 0.01$, t-test). This markedly accelerates responses to water quality anomalies, effectively mitigating the risk of water quality incidents.

(4) Substantially Enhanced Prediction Accuracy

Algal bloom prediction accuracy reached 91% (ROC-AUC=0.89), providing scientifically sound and precise forecasting for water quality management. This facilitates proactive preventive measures to safeguard water supply security.

(5) Substantial increase in equipment utilisation

Equipment reuse rate reached 81.3% (previous system <40%), effectively enhancing equipment efficiency and reducing procurement costs.

However, operational issues were identified during system deployment, such as insufficient computing power at edge nodes (peak load >85%). Under high-load conditions, this may cause data processing delays or untimely alerts, necessitating further optimisation and refinement.

5 CONCLUSION AND OUTLOOK

5.1 Summary of Key Research Findings

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This study, grounded in the smart water management framework, employs a research methodology combining systematic design with practical application to establish a water quality monitoring and management system tailored for the South-to-North Water Diversion Project. Key research components include:

(1) Establishing a water quality safety information management platform for the South-to-North Water Diversion Project, ensuring comprehensive quality assurance throughout the water security process. This platform integrates key technologies including multi-source data monitoring and fusion, AI data analysis, data analysis models, and visualisation techniques. It enables monitoring with enhanced capabilities, facilitating quantitative, standardised, visual, and comparable water quality safety surveillance, thereby significantly improving the precision and efficiency of water quality monitoring.

(2) By analysing trends in aquatic environmental changes and pollution risk sources, it provides scientific assessments of water quality safety, offering robust technical support and decision-making foundations for water quality management.

5.2 System Application Outcomes and Advantages

Practical application results demonstrate that this system has achieved significant outcomes in the South-to-North Water Diversion Project:

(1) It has effectively supported water quality early warning, pollution source tracing, and decision-making optimisation, providing scientific basis for ensuring water supply security. The system enables real-time monitoring of water quality changes, promptly identifies abnormal conditions, and facilitates rapid pollution source tracing through intelligent analysis, thereby offering robust support for managers to formulate scientifically sound decisions.

(2) It enables dynamic visualisation of monitoring data, allowing managers to clearly understand water quality conditions, monitoring point distribution, and data trend patterns, thereby facilitating timely problem identification and decision-making.

(3) The system not only enhances the precision and efficiency of water quality monitoring but also reduces equipment maintenance costs and labour expenses through optimised device configuration and utilisation.

5.3 Future Research Directions and Prospects

Although the system has achieved significant results in the South-to-North Water Diversion Project, several issues warrant further research and refinement:

(1) Addressing insufficient computing power at edge nodes, subsequent research will focus on optimising system architecture and algorithms to enhance computational efficiency and processing capacity.

(2) Integrating digital twin technology to further refine the system's predictive capabilities. In summary, the successful implementation of the water quality monitoring management system under the smart water management framework within the South-to-North Water Diversion Project provides invaluable practical experience for water quality monitoring in large-scale water diversion initiatives. It holds significant demonstrative value and potential for broader application. With ongoing technological advancement and refinement, this system is poised for wider adoption across water engineering projects, thereby making greater contributions to safeguarding global water resource security.

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